Green data centers: towards a sustainable digital transformation

A practitioner's guide

2023

Copyright and publication information

ITU and The World Bank. 2023. Green data centers: towards a sustainable digital transformation - A practitioner's guide. Geneva and Washington, D.C.

ISBN Print: 978-92-61-37481-5
ISBN PDF: 978-92-61-37491-4
ISBN Epub: 978-92-61-37501-0

Acknowledgements

The World Bank Group and ITU developed this guide with support from the Digital Development Partnership. This guide is also a product of the Data Economy and GovStack initiatives funded by the Federal Ministry for Economic Cooperation and Development (BMZ) and supported by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Rosie McDonald, ITU, and Sara Ballan, World Bank, led development of the guide. Core external contributors were Xiao Bukas, John Watt, and Maarten Voorneveld. The authors wish to thank experts from ITU (including ITU-T Study Group 5), the World Bank, Smart Africa, and the Sustainable Digital Infrastructure Alliance who contributed their time and insights to reviewing the guide.

Design

Nienke Haccoû | bureauopdekaart.nl

Table of contents

List of figures and cases

FIGURES

CASES

List of tables

TABLES

Acronyms

ABBREVIATIONS	DESCRIPTION
ESG	Environmental, social, and governance
GHG	Greenhouse gas
GPP	Green public procurement
ICT	Information and communications technology
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
ITU	International Telecommunication Union
IXP	Internet exchange point
LCA	Lifecycle assessment
LMIC	Low- and middle-income country
PPA	Power purchase agreement
PUE	Power use effectiveness
WUE	Water use effectiveness

Executive summary

Reliable, secure data hosting solutions are becoming increasingly important to support everyday functions across societies, including for public management and service delivery. As a result, investments in data infrastructure are increasing around the world, contributing to growth of the digital economy and to goals for digital transformation of public administration and services. Data infrastructure such as data centers and cloud solutions are essential for modern societies, but they are also highly energy intensive and consume refrigerants and often large amounts of water for cooling. As such, they leave a large environmental footprint and contribute to greenhouse gas (GHG) emissions. Climate change also affects data centers. Climate hazards such as floods and increasing temperatures put data centers at risk and require site specific adaptation measures to protect investments and ensure resilient data storage. To ensure sustainable digital transformation, efforts are needed to green digital infrastructure, this includes managing climate risks and reducing the climate and environmental footprint of data centers.

A wide range of practitioners are involved in decisions related to greening data centers. These individuals encompass policy makers developing digital economy and digital transformation strategies, as well as the engineers and technicians working every day on the floors of data centers. This guide takes the vantage point of public practitioners, but its fundamental principles apply to any stakeholder engaged in policymaking, regulation, or the development, operation, or procurement of data center infrastructure and services. Opportunities for and barriers to greening data centers are context specific, and strategies and policies should consider local conditions. Designed with a global outlook, the guide examines specific challenges and opportunities in low- and middle-income countries (LMICs).

Greening data centers supports climate change mitigation and adaptation efforts, contributing to decarbonization of a country's economy and helping meet wider sustainability goals. Addressing the climate footprint of data centers requires a circular, life-cycle approach, spanning design, manufacturing, procurement, operations, reuse, recycling, and e-waste disposal. The guide covers six dimensions that practitioners can consider in efforts to green data centers (Figure 1). The first dimension responds to climate risks to data centers, while the other five dimensions seek to mitigate the climate and environmental footprint from data centers. These dimensions should also be considered as part of public procurement strategies and requirements, and in wider policies and regulations to encourage investment in green data centers and increased resilience and efficiency of existing data center infrastructure.

The guide covers six dimensions that practitioners can consider to green data centers.

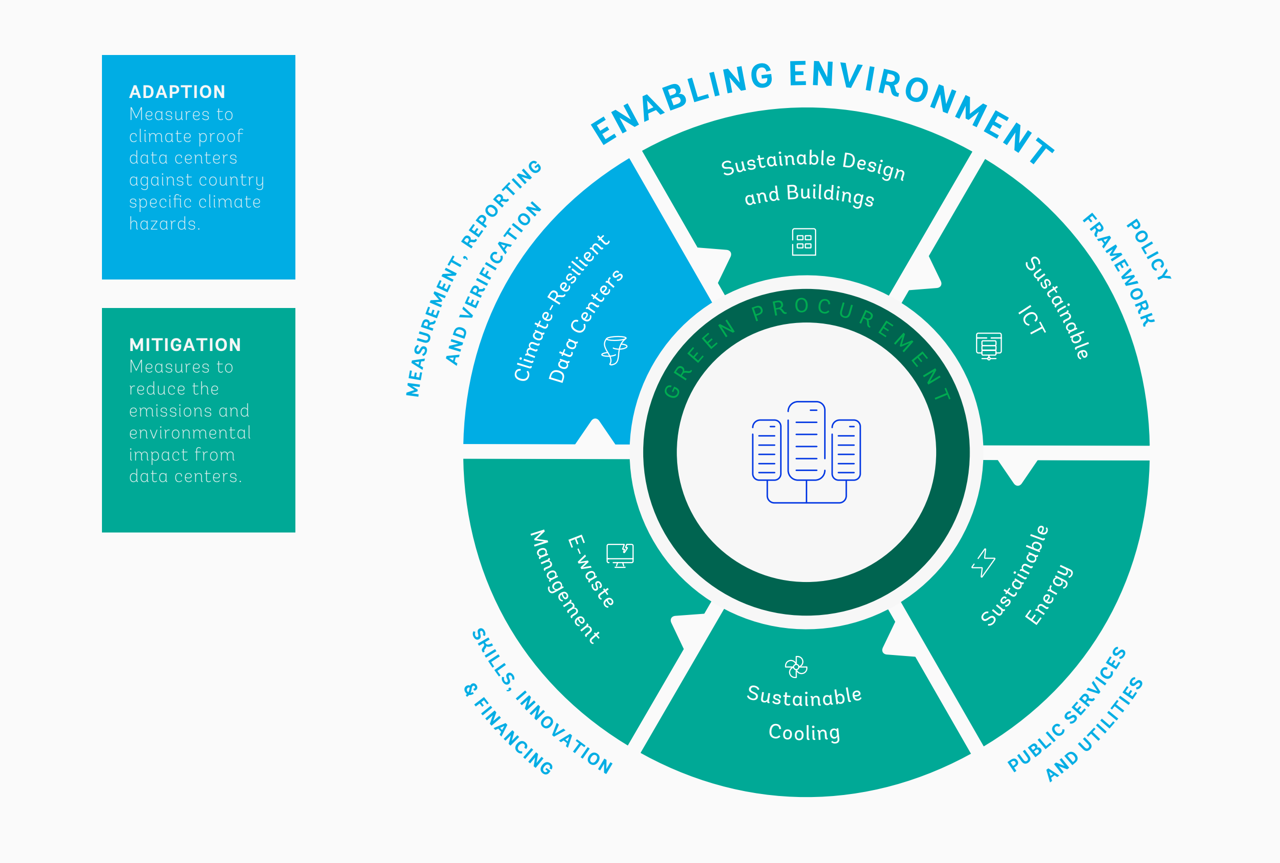


Figure 1. Green Data Center Dimensions

Climate-Resilient Data Centers

As economies digitalize, disruptions to digital infrastructure can have economy-wide implications, including taking down payment systems and access to critical communications and other essential public and private services. Data centers are susceptible to climate hazards. For example, flooding can damage data center information and communications technology (ICT) equipment, drought can restrict water access for cooling, and high temperatures can stress cooling systems. Although risks differ according to geography and climate zone, LMICs are particularly vulnerable. Eight of the 10 countries most affected by extreme weather events in 2019 were classified as LMICs. Climate resiliency should be considered not only when planning and operating individual data centers, but also at a national level to protect critical infrastructure. Risk assessments are the first step in identifying vulnerabilities and can guide resiliency measures, including redundancy planning, site selection, the use of weather-resilient building materials and design, as well as backup and recovery plans.

Sustainable Design and Buildings

Most sustainable management of data centers focuses on the operational stage and overlooks green building aspects, including opportunities to retrofit or expand existing facilities. Site selection determines access to resources such as renewable energy and water and can affect energy use. For example, choosing a cooler location within a country can reduce cooling needs. In some countries data centers are competing for scarce water and energy resources and governments need to factor this into planning and land zoning. The design of the data center building affects environmental risks, cooling needs, resource use, and energy inefficiency. Proper dimensioning is one of the most important parameters for net sustainability. Modular data center design is increasingly applied to allow for future expansion and avoid idle capacity. In addition, choosing sustainable building materials and recycling or reusing materials when possible, substantially affects the GHG footprint of a data center. Governments can promote green building standards and lead the way applying these in public procurement, while schemes such as EDGE certification can provide useful guidance and tools for verification.

Sustainable ICT

ICT equipment in data centers requires power and cooling. Utilizing energy-efficient equipment, implementing virtualization technology to ensure efficient server management, ensuring timely upgrades and refreshes, and leveraging real-time monitoring of equipment performance are key strategies for sustainable ICT use in data centers. Investing in more energy efficient ICT equipment may increase initial costs, but the resulting long-term gains in efficiency and reduced energy costs often compensate for initial outlays. Incremental increases in processing speed of new ICT equipment are slowing. As a result, data center operators globally can consider investing in refurbished ICT equipment for facilities that do not require cutting edge performance. Strengthening markets for refurbished equipment in LMICs can simultaneously reduce market barriers such as price and access and drive environmental gains.

Sustainable Energy

Data centers are very energy intensive. To diversify energy sources and mitigate emissions, data centers are increasingly looking toward renewable energy sources. Shifting wholly or partially to renewable energy sources is the most effective way to reduce the climate footprint of a data center but is complicated by the energy consumption patterns of data centers. Data centers demand steady power 24/7 which cannot always be met by renewable energy sources alone. In addition, the lack of local availability of renewable energy infrastructure and services can be a significant barrier. Many LMICs have ample renewable energy potential but lack infrastructure and markets for generation and distribution. When planning for a green energy transition, governments should consider the digital sector as part of the ecosystem. In some LMICs, data center operators are already aiding energy transition as developers or anchor tenants in renewable energy projects. Data centers are also partnering to find ways to reuse waste heat. Regardless of energy source, efficient management of energy consumption is critical, including creating efficient metrics and goals to drive energy efficiency improvements.

Sustainable Cooling

Efficient cooling is crucial for high-performance computing and server technologies, which generate substantial heat. Data center temperature must be maintained within a certain range to prevent condensation and damage to ICT equipment to prevent downtime and data loss. Many LMICs are in areas with high temperate and humidity. Strategies for sustainable cooling include implementing energy-efficient cooling technologies such as precision air conditioning, economizers, and containment systems to optimize cooling efficiency. It is also important to implement proper airflow management techniques, including hot and cold aisle containment, raised floors, and optimized server rack layouts to ensure efficient heat dissipation and minimize hotspots. Traditional refrigerants used in cooling systems contribute substantially to GHG emissions and climate change. Adopting alternative refrigerants as substitutes for hydrofluorocarbons in data center cooling systems holds the potential to mitigate emissions, resulting in a reduction equivalent to approximately 43.5 gigatons to 50.5 gigatons of carbon dioxide from 2020 to 2050.[1] At country level governments can regulate and support use of alternative refrigerants, and work with industry associations to strengthen market availability.

E-Waste Management

Production of ICT equipment strains scarce resources and contributes to GHG emissions. In addition, e-waste (discarded electronic equipment) poses significant environmental and health risks because of the hazardous substances it contains, such as mercury. The typical rapid technology refresh rate in data centers contributes to the global e-waste challenge. When planning data centers, it is important to consider equipment lifespan. Many companies are moving away from conventional short refresh cycles because servers are no longer getting exponentially faster. Efficient e-waste management, including reuse, refurbishment, and proper recycling, can mitigate environmental impacts and improve resource recovery. Many LMICs do not have adequate public or private e-waste disposal and recycling infrastructure. Public support for the e-waste management ecosystem is important to enable sustainable practices in data centers and to manage e-waste more broadly.

Greening Procurement and the Enabling Environment

Ensuring a sustainable digital transformation requires joint effort from both the private public sectors. While the private sector has championed many innovations in the data center space in recent years, there remains ample room for further progress. Governments can incentivize the private sector through green procurement of public digital infrastructure and services, for example by defining minimum standards or by enabling bidders to propose innovative solutions that meet certain criteria. Governments also influence the enabling environment through policy instruments. In some countries, digital transformation strategies include environmental targets, while others utilize zoning laws to distribute data centers based on water and energy resources, or incentivizing decommissioning of ineffective legacy technology. Additionally, governments play an important role in removing barriers, such as those hindering the widespread adoption of renewable energy sources. Other aspects of the enabling environment involve more complex relationships with various stakeholders. Global innovations, such as advanced cooling technologies, need to be adapted to suit the specific needs of LMICs while also supporting development of local solutions. This will require the support of local and global innovation ecosystems. Highly technical skills are needed to design and operate green data centers. Including green modules into educational curricula is an important first step but wider investments are needed to build technical expertise among private and public practitioners in areas such as climate resilience and energy efficiency. Finally, financing is a significant barrier. It is critical to bring down the overhead of green choices and mitigate the risks associated with the adoption of newer, more sustainable technologies. This challenge calls for novel approaches from governments, development partners, and cross-sector collaboration to create effective solutions.

Introduction

Data infrastructure such as server rooms, data centers, and cloud solutions support numerous public tasks and services. Access to efficient, secure data infrastructure is critical for the public sector and well-functioning societies. Globally, data traffic has grown rapidly over the last decades. Although there are still large global disparities in data infrastructure availability, low- and middle-income countries (LMICs) are increasingly investing in storage and hosting solutions to meet their needs.

Although there are still large global disparities in data infrastructure availability, low- and middle-income countries (LMICs) are increasingly investing in storage and hosting solutions to meet their needs.

Data Centers, Climate Change, and the Environment

While data centers are essential for storing and processing data, they are highly energy intensive and consume refrigerants and often large quantities of water for cooling. Global digitalization of industry and societies drives energy consumption and greenhouse gas (GHG) emissions, which are estimated to equal emissions from the airline and maritime industries.[2] In countries where renewable energy sources are not readily available or used, data centers can contribute significantly to fossil fuel consumption.[3] In turn, climate change affects data centers, and operators are increasingly factoring climate hazards into risk management.

Although LMICs are investing in data centers and the digital economy, there are knowledge and financing gaps when it comes to greening efforts. In LMICs, and globally, there is a need to de-risk and support green digital investments and demystify how and why to promote greener digital development.

Role of Government

Most information on green data centers pertains to the private sector, because of the ambitious net-zero goals and concerted effort of many global service providers, but governments also play a role in promoting development of green, climate-resilient data centers by shaping the enabling environment (laws, standards, guidelines) and upholding green standards for public digital infrastructure. The incentives for public and private decision making vary considerably, and procurement practices in the public sector are often more restrictive. Overcoming these barriers is necessary for the public sector to accelerate greener sector development. Some governments are already facilitating and promoting greener data centers, examples of which will be highlighted throughout this guide, but in many countries, there is further opportunity to bridge green commitments with digital transformation plans. In other words, work towards a twin green and digital transition. Efforts to green data centers are also closely linked to the Sustainable Development Goals and should be considered part of efforts to meet these goals.

A Holistic Approach

Greening data centers supports climate change mitigation and adaptation, contributing to decarbonization and wider sustainability goals. Addressing the climate footprint of data centers requires a holistic approach, including design, manufacturing, procurement, operations, reuse, recycling, and e-waste disposal. Beyond increasing energy efficiency and reducing carbon emissions, these steps can reduce e-waste and limit the data center's environmental footprint throughout the data center lifecycle. As such, data centers can contribute to circular economic development.

Balancing Objectives

Environmental sustainability is only one of several reasons to green digital infrastructure. For example, making data infrastructure climate resilient is closely linked to risk management of critical infrastructure. Other substantial benefits can be reaped by mainstreaming green data center practices. In many LMICs, data centers compete for scarce energy resources and in some cases water resources. Greening efforts can decrease pressure on national energy grids and water supply. Powering data centers with renewable energy is linked to wider energy supply considerations and is often prioritized to ensure a sufficient, diverse energy supply. Cost savings are also a key driver for energy efficiency efforts or when opting for refurbished ICT equipment. Although capital investments in green solutions can be higher than in traditional data centers, lower operating costs and environmental gains can offset these costs in the long-term. Decisions must be made based on cost-benefit analysis, technical feasibility, and consideration of objectives such as digital reach and inclusion.

Resources

This guide complements other International Telecommunication Union (ITU) and World Bank Group resources, including

- *Government Migration to Cloud Ecosystems: Multiple Options, Significant Benefits, Manageable Risks.* World Bank. 2022
- *Catalyzing the Green Digital Transformation.* World Bank Group. 2023 [forthcoming]
- *Circular and Sustainable ICT Public Procurement Guide.* International Telecommunication Union. 2023
- *Greening Digital Companies: Monitoring Emissions and Climate Commitments.* International Telecommunication Union and World Benchmarking Alliance. 2022
- *Internet Waste.* International Telecommunication Union, and the Waste from Electrical and Electronic Equipment Forum. 2020
- *ITU-T Green ICT Standards and Supplements*

Data Centers

The public sector requires various types of data storage and hosting to manage sensitive and non-sensitive data, deliver e-services to citizens, and support digital transformation. For ease, the term *data center* is used throughout the guide and covers everything from individual server rooms within institutions to full-fledged data centers, as well as cloud and hybrid solutions. Although there are differences between onsite servers and networks of data centers for cloud solutions, all rely on a physical premise (room or building), energy-consuming hardware and software that emit heat, and often cooling solutions that consume water and energy. Appendix A provides more-tailored guidance.

The term *data center* covers everything from individual server rooms within institutions to full-fledged data centers, as well as cloud and hybrid solutions.

The following are typical examples of data storage and hosting solutions:

Server room: used to store, power, and operate one or more servers on site. Provides a controlled environment with hardware, racks, cabling systems, and network equipment.

Data center: used for data processing and storage for one or more organizations. Often relies on resilient power supply, high-speed connectivity, a security system, and building management controls.[4] In a colocation data center, organizations can rent space, equipment, and bandwidth.

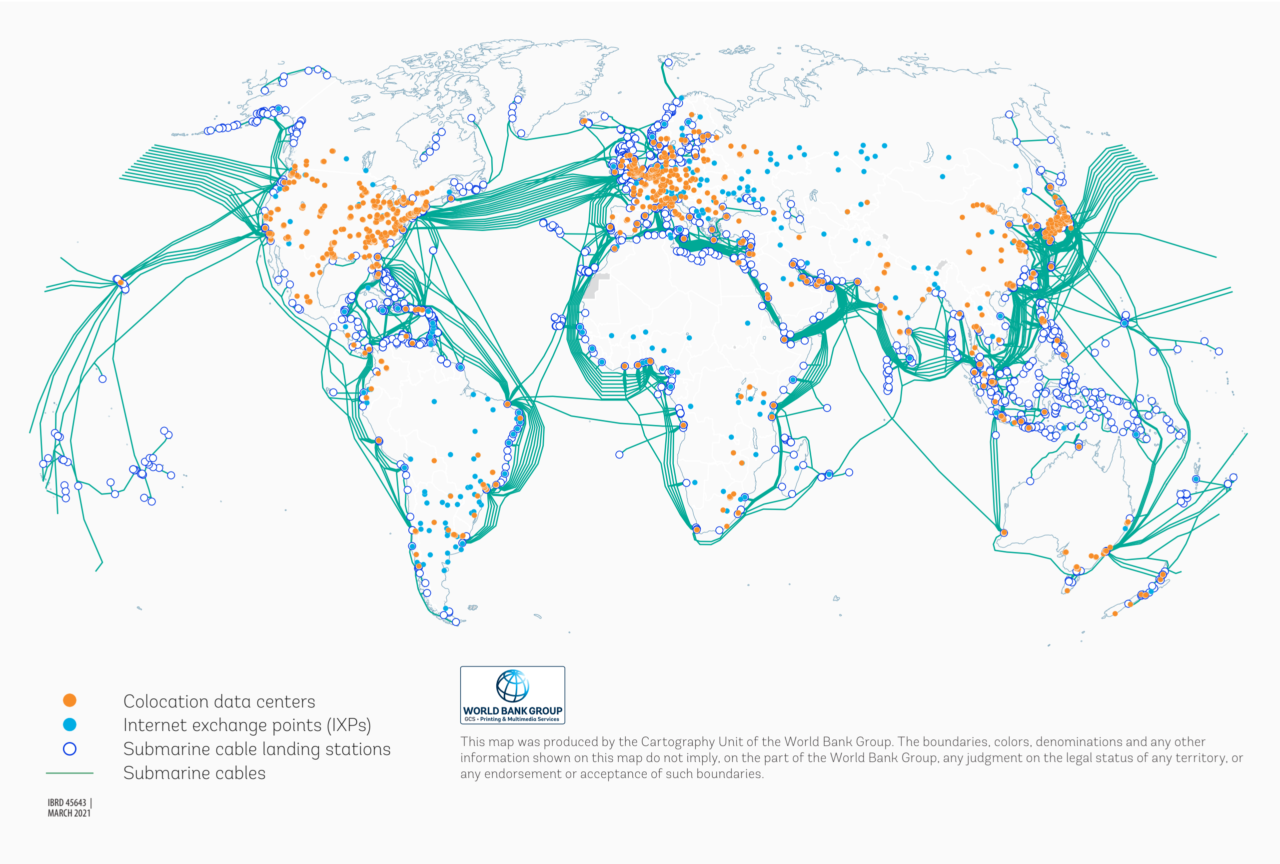
Cloud: physical or virtual data storage solution that enables access to a scalable, elastic pool of resources. Cloud solutions rely on data centers or networks of data centers. Cloud can be private, meaning that only one organization uses it, or public, meaning that more than one organization shares it (often purchased as a service).

Hybrid: combines public and private cloud resources. Hybrid cloud includes onsite, colocation, public cloud, and edge storage infrastructure.[5]

The terms "public" and "private" are also used to distinguish ownership and operational modes. The public sector uses various models, including publicly owned and operated data infrastructure, public-private partnership models,[6] and purchase of data hosting as a service. In many LMICs, onsite server rooms and legacy systems are widely used in the public sector for data storage, but an increasing number of countries are prioritizing consolidation to modernize systems, reduce ownership costs, and sometimes migrate to an internal cloud platform or outsource to a cloud service provider.[7] Choosing between different models depends on the preferences and needs of the public entity. This guide does not discuss pros and cons of different models but rather green considerations as part of wider decision making.

Data Center Availability in LMICs

There are large global disparities in data center capacity (Map 1). Only a few emerging markets, such as Brazil and South Africa, have attracted large-scale cloud service providers to set up data center facilities. As of 2020 only 1 percent of the world's data center capacity is in Africa, although major cloud service providers are entering the market.[8] The data center market in Asia is fragmented and highly competitive. Although there are strong regional hubs, such as Singapore, vendors are expanding their geographic presence.



Map 1. Distribution of Data Infrastructure and the Submarine Fiber-Optic Cable Network[9] [10]

Small island developing states also lack data center capacity but are increasing their data center investments (Case 1).

Small island developing states face unique challenges in accessing affordable, reliable digital infrastructure because of their size, isolated locations, and susceptibility to environmental risks.[11] Many Pacific Island nations have developed core government IT infrastructure in the last decade, including government data centers and networks. For example, Papua New Guinea launched a government data center in 2005, the Solomon Islands set up a new data center in 2019, and Tonga established a cloud service - government data center in 2017.[12]

Case 1. Data Center Infrastructure Enabling E-Government Services: Pacific Islands

The market for data infrastructure goes beyond data centers themselves. One starting point for national data infrastructure is establishment of Internet Exchange Points (IXP), which allow domestic data traffic to be exchanged locally without the need for the data to travel distances to reach overseas IXPs, which increases costs and creates delays. Latin America, for example, spends billions annually on international bandwidth - a sum that greater use of IXPs could reduce.

Latin America spends billions annually on international bandwidth.

Despite Djibouti's role as a regional data hub serving East Africa, local internet users face exorbitant data rates because of a domestic market monopoly. In contrast, Kenya's non-profit IXP organization operates with a multi-stakeholder board, attracting diverse players, including foreign content and cloud providers, increasing the availability and efficiency of data services.[13]

Case 2. Internet Exchange Point Development: Djibouti and Kenya

Green Data Centers

There are many definitions of green data centers, for example:

International Telecommunication Union (ITU) Green Data Center Definition

According to ITU-T L.1300, "A green data center can be defined as a repository for the storage, management, and dissemination of data in which the mechanical, lighting, electrical and computer systems are designed for maximum energy efficiency and minimum environmental impact."[14]

In the context of this guide, *green data centers* refer to facilities designed and managed with a strong emphasis on managing both climate risks and minimizing environmental footprint. Strategies include choosing sustainable building materials, reducing water and energy consumption, and considering refrigerants and e-waste. A green data center thus incorporates resilience and sustainability principles throughout its lifecycle.

There is a growing landscape of green data center initiatives, guidelines, and standards along the data center value chain (Appendix A). The landscape is, however, still somewhat fragmented, without clear consolidation around a specific standard. The environmental pros and cons of different types of data storage and hosting solutions are subject to intense discussion, as are some greening choices, for example use of carbon credits in support of net zero goals.

Climate Change Risks to Data Centers and Resiliency Measures

Digital infrastructure has become increasingly vulnerable to climate risks. Floods, landslides, cyclones, powerful storms and winds, water scarcity, and extreme heat can damage critical digital infrastructure, disrupting, for example, power supply, transport, banking, and government services.[15] As economies become increasingly digitalized, the social and economic impacts increase.

With climate change, a data center designed initially for an annual 0.2 percent flood risk could face a 1 percent risk, effectively reducing its planned lifespan by 20 percent.[16] Data center downtime is becoming more costly, with longer outages and an increasing number of failures resulting in significant financial losses. Onsite power problems and cooling failures are reported to be key causes of significant site outages, emphasizing the need for resiliency measures.[17] Governments and organizations must take measures to prevent disruptions, for example by assessing risk, promoting climate-resilient design, and preparing and implementing disaster recovery plans. By enhancing resilience, data centers can maintain reliable service delivery, protect customer data, and minimize costly downtime.

There is a growing landscape of green data center initiatives.

Data Centers and Energy Use

Between 2015 and 2021, the International Energy Agency reported a 260 percent rise in data center workload, reflecting growing digital technology adoption (Figure 2).[18] The global rise in digital data collection and data-intensive applications is driving demand for data center capacity and cloud computing. The technological advances enable more-efficient data processing, which in turn increases use of and demand for data. In addition, the pay-as-you-go business model affects demand by shifting capital expenditures to operational expenditures. To meet demand, a growing number of data centers are consuming vast amounts of energy to power servers, network equipment, lighting, air distribution fans, and cooling systems. In Ireland, a global data center hub, data centers accounted for almost one-fifth of electricity used in 2022.[19]

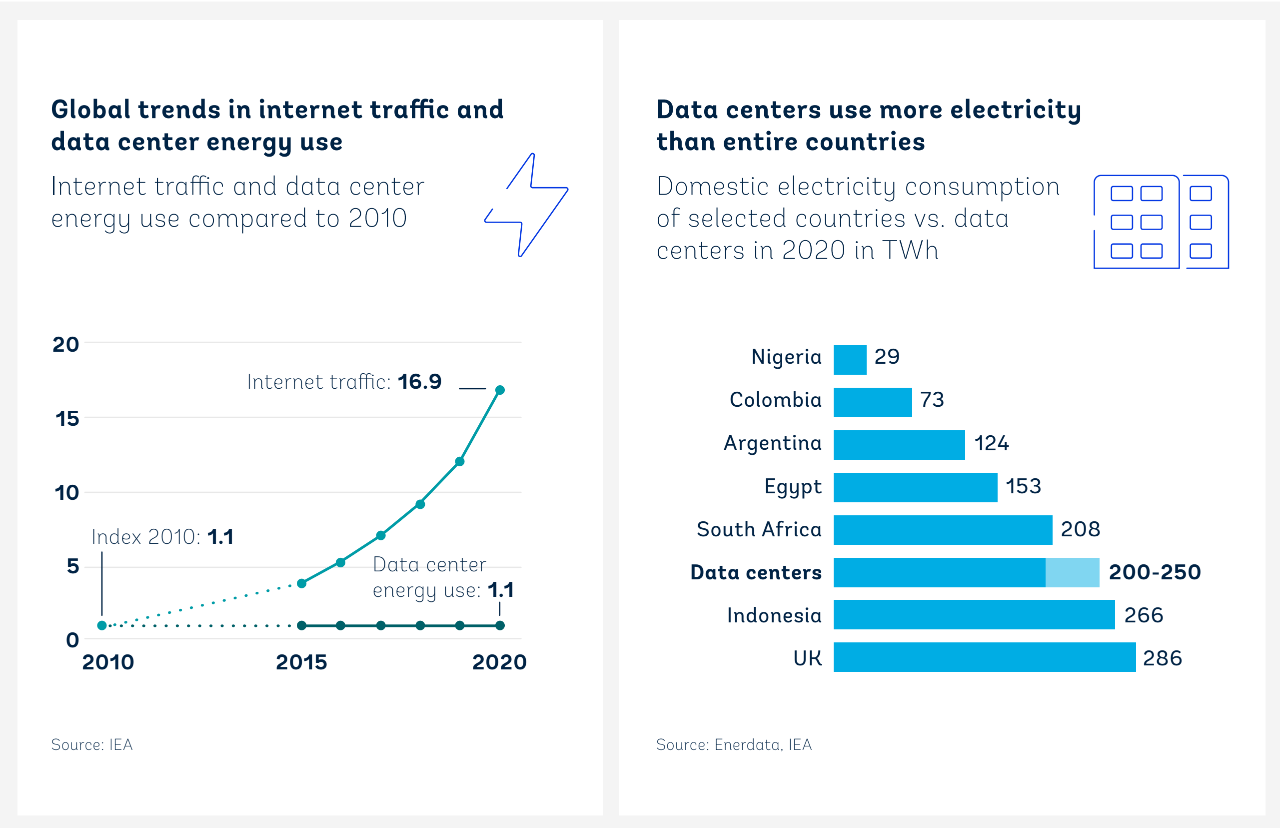


Figure 2. Data Centers' Energy Use Magnitude and Trends (Source: [Deutsche Welle. Data Centers Keep Energy Use Steady Despite Big Growth. 2020.])

Despite the growing number and capacity of data centers, the industry has seen lower-than-expected growth in energy use, thanks to greater server efficiency, more-energy-efficient software, and advances in cooling and power-supply systems.[20] It is vital to sustain these efforts as demand for data processing accelerates.

Power Use Effectiveness

Power use effectiveness (PUE) is often cited when discussing green data centers. It is a measure of a data center's energy allocation (per ISO/IEC 30134-2) and is calculated by dividing total energy that a center consumes by the energy that the IT equipment consumes. The closer PUE is to 1.0, the more efficient it is. For instance, a PUE of 3.0 means that the total energy that a data center consumes is three times the energy required solely for powering the IT equipment. PUE serves as a multiplier for determining the actual effect of a system's power requirements. To illustrate, if a server uses 900 kWh of electricity, and the data center has a PUE of 3.0, the utility grid would need to supply 2,700 kWh of energy to deliver the required 900 kWh to the server. Influences on PUE include cooling systems, temperature, humidity, and data center design. An energy-efficient data center design should consider all these factors.[21] [22] Warmer climates require more cooling. Energy needs and hence PUE vary geographically. The International Financial Corporation EDGE Certification includes PUE targets based on this factor.[23] Although PUE is a useful metric, it should be assessed in combination with other metrics.

Information on data center environmental performance metrics can be found in EN 50600, including on water and carbon use effectiveness and energy reuse effectiveness.

Lifecycle Impact of Data Centers

Data centers have an environmental effect throughout their lifecycle, including materials for the building, raw materials and energy to manufacture ICT equipment, energy, refrigerants and water for operations, and energy and pollutants during decommissioning.[24] Figure 3 demonstrates a simplified data center lifecycle, including material and energy use in each phase and opportunities for material and energy reuse.

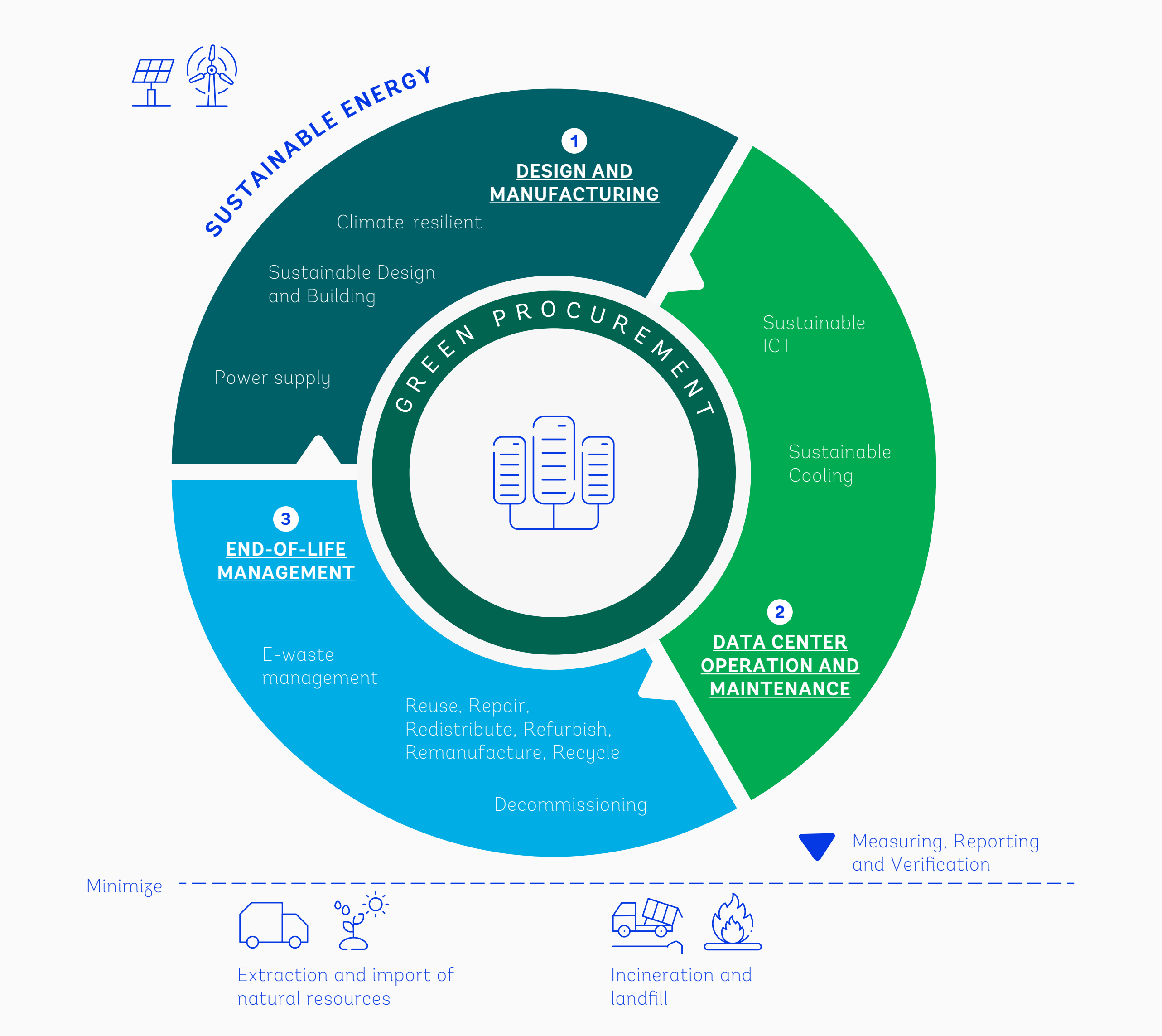


Figure 3. Data Center Lifecycle

By adopting circular economy principles, such as designing for durability and reparability, reusing and refurbishing equipment, and using renewable materials, the environmental impact of data centers can be minimized. Transitioning the energy source to renewables is important, but because data centers have a "baseload" or flat power curve (they demand 24/7 power), it is equally important to consider how data center design can be less resource intensive for always-on power, which is especially challenging in LMICs. Integration of data centers into the energy system will ultimately help drive sustainability, for example, by helping with grid congestion and leveraging residual heat.

The key to achieving energy savings lies in the design of the data center, which should incorporate energy-efficient technologies, optimized cooling systems, and efficient power distribution to minimize waste and maximize overall operational efficiency. By prioritizing energy-saving measures in the design phase, data centers can significantly reduce their energy consumption and operational costs.

Reporting

Environmental reporting plays an important role in promoting greener data centers because it fosters awareness, transparency, and accountability. Establishing quantifiable baseline metrics, setting concrete targets and key performance indicators, and engaging the entire organization can lead to more-efficient, more-cost-effective, more-sustainable data center operations. Reporting helps in measuring progress over time and supports development of strategies and initiatives to achieve desired outcomes, especially if accompanied by transition plans that help map how targets are to be met. Reporting and monitoring also enable data center operators to forecast the future impact of their facilities, helping them map how targets will be achieved; prioritize initiatives; allocate resources effectively; and make informed decisions to ensure sustainable, efficient operation. Finally, reporting enables data center operators to assess and communicate their environmental impact, including GHG emissions, energy use, water consumption, and e-waste generation, and promotes transparency, allowing stakeholders to understand the size of the centers' footprint and identify areas for improvement.

Reporting Tools

The Greenhouse Gas Protocol, which the World Resources Institute and the World Business Council for Sustainable Development developed, has become a widely recognized standard for measuring and reporting GHG emissions. Governments, companies, and organizations use its guidelines to translate their activities into quantifiable inventories of carbon dioxide and other emissions. In addition, ITU-T Recommendation L.1410 provides guidance on conducting environmental lifecycle assessments (LCAs) of ICT goods, networks, and services.

Greening Data Centers
Climate Resilience

As economies digitalize, reliable digital infrastructure becomes crucial. Making data centers climate resilient should be considered not only when each one is being planned, operated, and procured, but also at a national level to protect critical infrastructure. This section highlights the importance of climate resilience, outlines climate hazards, and presents steps for increasing data center resilience to climate change. From an operational perspective, climate risks will be addressed alongside a wider range of risks, so other environmental hazards such as earthquakes are included when relevant.

Climate-Resilient Data Centers

Key Issues and Steps to Increase Climate Resilience

Climate hazards are increasing globally, especially in LMICs, which are particularly vulnerable to the impacts of climate change. Many LMICs are for example located in areas of low elevation and have high population density along coastlines, which exposes them to the direct effects of rising temperatures and flooding. Eight of the 10 countries most affected by extreme weather events in 2019 were classified as LMICs, and four were low-income countries.[25] Considering country- and site-specific risks is thus of extra importance when investing in data center infrastructure in LMICs.

Climate hazards affect data centers in diverse ways, ranging from gradual changes (sea level rise and changes in temperature) to sudden disasters (storms and floods). Table 1 shows site effects of typical climate hazards on data centers.

CLIMATE HAZARD	EFFECTS [26] [27] [28] [29]
Fluvial and coastal flooding (including sea-level rise), erosion, inundation (including salt, silt, sewage)	Water damage to equipment, electrical shorts, limited staff access, structural damage, recurring challenges if built in flood zones
Lightning storms	Power surges leading to equipment failure and an unstable grid
Drought	Lack of water for cooling and fire suppression systems, power outages, dust accumulation
Sustained high temperature or heatwaves	Utility power instability, component stress, high cooling costs
Sustained high humidity	System failures, reduced cooling effectiveness, corrosion of metal components
Wildfires	Reduced air economization, equipment clogging from smoke and ash, restricted staff access, power outages, water use restrictions
Earthquakes and landslides	Structural damage, power supply disruption, network infrastructure damage, injuries to staff, lack of access
Extreme weather events	Infrastructure damage from wind and debris, water damage, power outages, service interruptions

Table 1. Effects of Climate Hazards on Data Centers

Assessing national risks to public and private data infrastructure is important for disaster preparedness. This involves vulnerability assessment and system-level planning to maximize redundancy. Climate risks, such as extreme weather, rising temperatures, and flooding, can affect not just data centers, but also regional infrastructure and utilities: increasing operating costs, disrupting supply chains, forcing relocation, destabilizing the power grid, and damaging infrastructure.[30] [31] Site-specific and regional risks must be considered. The following steps can be taken to increase overall resiliency.

Climate risks can affect not just data centers, but also regional infrastructure and utilities.

- **Assess climate risk:** Evaluate effects of climate change on the data center, considering extreme weather, rising temperatures, water scarcity, and precipitation patterns. Identify vulnerabilities and prioritize improvements. Integrate climate resilience strategies into the early stages of data infrastructure projects and develop proactive action plans to prepare in advance.

- **Enhance site selection:** Consider climate risks in site-specific locations, opting for areas with lower flood, seismic, and extreme weather risks. Evaluate long-term climate projections for resilience. Build specific climate-risk profiles to calculate the likelihood of natural disasters and temperature extremes. Build distributed data centers and robust data replication strategies to minimize risk of data loss, enable quick recovery, and provide redundancy and resilience by spreading data and workloads across multiple geographically dispersed sites.

- **Implement resilient design:** For areas prone to pluvial floods, incorporate effective drainage systems into building design to prevent accumulation of rainwater around the building after heavy rainstorms. Similarly, in areas at risk of coastal floods, include installation of barriers in the design plan to prevent incoming seawater.[32] Elevate equipment to withstand climate hazards and minimize damage, although placing equipment in higher positions within a rack can amplify the impact of an earthquake. Construct earthquake-resilient buildings based on location and install earthquake-resistant equipment (e.g., seismic isolators).

- **Improve operational practices:** Install advanced monitoring systems to allow automation and remote management to enable access if physical access is not possible because of extreme weather conditions. Integrate virtualization or software-based redundancy measures such as load balancing to increase resilience and tolerate failure or loss of any single facility. Use closed-loop water systems for cooling (e.g., adiabatic or evaporative air-cooling systems) to avoid exposure to droughts or making them worse.

- **Establish backup power and recovery plans:** Install reliable backup systems (uninterruptible power supplies, batteries, generators, fuel tank, water tank) for uninterrupted operation, considering cooling need during power outages. Develop comprehensive recovery plans for data backup, system restoration, and business continuity. Maintain off-site backups to protect against unforeseen events, especially in more-vulnerable locations.

- **Leverage new technologies:** Automate risk assessments using digital technologies such as sensors, data aggregation, and advanced simulation. Use big data to conduct resilience analytics for efficient climate resilience and monitoring systems based on Internet of things technology to collect information and issue warnings based on temperature variations and energy data. Use digital twin monitoring data with machine learning to create dynamic models that simulate hazards and detect infrastructure deterioration and damage.[33] [34]

- **Regularly review and update resilience plans:** Continuously assess and adapt to climate change by reviewing measures and staying informed about new risks, technological advances, and industry best practices. Include digital infrastructure in national disaster preparedness efforts and map critical infrastructure.

Although assessing risk and implementing resiliency measures may require an upfront investment, they prevent service interruption and data loss; protect costly network equipment; and enable smooth functioning of organizations during climate-related events. There are however trade-offs between cost, performance, and resiliency and between resiliency and sustainability. Data center redundancy, for example, adds to costs and energy consumption.

Extreme heat in July 2022 resulted in cooling unit outages at Oracle's and Google's Europe-based data centers. Temperatures exceeded the design specifications for operating temperatures, straining cooling systems and increasing chance of failure. With increasing extreme weather events, operators must regularly assess climate resilience, update design conditions, and consider long-term adjustments such as direct liquid cooling. Smaller cooling systems that depend on ambient air are particularly vulnerable.[35] [36]

Case 3. Protective Shutdowns due to Extreme Heat: Europe

In India, it is advised that data centers be located in areas classified as seismic zone 4 or lower to reduce risk from earthquakes. If data centers are situated in zones with higher seismic ratings, measures such as installing snubbers and other materials are necessary to mitigate shocks.[37]

Case 4. Data Center Resilience: India

Building resilience is a continuous process requiring constant vigilance and adaptability. See Appendix B for a detailed elaboration of resiliency strategies and further resources.

Greening Data Infrastructure
Climate Change Mitigation

In this section, the focus shifts to climate change mitigation strategies for data centers. By implementing climate change mitigation measures, data center owners and developers can reduce energy consumption and carbon emissions and enhance system efficiency. There are five main dimensions to consider: sustainable design and building, sustainable and circular - circular in this context means designed for sustainability through strategies such as reuse, refurbishment, and recycling, minimizing waste and resource consumption - ICT equipment, sustainable energy, sustainable cooling, and e-waste management (Figure 4).

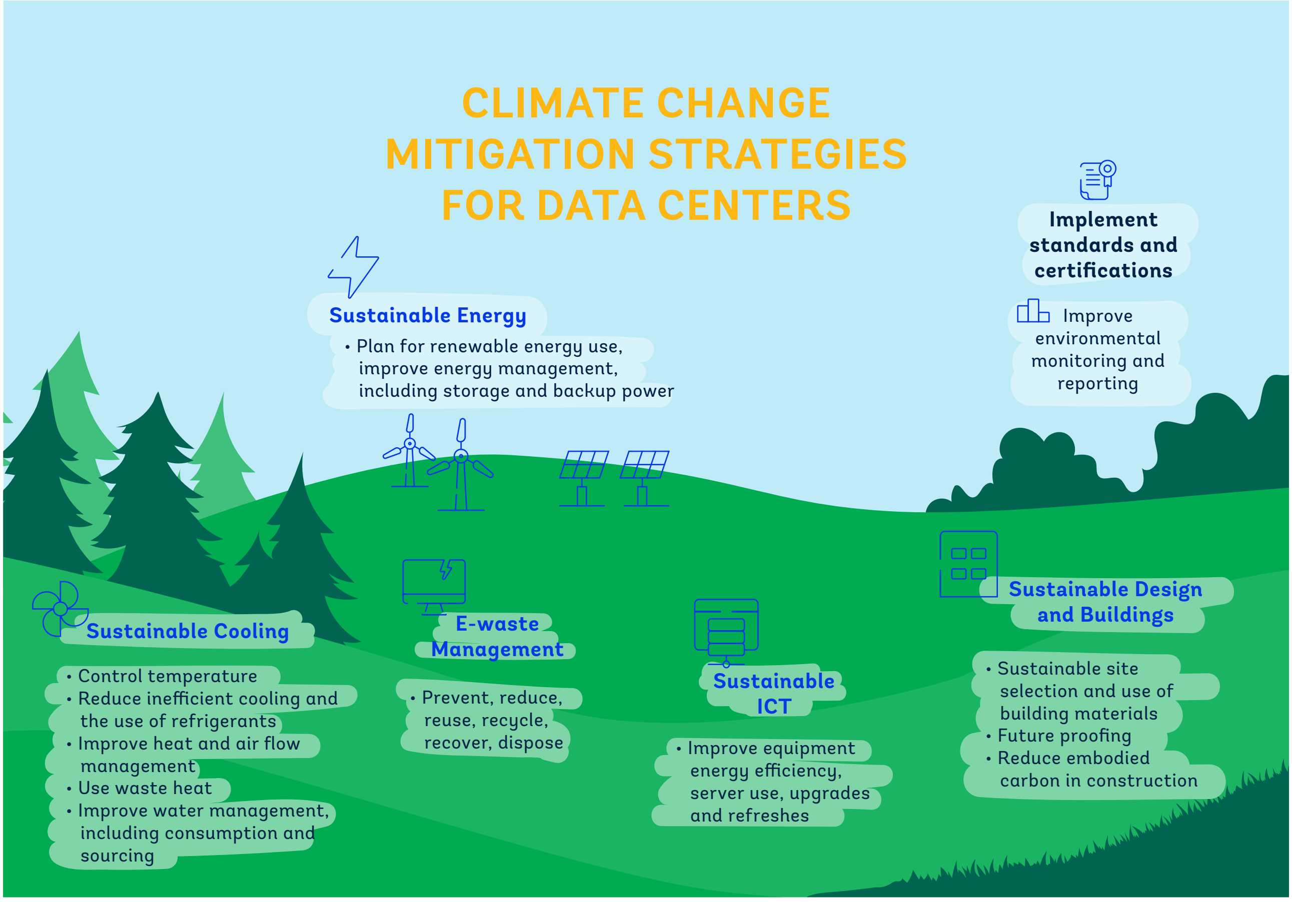


Figure 4. Mitigation Strategies for Data Centers

Sustainable Design and Buildings

Data center design and planning start with the building envelope. The data center's location and design affect operational reliability, resource use, and energy efficiency. In addition, environmental risks must be considered when determining the data center's location and design. Most sustainable management of data centers focuses on the operational stage and overlooks green design and construction aspects. Strategically addressing emissions reduction during design and construction lays the groundwork for an environmentally responsible future, with lasting positive effects on operational efficiency and overall sustainability throughout a data center's lifecycle. When planning new data infrastructure, total cost of ownership must be considered, including initial capital, operational expenses, and disposal of the facility at the end of its lifespan. Sustainable design options might be more expensive in the short term (e.g., within a 3-year return on investment) but save money in the longer term. Proper dimensioning is a cost and sustainability driver. A top-tier green data center might not be sustainable if operating at only 10 percent capacity. In many LMICs, instances have emerged where data centers, despite being established, experience underutilization due to a range of factors including limited awareness of efficient data storage practices and inadequate capacity within the public sector. To address this challenge comprehensively, it is important that efforts to enhance data center utilization extend beyond mere infrastructure investment. Alongside the establishment and maintenance of these data centers, there is a clear need to focus on the demand-side dynamics, with a particular emphasis on capacity building initiatives aimed at educating and empowering public sector stakeholders. By providing training and knowledge-sharing, LMICs can equip public sector entities with the necessary skills and understanding to optimize data storage practices, thereby maximizing the utility of data centers. This approach not only ensures that data centers operate at their full potential but also enhances the overall data management ecosystem within the country.

Key Issues and Steps to Improve Design and Building to Enhance Sustainability

Refurbishment

Before deciding to invest in new data centers, it is worth exploring whether existing facilities can be upgraded or expanded. In some cases, more-modern, more-energy-efficient data center design can result in greater sustainability than continuing to use an existing inefficient data center, but refurbishing an existing data center often offers cost savings, enables faster deployment than building a new facility, and reduces environmental impact. Using existing buildings for expansion while increasing capacity e.g. through in-place upgrades to hardware installed in those buildings can substantially reduce embodied carbon emissions, which has been reported to amount to as much as an 88 percent smaller carbon footprint than a new construction project.[38] Challenges include space constraints and minimizing disruptions. Before committing to a brownfield renovation, it is crucial to fully consider site-specific limitations on installing state-of-the-art heating and cooling options-active and passive-and evaluate this from a lifecycle perspective, although green considerations such as more-energy-efficient ICT equipment, renewable energy integration, and water efficiency can often be implemented during refurbishment. Assessing factors such as cost and environmental goals helps determine the best approach.

New Facilities-Steps to Sustainable Design and Building

If new facilities are constructed, many measures can be implemented in the design and construction phases to reduce the environmental footprint of the data center in the short and longer terms.

Site selection

- Sustainable site selection (figure 5) must factor in many things, for example:
  - Environmental assessment of flora and fauna (e.g., endangered species, sensitive habitats, water scarce areas)
  - Risk profile of the site (e.g., proximity to rivers and distance to ocean to minimize risk of flooding)
  - Temperature of location for low-cost or cost-free cooling solutions
  - Access to reliable water and energy (including renewable energy)
  - Opportunity for onsite renewable energy generation
  - Employee commuting needs and services available in the area
  - Opportunities for auxiliary industries to reuse heat or other data center systems (e.g., combining data centers with office spaces and heat- and energy-intensive industries and co-creating district cooling systems and power plants for the whole ecosystem to balance environmental impacts and energy use of each participant)
  - Trade-offs with other business needs such as resiliency, response time, network links

Dimensioning and future proofing

- Proper dimensioning is one of the most important parameters for net sustainability. The process of right-sizing allows for better planning and ensures that capacity is not being reserved that may never be used.[39]
- Some data centers are overprotected for worst-case scenarios. Servers might operate at 12 percent to 18 percent of their capacity but consume 30 percent to 60 percent of the data center's total power because they are overdesigned for extreme situations.[40] Making data centers as uniform as possible using virtualization and software to allow the many computers they contain to act as a single large data storage and processing machine can prevent wasted computing and data storage capacity.
- Future needs for data center capacity should be considered. Instead of over-dimensioning data centers, modular design can allow for efficient expansion. Conducting regular reviews and modeling expected demand growth at specific intervals helps ensure scalability and optimizes resource use.

Sustainable design, construction, and building materials

- Data center design sets boundaries for sustainability and spans many options. Examples include:
  - Design for efficient power and cooling of ICT equipment. For example, Yahoo designed data centers to maximize use of outside air for cooling, drawing inspiration from the design of chicken coops.[41] A flat roof might allow for a rooftop solar solution.
  - Consider containerized modular data center design to reduce construction waste, cooling demand, and use of concrete.
- Choosing sustainable building materials (e.g., wood) and recycling or reusing materials as much as possible decreases GHG emissions during construction of a data center.[42] EcoDataCenter constructed the framework of its first data center in Fulun, Sweden, using renewable cross-laminated timber, a type of engineered wood that is sustainable and has a significantly lower carbon footprint than traditional building materials such as concrete and steel.

Standards and certifications

- Adopt publicly available industry standards and certifications (Appendix A) for data center design and build e.g., EN50600 series and the ISO/IEC 22237 series. In addition, EDGE certification, a green building certification system for emerging markets created by the International Financial Corporation that targets data centers, enables developers to optimize design, promote sustainability, and create marketable, cost-effective projects.[43]

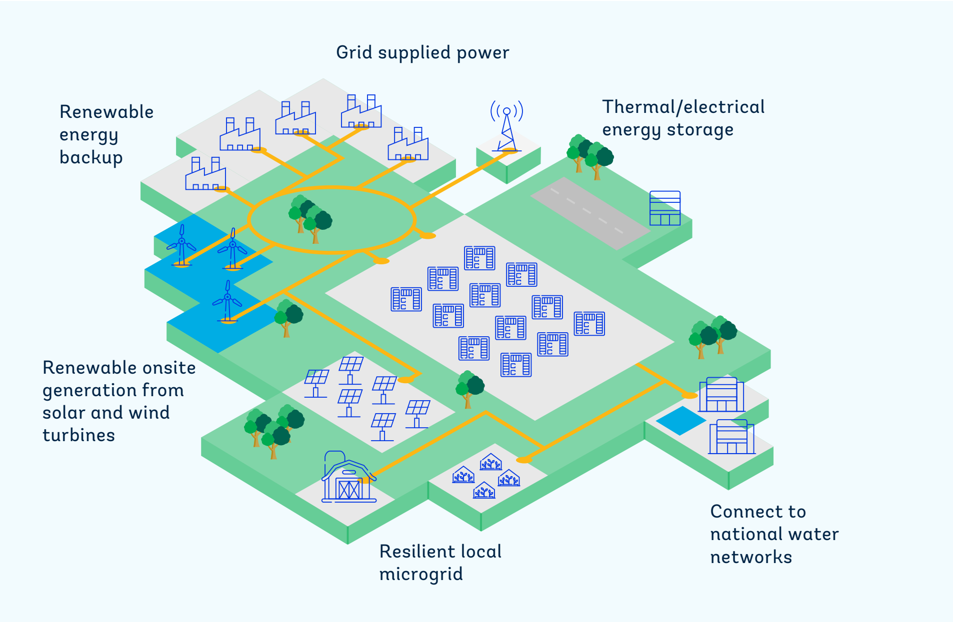


Figure 5. Data Center Site Selection[44] (Source: Adapted from Engine, 2023)

In Colombia, the Nebula Data Center is EDGE certified. EDGE recognizes buildings whose design and infrastructure use at least 20 percent less water and energy than conventionally designed buildings. Nebula consumes an estimated 5,000 kWh per month when at full capacity. An equivalent center designed conventionally can have a consumption greater than 6,000 kWh (20 percent higher).

In Nigeria, the Rack Centre is EDGE certified. To ensure that it could meet the rapid growth in demand for hosting capacity in Africa while minimizing its environmental impact and operating costs, Actis (a global investor in sustainable infrastructure) has spearheaded a program of green design philosophies and initiatives that will result in the data center achieving 35 percent energy savings and 41 percent water savings and deliver 45 percent savings in embodied energy in materials used.[45]

Case 5. EDGE Certification: Nigeria and Colombia

The Konza National Data Center in Kenya is Leadership in Energy and Environmental Design certified, which means it has been scored on a wide range of sustainable design parameters including site selection, construction waste management, certified wood, water efficiency, and renewable energy.

Case 6. Leadership in Energy and Environmental Design Certification: Kenya

The Green Mountain Data Center, housed in a former North Atlantic Treaty Organization facility inside a mountain in Rennesøy with approximately 21,000 m^2 of floor area, is said to be one of the greenest in the world. It uses the stable, cool temperature within the mountain and seawater for free cooling. The Norwegian government set a goal of using 100 percent renewable energy to power its data centers by 2020. They have achieved this by investing in hydroelectric power plants and wind farms and implementing energy-efficient cooling systems in their data centers.

Case 7. Green Mountain Data Center: Norway

Appendix C describes mitigation strategies and further resources more fully.

Sustainable ICT

Circular ICT equipment refers to technology devices designed under the circular economy model to reduce waste and optimize resource use. This approach extends product life, minimizes resource consumption, and enhances material recovery. Key aspects include durable designs, modular components for easy upgrades, refurbishing equipment, remanufacturing used devices, recycling valuable materials, and utilizing take-back initiatives. This concept supports sustainability goals by curbing e-waste, conserving resources, and fostering responsible technology production and consumption. ICT equipment in data centers is resource and energy intensive to manufacture and requires power and cooling to operate. Figure 6 shows typical data center equipment and the materials used to manufacture it.

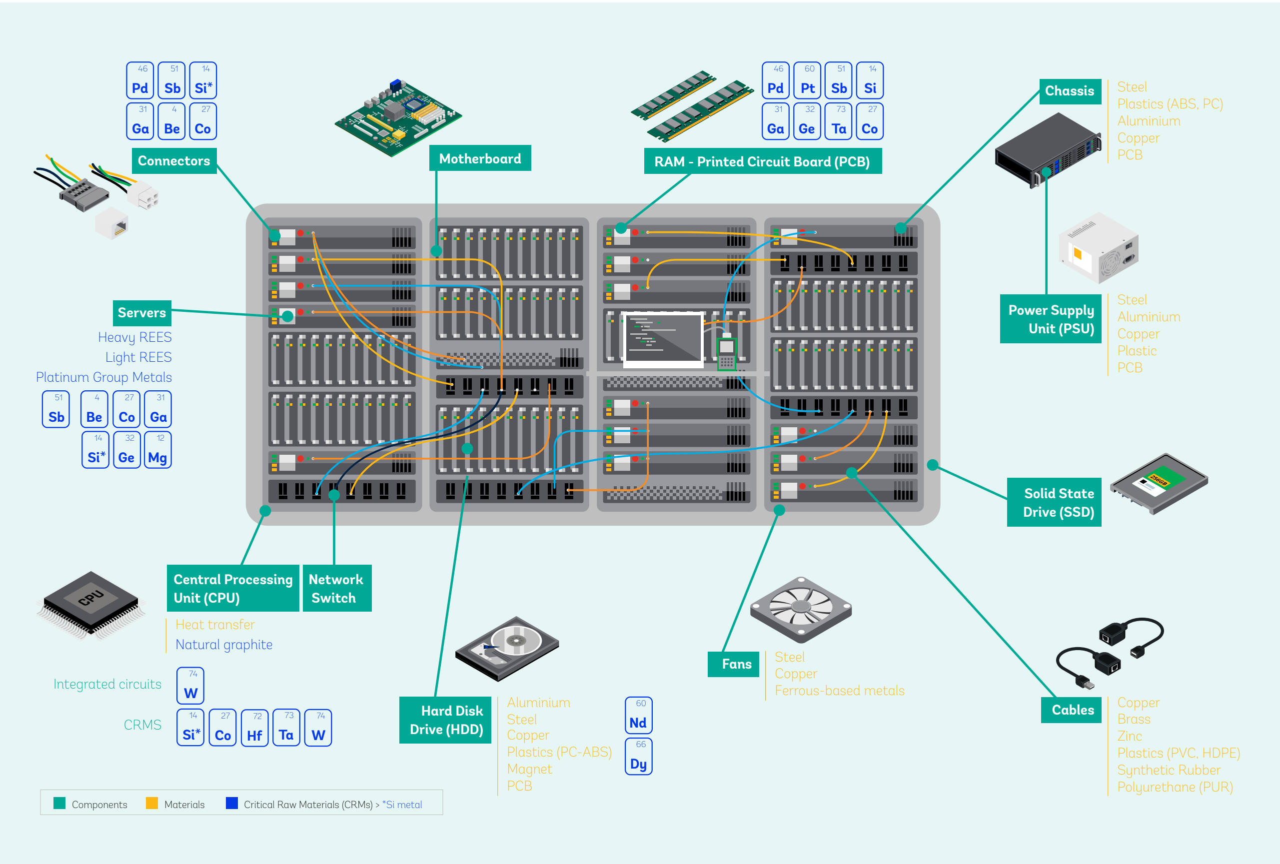


Figure 6. Typical Information and Communications Technology Equipment in a Data Center (Source: Adapted from Internet Waste, 2020.[46])

Network equipment accounts for 2 percent to 5 percent of energy use in a typical data center, storage equipment uses 20 percent to 30 percent, and servers consume the rest.[47] Although the initial cost of procuring energy-efficient hardware is likely to be higher, it can result in lower lifecycle costs, making it a more-cost-effective choice in the long run. A wide range of ICT equipment might not be available in some LMICs. Although ICT equipment historically has become exponentially faster, this trend has slowed, so investing in refurbished equipment can be a good option. Refurbishing equipment leads to longer intervals between maintenance shutdowns, increasing operational efficiency and reducing disruption of regular operations.

Key Issues and Steps for ICT Equipment Efficiency

Choice and configuration of ICT equipment significantly affect a data center's environmental footprint. Sustainable procurement and use of ICT equipment can be achieved in many ways, including through the following steps.[48 49 50 51 52]

Choosing energy efficient equipment

- Use energy efficiency-certified equipment and products such as Energy Star- and TCO-certified servers and storage devices to reduce overall energy consumption.

Improve server use

- Idle servers draw significant power, even though they are not actively processing tasks. With server use typically less than 30 percent, idle servers consume about 60 percent of peak power, resulting in excess energy use and carbon emissions.[53] Given that these idle periods last seconds or less, simple energy-conservation approaches may not be practical,[54] so it is critical to develop sophisticated strategies to address such inefficiencies, for example:
  - Implement virtualization technology to ensure efficient server management by better allocating resources and reducing server underuse. Strategies such as shutting down servers when they are below a specific threshold, forecasting demand, incorporating day-night rhythms, and modeling seasonality should be implemented.
  - Right-size hardware based on specific workloads. Use load-balancing techniques to distribute workload evenly across servers to improve resource use. For instance, if there is high demand for parallel processes, incorporating more graphics processing units would be advantageous.[55]
  - De-duplicate and compress data to boost storage equipment's efficiency by freeing up storage and allowing for better storage utilization. However, it is essential to ensure that these measures do not compromise the resilience of the storage system.

Upgrades & refreshes

- Conduct regular assessments of existing ICT equipment to identify outdated or underperforming hardware that requires upgrading or refreshing. Automation and connectivity can be leveraged to perform benchmark gap analysis in data centers by integrating with state-of-the-art industry tools and systems.
- Create a lifecycle management approach/strategic plan for upgrades and refreshes considering technology advancements, energy efficiency improvements, warranty periods. Regularly review the plan to ensure upgrades/refreshes occur in a timely manner to maintain optimal performance and evolving business needs. The focus should be on refurbishing and repairing existing equipment instead of buying new equipment to ensure the circular data center is circular, especially considering hardware efficient gains will be limited.

Ensure monitoring and reporting

- Implement common data center environmental performance metrics as outlined in EN 50600, including measuring power, water and carbon use effectiveness and energy reuse effectiveness.
- Implement appropriate key performance indicators for measuring, benchmarking, and tracking to provide a clear understanding of challenges such as unplanned downtime, capacity use, and resource allocation.

Appendix C provides a detailed description of mitigation strategies and further resources.

Sustainable Energy

Data centers are energy intensive, consuming 10 to 100 times as much electricity per floor space area as most commercial buildings.[56] Effective energy management is important for all data centers so that energy consumption and costs can be minimized. Data center operators can consider use of renewable energy, reuse of residual heat, and onsite generation of energy for parts of the facility, although this might not alleviate the need for back-up generators that can run the minimum baseloads. The initial capital investment and ongoing costs associated with renewable energy systems can be barriers to adoption. To make informed decisions, it is necessary to consider the long-term benefits, cost savings, and return on investment of renewable energy systems to explore their economic viability.

The grid mix often determines the viability of powering data centers with renewable energy. Many LMICs have abundant renewable energy resources, including solar energy, wind power, and geothermal energy, but lack infrastructure and markets for renewable energy generation and distribution. Many global cloud providers include access to renewable energy in their investment decisions. Investing in rewnewable energy projects holds significant potential for substantial environmental benefits to both data centers and the digital sector, whilst also contributing to long-term operational efficiency and energy stability.[57]

Key Issues and Steps for Sustainable Energy Use

The following steps can be taken to achieve more sustainable energy consumption in data centers.

Energy management

- Develop an energy management plan to monitor, regulate, and conserve energy based on performance metrics and goals to drive efficiency improvements. It can reference standards such as ISO 50001 Energy Management and be verified internally or through third parties.
- Use submetering when possible to collect information on use for primary facilities and information and communications technology systems or use equipment with embedded energy-consumption metering.
- Use digital tools to monitor and optimize energy use, identify areas of inefficiency, and implement energy-saving measures. Implementing Internet of Things-based and artificial intelligence solutions for energy monitoring at the individual unit level allows for in-depth insights into the performance of equipment, enabling opportunities for predictive maintenance and optimizing energy consumption.
- Adjust energy consumption in accordance with availability of renewable energy and grid conditions to save costs and decrease environmental impact. This can include creating incentives to schedule intensive activities during off-peak tariff periods or when renewable energy is available.

Planning for renewable energy

- Select data center locations where renewable energy resources are accessible. A comprehensive approach is necessary, which may involve a combination of renewable sources, energy storage systems, and grid integration to ensure a reliable, sustainable energy supply for data centers while considering the environmental impacts of each source.
- Establish power purchase agreements with renewable energy providers to secure a consistent, reliable supply of renewable energy for data center operations.
- Install onsite renewable energy-generation systems such as solar panels or wind turbines to source renewable energy directly for data center operations. Use of renewable energy, for example solar with a backup energy storage solution,[58] can reduce emissions, noise pollution, and fuel consumption.
- Data centers can contribute to the urban environment by leveraging their substantial grid connections to support the energy system (e.g., by waste-heat sharing and generating additional energy resources such as hydrogen and heat).[59]
- Explore partnerships with other organizations with similar needs to colocate or build energy production and storage. Partnerships could be formed with other large energy consumers to create economies of scale, facilitating capital-intensive projects that secure renewables and grid tie-ins.

Energy storage

- Renewable energy sources can be intermittent, and energy storage solutions and quick-ramping power supplies are necessary to manage fluctuations and ensure continuous power supply. Invest in demand-response capabilities to help integrate renewable energy.
- Deploy energy storage systems such as batteries to store excess renewable energy during peak production periods and use it during periods of low renewable generation or high demand.
- Implement modular renewable energy solutions that can be easily scaled up or down to match the data center's energy requirements, allowing for flexible capacity expansion. Energy storage (e.g., batteries) coupled with renewable sources (e.g., solar, wind, biodiesel) can help stabilize the grid network, including by offsetting peaks and short-term intermittencies.

Backup power

- Ensure reliability during unexpected events by installing backup power systems that are appropriately sized, neither overdimensioned nor underdimensioned, to provide reliable support when needed. Scrutinize power backup requirements to eliminate energy costs from unnecessary or oversized redundant power supplies or uninterruptible power supply equipment.[60 61]
- Use energy-efficient uninterrupted power supplies; 96 percent to 97 percent efficiency is good and is available on the market.[62 63]

Financing and stakeholder engagement

- Explore funding options and grants for renewable energy projects.
- Form partnerships with renewable energy providers, different agencies across the government, and industry associations to access expertise and resources for renewable energy integration.

Transparency and reporting

- Ensuring the authenticity and traceability of renewable energy sources can be complex, especially when dealing with third-party energy providers. Purchase renewable energy certificates to verify and track renewable attributes of energy consumed, ensuring transparency and accountability.
- Develop and adopt standardized energy reporting metrics such as renewable energy factor, to track the effectiveness of renewable energy integration.

24/7 Carbon-Free Energy Compact

The 24/7 Carbon-Free Energy Compact encompasses a set of principles and initiatives that stakeholders in the energy ecosystem can adopt to catalyze transformative change. Several data center providers, including Iron Mountain, Google, and Microsoft, have committed to this compact, demonstrating their efforts to achieve carbon-free energy sources.

Scala Data Centers is a sustainable hyperscale data center operator in Latin America that was the first to use 100 percent certified renewable energy and achieve a PUE of 1.5, which is significantly lower than the regional average. As a member of the iMasons Climate Accord, Scala has received CarbonNeutral certification.[64 65]

Case 8. Use of Renewable Energy: Latin America

The Facebook Odense data center has deployed various energy-efficiency solutions: hyper-efficient hardware, indirect evaporate cooling, renewable wind energy. It also uses waste heat resources to power the local community through a district heating system. The energy recovered from its servers is recycled using a newly constructed heat pump facility supported by 100 percent renewable energy. The heat recovery project is designed to recover 100,000 MWh of power annually to warm 6,900 homes.[66]

Case 9. Facebook Uses Waste Heat: Odense, Denmark

Appendix C provides a detailed description of mitigation strategies and additional resources.

Sustainable Cooling

Efficient cooling is crucial for high-performance computing and server technologies, which generate substantial heat. The data center temperature must be maintained within a certain range to prevent condensation and damage to IT equipment, which causes downtime and data loss.[67] Cooling data center IT equipment can account for more than 40 percent of total energy consumption in large data centers and even more in smaller ones.[68] Excessive use of energy to cool increases carbon emissions. Many LMICs are in climate zones with high temperate and humidity, such as humid subtropical and monsoon regions, which requires extra cooling, and some cooling technologies available in cold, dry climates, for example using cold external air, are unavailable. Continued efforts are needed to develop and adjust cooling technologies to diverse climate zones.[69]

Smaller data centers often prioritize reliability over energy efficiency, leading to inefficient workload distribution. Installing proper air management systems can mitigate overcooling due to redundancy and hot spots, but smaller data centers often lack such systems. Addressing energy consumption in smaller data centers is essential to reduce overall energy waste. Finally, data centers consume significant amounts of water for cooling, which puts pressure on local water sources and can contribute to water scarcity in regions already facing water stress. Careful management of water resources is critical at the national and facility levels.

Key Issues and Steps for Efficient Cooling

Controlling temperature and reducing heat is crucial for data center functionality and safety. Several factors lead to inefficient cooling, for example:[70] [71]

- Inadequate cool air supply, resulting in hot air recirculation
- Server overheating due to poor rack airflow
- Overcooling from poor air management, improper needs assessment, and redundant systems operating at installed capacity, rather than in a failover configuration
- Uneven cooling due to rack configuration

Traditional refrigerants, such as hydrofluorocarbons, used in cooling systems, including computer room air conditioning systems, have high global warning potential, which contributes to GHG emissions and climate change.[72] Adopting alternative refrigerants as substitutes for hydrofluorocarbons in data center cooling systems has the potential to reduce the emission of approximately 43.5 gigatons to 50.5 gigatons of carbon dioxide equivalent from 2020 to 2050.[73]

Data center operators can enhance their cooling practices by considering the following issues and steps:

Cooling solution

- Use natural or ambient air cooling when environmental conditions allow by selecting data center location carefully and reducing reliance on mechanical cooling systems.
- Implement energy-efficient cooling technologies such as precision air conditioning, economizers, and containment systems to optimize cooling efficiency and reduce energy consumption.
- Use innovative technologies such as liquid cooling to increase cooling energy efficiency.[74] Liquid cooling or liquid-based heat transfer uses less energy than air cooling. Adherence to relevant standards (Appendix A) is crucial for liquid cooling solutions.
- Adopt modular cooling solutions that can be easily scaled up or down based on load requirements to optimize cooling capacity.
- Traditional cooling methods like water-based cooling can consume substantial amounts of water, straining local water resources. Adopt water-saving cooling solutions such as closed-loop cooling systems, liquid cooling or liquid-based heat transfer, and waterless cooling technologies to minimize water consumption. Closed-loop water cycles, although equipment intensive, can be implemented in collaboration with external organizations such as wastewater treatment companies, and district heating and cooling providers to share costs and resources.

Appropriate heat and air flow management

- Manage heat properly to avoid hotspots and inefficient cooling (including overcooling), which results in equipment failure and poor performance.
- Implement proper airflow management techniques, including hot and cold aisle containment, raised floors, and optimized server rack layouts (front to back), to ensure efficient heat dissipation and minimize hotspots. Deploy hot and cold aisle containment systems to segregate hot and cold airflows, preventing mixing and increasing cooling efficiency. Raised-floor computer rooms have, for example, become more prevalent, allowing cool air to circulate more effectively.[75] Figure 7 illustrates how raised-floor and overhead air supply systems, such as computer room air- conditioners (CRAC), are used to deliver chilled airflow to computer racks, with the airflow passing through perforated tiles or ceilings into the cold aisles for heat exchange. The heated air collects in the hot aisle and circulates back to the CRAC. Air conditioning units can also be placed near or inside the computer racks to minimize hot-air recirculation.
- Establish energy performance metrics that are aligned with individual goals and objectives.

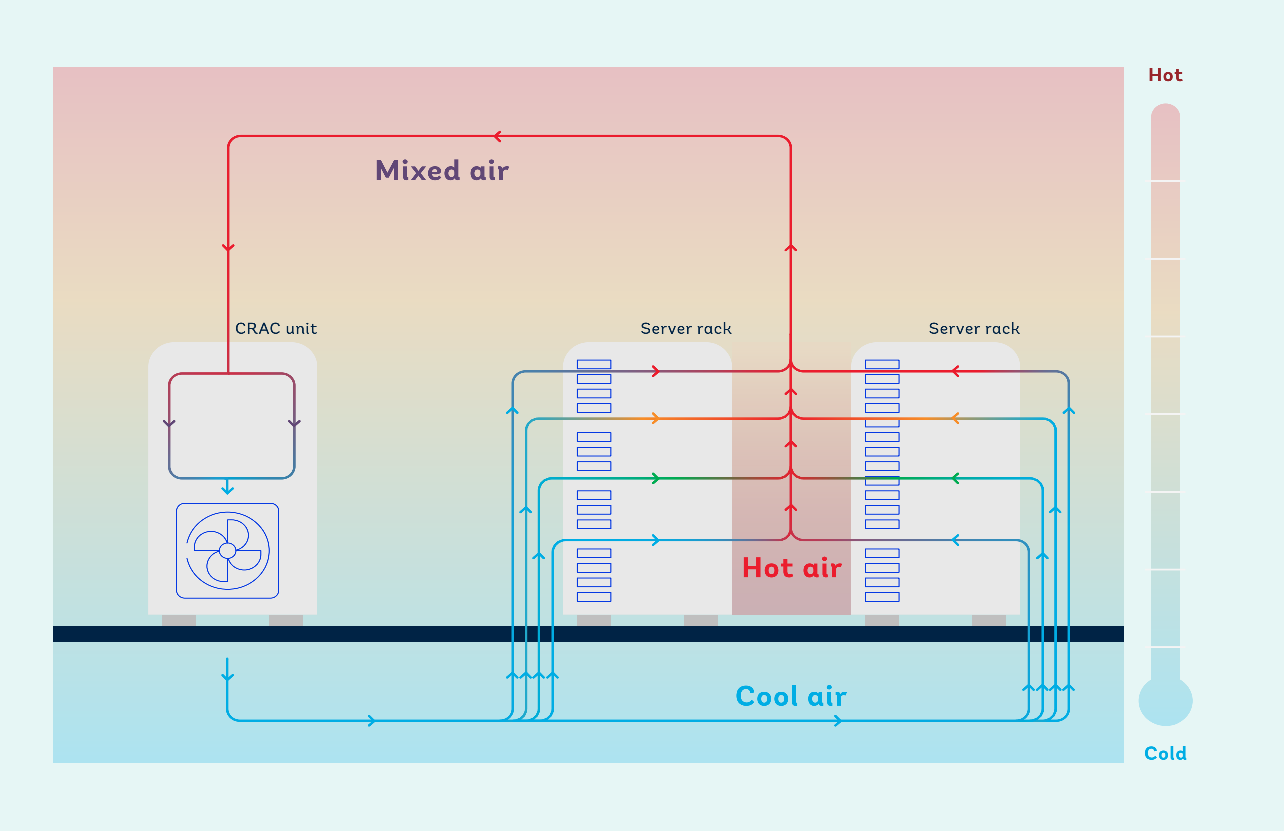


Figure 7. Raised Floor and Overhead Air Supply System (Source: Kevin Heslin. A Look at Data Center Cooling Technologies. Uptime Institute.)

Temperature increase

- Allow temperature to increase within acceptable limits to reduce cooling demand. There are several guidelines on thermal management for data centers, including on appropriate operating temperatures, such as those by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE),[76] European Telecommunications Standards Institute (ETSI)[77 78] , and ITU[79 80]
- According to ASHRAE, the recommended temperature range for A1 to A4 class hardware is 18°C to 27°C, which is higher than many data centers are configured.[81 82]

Monitoring

- Keep room temperature stable and humidity low to ensure server reliability. Implementing temperature and humidity monitoring solutions is recommended.
- Deploy solutions that provide real-time monitoring, enabling optimization by making it easier to identify areas for improvement and measure the impact of changes, and manage cooling efficiently.
- Use advanced analytics and machine learning to predict cooling requirements and identify potential for efficiency increases.

Use of refrigerants

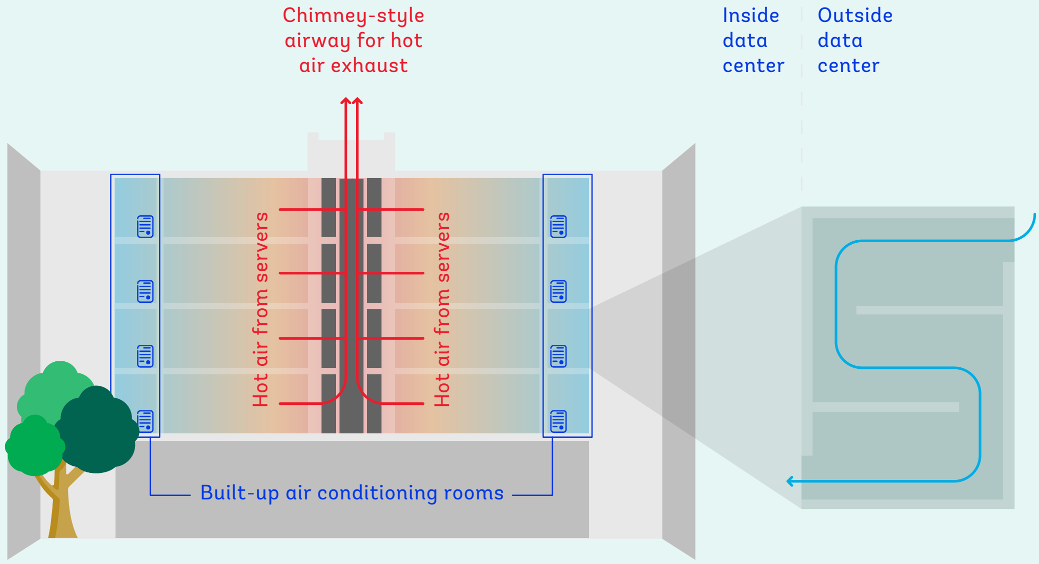
- Conduct a comprehensive assessment to identify the most suitable refrigerant options based on safety, efficiency, and environmental impact. Replace high-global warning potential refrigerants with low-global warning potential alternatives (e.g., hydrofluoroolefins) or natural refrigerants such as ammonia or carbon dioxide.[83] A carbon dioxide heating, ventilation, and air conditioning system is 12 times as economical as a system using traditional hydrofluorocarbons.[84] Explore innovative cooling technologies such as liquid cooling or exploit low-temperature ambient i.e. outdoor air) that can help optimize cooling efficiency and reduce reliance on refrigerants.
- Use advanced monitoring systems to identify and address refrigerant leaks quickly. Conduct preventive maintenance to ensure proper functioning of cooling systems and minimize leakage risks.
- Establish procedures for proper handling, storage, and disposal of refrigerants to prevent accidental releases. Ensure compliance with regulations and best practices for refrigerant management such as the Montreal Protocol.

Waste heat use

- Encourage use of waste heat and sector coupling when possible. Sector coupling involves the increased integration of energy end-use and supply sectors with one another, resulting in heightened efficiency, flexibility, reliability, and sufficiency within an energy system. Challenges include high upfront investment costs and complex infrastructure integration into existing infrastructure or designing new distribution systemst. Building facilities that use internal and external waste heat for cooling and electricity generation can offer several benefits, such as reducing waste and curbing energy requirements from conventional sources, thereby enhancing sustainability efforts.[85 86]

Some data center operators in Latin America are adopting free cooling. For instance, Equinix uses free cooling in its SP3 data center in Sao Paulo.[87] SP3 has been intentionally designed with a strong focus on environmental responsibility and energy efficiency. Its infrastructure will seamlessly incorporate evaporative air cooling techniques and indirect free cooling strategies, harnessing external air to efficiently cool the data center when temperatures drop.

Case 10. Free Cooling: Brazil



LG CNS operates data centers in the Republic of Korea and globally. The Busan Global Cloud Data Center has been recognized for its high energy efficiency, with an annual average PUE of 1.39, and a winter low of 1.15 when cooling devices are not in operation. The Busan Global Cloud Data Center uses a unique chimney-style hot-air exhaust and a hybrid cooling system called the Built-Up Outside Air-cooling System to increase energy efficiency.[88] Read more about the Republic of Korea's effort to green the ICT sector here.

Case 11. Chimney-Style Airway: Republic of Korea

Water Management

Water is critical for data center efficiency, facilitating server and other equipment cooling and removing dust and other particles from the air. Sourcing water from local municipal supplies or natural sources may have implications for water availability in the surrounding area. To address water management, it is important to consider the following.[89] [90] [91] [92] [93]

Water consumption and sourcing

- Consider sustainable water sourcing options and explore alternatives, such as using reclaimed (grey water) or recycled (rainwater) water. Implement systems for treating and reusing wastewater that data centers generate. Implement community water programs that redirect clean cooling water from data centers to canals, benefiting local farmers for irrigation purposes. For example, up to 96 percent of the wastewater discharged from Amazon Web Services (AWS) data centers in Oregon (United States) can be reused, reducing strain on wastewater treatment plants.[94]
- Incorporate water-efficient design principles into data centers, including by using water-saving fixtures and optimizing equipment layout.
- Use proactive measures such as leakage detection and smart monitoring in water and cooling management.

Water discharge

- Manage wastewater properly to minimize environmental impact.

Water risk management

- Develop risk assessments and contingency plans for potential supply disruptions and have back-up cooling strategies.
- Establish a collaborative water buffer system that can multiple large water users can share.

Smart water solutions

- Identify areas where investments can be made to use digital technologies to optimize water use, enhance efficiency, and improve monitoring, including smart metering, real-time monitoring sensors, and automated control systems. Ensuring leakage detection is vital, as exemplified by previous incidents such as the Google Cloud 2023 Paris data center flooding.[95]
- Engage with smart water solution providers to enhance data center water management. These providers offer systems to monitor, control, and optimize water use that should be tailored to specific needs, aligning with sustainability objectives of the data centre, and offering benefits like real-time insights and supporting regulatory compliance.
- Implement pilot projects to test smart water management solutions, including evaluating performance and gathering data to assess effectiveness before expanding.
- Ensure that staff are equipped with skills and training to manage and use smart solutions effectively.

Monitoring

- Implement water management plans to support compliance through recycling and reusing water, which minimizes water use and reduces the potential impact on the environment. This is particularly important when choosing cooling systems based on water prices, availability, and expected operational demand.
- Monitor water use effectiveness. Implement standards and certifications relevant to your country that support water usage monitoring, such as Leadership in Energy and Environmental Design and Building Research Establishment Environmental Assessment Method.

Regulatory compliance

- Consult regulatory agencies and environmental experts to understand and meet requirements for country-specific water laws and regulations.
- Ensure regulatory compliance; obtain permits; monitor use, discharge, and treatment; and report this to authorities. Regulatory compliance includes obtaining permits for water withdrawal from surface or groundwater sources; treating and discharging wastewater; and monitoring and reporting water use, discharge, and quality to government authorities.

Appendix C provides details on mitigation strategies and resources.

E-Waste Management

E-waste, or discarded electronic equipment, poses significant environmental and health risks because it contains hazardous substances such as mercury. The rapid technology refresh rate in data centers, driven by increasing data demands, has contributed to the global e-waste challenge; 53.6 million metric tons of e-waste was generated in 2019 (only 17.4 percent of which was formally collected and recycled), resulting in an estimated US$57 billion lost in recoverable materials.[96]

When planning for a data center, it is crucial to consider equipment lifespan, typically 1 to 5 years for servers but up to 10 years with secondary use.[97] Efficient e-waste management, including reuse, refurbishment, and proper recycling, can mitigate environmental impacts and increase resource recovery. Integrating these strategies into the data center lifecycle is essential to meet sustainability objectives.

Many organizations lack an e-waste management strategy, making recovering and recycling data center e-waste challenging. Similarly, many countries, especially LMICs, lack comprehensive e-waste management regulations and strategies. Lack of proper regulation poses significant challenges in addressing the growing problem of e-waste. Without effective e-waste management systems in place, there is risk of improper disposal, environmental contamination, and loss of valuable resources.[98] It is important to exercise due diligence when selecting collaborators to ensure the responsible handling and lawful disposal of equipment at end-of-life, mitigating the risk of adverse outcomes.

Key Issues and Steps to Improve E-Waste Management

The frequent hardware refresh cycle means that 47 percent of data centers renew their systems every 1 to 3 years and an additional 28 percent every 4 to 5 years,[99] although many organizations are moving away from these short refresh cycles because servers are not becoming faster, with 5 to 8 years becoming more common and cloud hosting companies using equipment for 8 to 10 years.[100]

The technical complexity of server racks means that they are constructed of mixed metals, which makes them challenging to separate and sort, requiring design improvements so that the materials can be recovered and recycled. Reliable, accredited IT asset disposition providers can be contracted with to dispose of and recycle e-waste or harvest or refurbish parts, but they are not available in all countries.

It is important to follow the waste hierarchy (Figure 8) to help reduce e-waste. The waste hierarch is a ranking system used for the different waste management options according to which is the best for the environment.

Figure 8. Waste Hierarchy Ranking System to Determine the Most Environmentally Favorable Option

By implementing the following steps, data centers can enhance their e-waste management practices, reducing their environmental footprint.

E-waste management plan

- Establish e-waste recycling and repurposing programs to enable data center equipment to be used elsewhere within the organization. Optimizing refresh cycles can notably reduce e-waste and enhance performance.[101]

Technology choice

- Use products that are easily disassembled, allowing for recovery of valuable materials and components during end-of-life recycling.

Disposal

- Collaborate with certified e-waste recyclers who adhere to proper recycling and disposal practices, ensuring safe, environmentally sound management.
- Identify local or regional solutions to dispose of and recycle e-waste.
- Partner with other organizations with similar disposal needs. Use and support development of regional IT asset disposition providers that can take hardware, harvest parts, and sell them to consumers as low-cost computing equipment (e.g., for laptops and desktop computers).

Data security

- Destroy data securely to avoid data breaches and address privacy concerns.
- Implement strict protocols and standards for data destruction before disposing of IT equipment and work with certified IT asset disposition companies. This may involve data wiping and degaussing to ensure complete removal of sensitive data from electronic devices.[102] Physical destruction (e.g., shredding of hard drives) should be avoided when possible to reduce waste, especially when data security-compliant software wiping is available.

Supply chain management

- Track and manage used equipment and e-waste throughout its lifecycle.
- Include e-waste management criteria in procurement policies for IT equipment. Prioritize vendors that offer take-back programs, responsible recycling practices, and environmentally friendly products.
- Regularly assess and audit vendors to ensure compliance with e-waste management standards.

Knowledge and awareness

- Conduct awareness campaigns and training programs to educate data center staff and stakeholders about the importance of proper e-waste management and how to follow proper practices.

Monitoring of e-waste quantities and flows

- Monitor e-waste quantities and flows in data centers to understand e-waste generation, facilitate proper waste management strategies, and ensure regulatory compliance.
- Promote transparent disclosure of sustainability goals and commitments for end-of-life management to foster accountability while closely monitoring quantities and flows of e-waste to measure progress, assess sustainability targets, and formulate effective strategies for data center infrastructure equipment.[103]

Implementation of standards

- Circular solutions require product designs that support material reduction, reuse, and recycling. Recommendation ITU-T L.1023 provides a framework for evaluating circularity and design criteria related to manufacturer capabilities and product durability, recyclability, repairability, and upgradability.
- Require that equipment suppliers and e-waste recyclers adhere to relevant standards.

Track and manage used equipment and e-waste throughout its lifecycle.

A study explored how Zimbabwean universities manage e-waste from data centers to promote environmental sustainability and mitigate health risks of improper disposal. Increasing use of ICT in universities has increased demand for data center infrastructure, resulting in improper disposal of obsolete equipment. It is crucial for universities to develop data center e-waste management strategies and establish partnerships for design and recycling.[104]

Case 12. Data Center E-Waste Management: Zimbabwe

A London South Bank University project on the circular economy for the data center industry (CEDaCI) is increasing reclamation and reuse of critical raw materials, prolonging product life through equipment reuse and remanufacture, and minimizing use of virgin materials and environmental impact associated with redundant equipment. The Circular Data Center Compass is a free online resource that was developed to guide the data center industry in choosing more circular options during the procurement, refurbishment, and disposal of servers by assessing the environment, social, and economic impacts and criticality of raw materials. The resource aligns with the EU Circular Economy Action Plan 2020 and other eco-design directives and regulations. [105]

Case 13. Circular Economy for the Data Center Industry: United Kingdom

Climate-Neutral Data Centre Pact and Circular Economy

The Climate-Neutral Data Centre Pact's circular economy working group prioritizes equipment repair and reuse to reduce natural capital consumption. Targets include achieving 100 percent assessment for reuse, repair, or recycling of used server equipment and increasing the amount of server material repaired or reused, with a specific target percentage for repair and reuse by 2025.[106]

Appendix C provides a detailed description of mitigation strategies and resources, including circularity metric tools.

Greening Public Procurement of Data Centers

Green public procurement (GPP) is an approach to enhancing environmental sustainability of procurement, including for data centers and server infrastructure. Introducing GPP in procurement of data infrastructure can also support the broader data center market's green transition.

Green procurement can span comprehensive green considerations or selected green priority areas. It is not a matter of all or nothing. Public organizations are encouraged to start integrating green aspects and learn from the experience.

Green procurement falls within the wider concept of sustainable public procurement that includes environmental, social, and economic components. Existing GPP criteria serve as a foundational guide for sustainable procurement, helping align practices with broader goals, but adapting guidelines and international standards to the organization's specific needs, sustainability goals, and market context is crucial.

This section builds on other resources developed by ITU and the World Bank (the key ones are listed below) that pertain to ICT and green procurement.

- Circular and Sustainable Public Procurement for ICTs Guide and Recommendation ITU-T L.1061 "Circular public procurement of information and communication technologies"
- Recommendation ITU-T L.1304: Procurement criteria for sustainable data centres
- GovTech Procurement Practice Note. World Bank Group.
- Institutional and Procurement Practice Note on Cloud Computing. World Bank Group
- World Bank Green Public Procurement: An Overview of Green Reforms in Country Procurement Systems
- World Bank Toward Environmentally Sustainable Public Institutions: The Green Government IT Index

Procurement Planning

The planning phase is crucial for green data center procurement, setting the tone for all subsequent procurement activities. During this stage, organizations identify needs, set objectives, conduct market research to explore options from different service providers, and establish criteria for their procurement process.

Making environmental sustainability and social and governance considerations a priority at this stage can embed green approaches in procurement decisions from the beginning. Thoughtful planning enables organizations to identify opportunities for energy efficiency, waste reduction, and water conservation and align their procurement practices with broader sustainability goals and regulatory requirements.

Choice of Procurement Route

As mentioned in the Introduction, procuring a new data center or using a service model encompasses several distinct pathways, each with its own considerations in terms of what aspects of the data center operation a buyer can influence. The pathway choice depends on the procuring organization's needs, budget, technical capabilities, and environmental goals and business models available in the market in a particular region.

Core Planning Questions

The planning phase for green procurement also requires that the procurement team ask questions to set the direction for the procurement process (Table 2). This blends technical needs with sustainability goals and regulatory and market questions.

QUESTION	APPROACH	KEY RESOURCES	EXAMPLES OF GUIDANCE
What are the needs?	Define precise requirements for data center. Consider capacity, performance, security, scalability, and resilience.	Internal data analysis, IT infrastructure assessment tools, professional consulting services.	• Data Center Knowledge: How to Plan a Data Center • United Nations Environment Program: Sustainable Public Procurement: How to Wake the Sleeping Giant! Introducing the United Nations Environment Programme's Approach • EU Green Public Procurement Toolkit: Needs assessment module • ITU-T L.1304
What are the sustainability goals?	Align procurement process with organization's sustainability objectives and priorities.	Sustainability policy documents, environmental impact assessment tools, sustainability consulting services.	• World Bank: Green Public Procurement: An Overview of Green Reforms in Country Procurement Systems • Australian Government: Sustainable Procurement Guide
What are the regulatory requirements?	Become familiar with local and regional environmental laws and regulations related to data centers.	Regulatory bodies' guidelines and resources, legal advisors, compliance assessment tools.	• Data Center Alliance: Policy Regulation and Compliance • Brazilian Government Decree on Data Center Energy Consumption
What are the market capabilities?	Understand what the market can offer in terms of green data centers.	Market research reports, vendor presentations and literature, industry trend analyses.	• Uptime Institute Reports: Data Center Studies • Make ICT Fair
What are the total costs?	Consider not just upfront costs, but also total cost of ownership, which includes energy, maintenance, and end-of-life disposal costs.	Financial analysis tools, lifecycle cost assessment software, financial advisors.	• Datacenter Total Cost of Ownership (TCO) Models: A Survey • European Commission: Lifecycle Costing Tools • Sustainable Public Procurement Regions: State of the Art Report: Lifecycle Costing
Who are the stakeholders?	Identify who will be involved in or affected by procurement process and operation of data center.	Stakeholder mapping tools, stakeholder engagement strategies, communication plan templates.	• ICLEI: The Procura+ Manual: A Guide to Implementing Sustainable Procurement

Table 2. Core Questions to Determine Needs

By answering these core questions at the outset, a clear roadmap for the green procurement process can be created, ensuring that every step aligns with the organization's needs and green objectives.

Green Leverage

Green leverage in procurement is when organizations strategically use their purchasing power to encourage environmentally sustainable practices among suppliers. This involves selecting vendors that prioritize energy efficiency, using environmentally sound materials, and responsible waste management. By integrating green criteria into procurement processes, organizations influence suppliers to adopt sustainable practices and contribute to broader environmental goals, promoting positive change in supply chains and industries through sustainability-focused purchasing decisions. Greening strategies in data center procurement requires tailored approaches based on the service model employed-colocation or Anything as a Service. Governments often encounter situations in green procurement of data services wherein specific considerations are beyond their control, particularly in outsourced models such as cloud services, whereas large providers can often take advantage of economies of scale and cross-site experience with sustainability efforts when making efficiency and green technology investments. Each model comes with a different set of responsibilities and control levels for the government. A non-exhaustive example of models and approaches is included in Table 3.

<table>
<tr><th>MODEL</th><th>LEVERAGE</th><th>APPROACH</th></tr>
<tr><td>Publicly owned facilities</td><td>• Complete facility control empowers public data centers to implement sustainable practices, optimize energy efficiency, adopt renewables, utilize efficient cooling, manage waste effectively, integrate eco-tech, and follow circular economy principles, highlighting a comprehensive approach for environmental sustainability and resource efficiency.
• Local conditions determine opportunities and barriers for renewable energy, cooling, etc.</td><td>• It is possible to design, build, operate, and decommission the data center using green practices and considering costs and other factors.</td></tr>
<tr><td>Colocation model</td><td>• Building-level considerations such as power and insulation fall under the data center hosting provider's purview, whereas IT hardware-level concerns, including server energy efficiency, lie within the government's service boundary.
• Buyers can select providers with green certifications for their facilities and specify energy-efficiency standards for servers and other hardware.</td><td rowspan="2">• Certifications and standards: Governments should request that vendors provide evidence of adherence to recognized environmental standards and certifications such as Leadership in Energy and Environmental Design, Building Research Establishment Environmental Assessment Method, Energy Star, and EU Code of Conduct for Data Centres, which serve as proof of vendor's commitment to green practices.
• Third-party audits: External environmental auditors can be employed to verify vendors' green claims. These independent audits provide an unbiased assessment of the vendor's environmental footprint and policy adherence.
• Green contract clauses: Governments can incorporate green requirements into contracts, obligating vendors to meet specific environmental standards or adopt green practices, including clauses requiring regular reporting on energy use, emissions, waste, and other relevant sustainability metrics.</td></tr>
<tr><td>Anything-as-a-Service model</td><td>• Service provider manages building- and IT hardware-level considerations.</td></tr>
</table>

Table 3. Data Center Models and Green Levers to Shape Environmentally Sustainable Choices in Data Center Procurement

Business Case for Green Procurement

Making a business case for green procurement necessitates long-term cost-benefit analysis. Lifecycle cost i.e. total cost of ownership plus externalities provides a comprehensive picture of costs. Total cost of ownership includes acquisition, operating, maintenance, and end-of-use costs, whereas lifecycle cost can encompass environmental and social costs.

Table 4 shows how lifecycle costs and opportunities for a buyer for sustainability and circularity are distributed across the lifecycle of a data center, depending on the procurement approach used and cost category.

COST CATEGORY	EXPECTED COST RANGE AS A PERCENTAGE OF LIFECYCLE COST				OPPORTUNITIES FOR GREEN AND CIRCULAR PROCUREMENT
	Server rooms	Enterprise	Colocation	Managed Service Provider	
Capital expenditures, facilities	1-5	15-20	1-5	0	Energy-efficient buildings and infrastructure (e.g., Leadership in Energy and Environmental Design, Building Research Establishment Environmental Assessment Method), waste reduction, end-of-life planning, and water efficiency can offset initial capital expenditures.
Capital expenditures, IT	30-60	30-40	40-50	0	Energy efficiency and server optimization can reduce costs by reducing need for expansion and energy use. Energy savings can offset higher initial capital expenditures for equipment operating in broader environmental conditions.
Operating expenses, facilities	10-30	10-15	5-15	35-50	Requesting specific criteria on power use effectiveness and best practices in cooling systems can lead to reduced operational costs, whilst improving energy efficiency. Avoiding high-global warning potential refrigerants by using free or economized cooling solutions can reduce operating costs, although significant initial investment may be required.
Operating expenses, IT	20-40	25-35	30-40	50-70	Server optimization, end-of-life management, and repairability and upgradability of IT equipment can reduce costs by reducing need for additional equipment, enabling recovery of equipment residual value, and reducing maintenance costs.
Decommissioning	5-10	5-10	1-5	0	Equipment decommissioning offers opportunities for resale, recycling, proper waste disposal, energy recovery, and supplier take-back schemes.
Reaching end of the facility's lifespan	1-5	1-5	N/A	N/A	Reaching the end of the facility's lifespan end of life allows for material recovery and reuse, responsible waste management, and potential conversion of the facility for other uses.

Table 4. Lifecycle Costs of Various Data Center Models and Opportunities for Sustainability

Considering these approaches and costs and asking suppliers for related information increases demand from suppliers for information related to total costs, lifecycle analysis, and associated certifications. The goal is to leverage procurement power to push the data center industry toward more-sustainable practices, regardless of the service model.

Navigating Green Data Center Market Engagement As demand for green data centers grows, understanding how to engage with the data center market effectively is crucial. Particularly when introducing new, advanced green and circular approaches to data center procurement, it is a good idea to engage with data center service providers to acquire valuable insights. Engagement can take place before, during, and after procurement.

- **Market research:** Conduct thorough market research to understand offerings and developments in green data center solutions in the relevant country or region, including energy-efficient hardware, renewable energy sources, and cutting-edge cooling technologies.
- **Supplier engagement:** Establish early communication with potential suppliers. Convey sustainability goals and requirements and evaluate suppliers' ability and readiness to meet these specifications.
- **Request for information:** Issue a request for information to gather in-depth information about suppliers' sustainable practices and technologies.
- **Innovation partnerships:** Foster a culture of innovation by establishing partnerships with suppliers. Encourage them to propose unique solutions that align with your sustainability objectives.
- **Education and training:** Provide the procurement team with current insights into sustainable technologies and practices, facilitating knowledgeable decision-making regarding environmentally sound options during supplier engagement and selection processes.
- **Communication:** Convery sustainability priorities to the market and potential service providers, underscoring commitment to sustainability and motivating suppliers to invest in sustainable solutions.

This section offers a brief overview; for more detailed information, see the ITU Circular and Sustainable Public Procurement ICT Equipment Guide.

Prioritizing Green Requirements

It is good practice to include green requirements early in the procurement process so that-in addition to cost, security, safety, and maintenance-sustainability, including circularity, is included and is not just considered a "tie breaker" among the lowest bidders.

Recommendation ITU-T L.1410 sets requirements and provides suggestions for selecting IT equipment, facilities, and other components, including for the operational phase, but its application is limited to existing data centers, making it less useful as a procurement criterion. This makes it important to develop a set of procurement criteria that consider data center design, including location, low-energy equipment, and a plan to reduce total environmental impact. See Table 5 for more details on prioritizing procurement objectives.

SCOPE	PLANNING QUESTION	APPROACH
Building	How can we ensure the building envelope is as green as possible?	Request certification with, for example, EDGE standard.
Efficient electricity consumption	How can we procure a data center that minimizes electricity consumption, particularly cooling and ancillary power?	Prioritize data centers with low power use effectiveness, water use effectiveness, energy reuse effectiveness ratings, and where the energy reuse factor (outlined in EN 50600) highlights greater use of renewable energy sources. Evaluate energy-saving technologies and solutions such as efficient cooling systems and advanced power management.
Renewable energy sources	How can we ensure that renewable energy sources are being used to power data center operations?	Prioritize data center providers that can supply or facilitate access to renewable energy sources. Follow principles and actions from the 24/7 Carbon-free Energy Compact and explore options for implementing power purchase agreements.
Adherence to optimal temperature range	Can we accept higher operating temperature ranges for greater energy efficiency?	Evaluate the potential for using the American Society of Heating, Refrigerating and Air-Conditioning Engineers Technical Committee 9.9 allowable temperature range in data centers.
Water use reduction	How can we reduce water use in our data center operations?	Consider data centers that use innovative methods to reduce water use, such as water-efficient cooling systems and recycled or grey water.
E-waste	How can we include provisions for responsible e-waste management?	Prioritize data center providers demonstrating adherence to local, national, or international e-waste management guidelines. Ask for information on how they handle and dispose of e-waste, including certifications (e.g., e-Stewards, R2). Use suppliers with take-back programs, which allow return of electronic equipment at end-of-life and guarantee its proper disposal. Include provisions that outline responsibilities for managing e-waste and associated costs.
Compliance with environmental regulations	How can we ensure compliance with emerging environmental regulations and reporting requirements?	Be aware of current and future regulations and select data center providers that demonstrate compliance with these regulations.
Environmental, social, and governance (ESG) issues	How can we incorporate ESG considerations into our data center procurement process?	Include ESG criteria in requests for proposals. Weigh ESG responses in selection scoring models and seek providers demonstrating firm commitments to ESG goals.
Comprehensive environmental impact reporting	How can we ensure transparency and accountability regarding the total environmental impact of our data center operations?	Seek data center providers that offer comprehensive environmental impact reporting, encompassing power use effectiveness and other metrics related to recycling, material sourcing, and broader ESG issues.

Table 5. Prioritizing Green Procurement Objectives

Power Purchase Agreements in Data Center Procurement

A power purchase agreement (PPA) is a tool that facilitates procurement of green energy in data centers. By including PPAs in the tender process, public authorities can promote sustainable energy procurement that contributes to their environmental objectives.

PPAs are contracts between data center operators and renewable energy providers that facilitate sustainable energy procurement. They guarantee a stable supply of renewable energy at a fixed price, reducing a data center's carbon footprint.

To incorporate PPAs into a data center tender, a public authority can specify sustainability goals and express the intention to procure renewable energy through PPAs. Supplier proposals can be evaluated based on their experience facilitating PPAs and renewable energy procurement. The PPA arrangement can be considered an evaluation criterion alongside other factors while explicit contractual provisions are defined to ensure compliance.

Find out more in the World Bank resources on PPAs and energy purchase agreements

Case 14. Case 14: Use of Power Purchase Agreements: South Africa

Africa Data Centres has signed a 20-year PPA with Distributed Power Africa to procure solar energy. Distributed Power Africa will supply renewable energy to power its South African operations via wheeling (energy delivered from the renewable energy site to the customer via existing distribution or transmission networks).

Procuring the Data Center

This section provides guidance to help navigate the procurement process. It gives ideas on defining requirements and evaluating suppliers by their sustainability criteria and considering lifecycle costs. It also offers links to additional technical resources for further support.

Bidding Type

Data center procurement usually involves acquiring goods, works, and services. Each of these might require different procurement methods and greening considerations.

- **Goods:** server hardware, storage devices, network equipment, cooling systems, backup power supplies. Energy Star or other standards can be used.
- **Works:** construction or modification work for the data center facility involving site preparation, construction of the data center building, and installation of cooling and power systems and security systems. Green building specifications can be included in procurement documents. It is important to consider capacity building, partnerships, and guidelines that can foster the needed skill set in local markets.
- **Services:** design and building of the data center, maintenance services, managed services for running data center operations. Specialized server providers are emerging that can advise during the planning phase, including on market-relevant green specifications for goods and works.

Standards, Labels, and Certifications

Labels, certifications, and standards can be employed to enhance data center environmental sustainability by providing established frameworks and benchmarks for assessing and improving various aspects such as energy efficiency, resource conservation, waste management, and overall environmental impact (Appendix A). Considerations for data center procurement include:

- **Use of existing labels, certifications and standards:** Leverage sustainability impact assessments, solutions, and verifications that established labels in the industry provide.
- **Flexibility in label and certification selection:** If a specific label limits the supplier pool or does not fully apply to data centers, consider specifying underlying criteria instead to allow broader participation.
- **Following good practices:** Ensure labels are objective, accessible to all interested parties, and based on verifiable, nondiscriminatory criteria.
- **Legal and transparent use:** Adhere to legal requirements and good practices for label use, including open participation, accessibility, and third-party establishment.

Green data center standards and certifications guide organizations in optimization of environmental sustainability and energy efficiency, offering recommendations, codes of conduct, and good practice guidance. They cover power and cooling efficiency, renewable energy use, carbon footprint reduction, waste management, and water conservation.

Adhering to these standards and certificates enables data centers to minimize environmental impact, enhance energy efficiency, and reduce operating costs. Various standards bodies and initiatives have established universal green data infrastructure standards. Although standards set the bar for good practices, approaches should be tailored to country- and project-specific circumstances.

Exactly how standards and certifications are incorporated into the procurement process may vary based on specific procurement policies and requirements, market capabilities and conditions, and the nature and scale of the data center project. Table 6 shows examples of standards and suggestions of how they might be applied in procurement, depending on the abovementioned variables.

AREA	APPLICATION IN PUBLIC PROCUREMENT	POSSIBLE LABELS AND CERTIFICATIONS
Greenhouse gas emissions	Procurement procedures can require that data centers report their carbon footprint and reduction plans. Potential suppliers could be asked to prove compliance with environmental regulations and initiatives.	ISO 14001 (Environmental Management), ISO 50001 (Energy Management), Science-Based Targets Initiative, ITU-T L.1410
Energy use	Procurement processes could prioritize data centers with lower energy use. Specifications for data centers can include expected energy draw and density. Energy use analysis could be requested, focusing on IT equipment and facility support hardware.	Energy Star, EU Code of Conduct for Data Centers, Uptime Institute's Tier Standard, ISO 50001 (Energy Management), Leadership in Energy and Environmental Design, ITU-T L.1420 (methodology for energy consumption)
Environmental key performance indicators	During procurement, measurement of environmental metrics such as power use effectiveness, water use effectiveness, energy reuse effectiveness, and energy reuse factor can be requested, specifying the condition of the measurement or assessment (load and external environment condition). Data centers could be required to have specific certifications, such as Energy Star ratings, or comply with the EU Code of Conduct for Data Centers or the EU Energy Efficiency Directive.	EU Code of Conduct for Data Centers, Green Grid Data Center Maturity Model
Power and cooling analysis	Data center providers could be asked to submit a power and cooling analysis demonstrating efficient power use and cooling management.	Green Grid Data Center Maturity Model
Energy reuse	Public procurement processes could encourage the installation and use of effective heat reuse systems in data centers.	ISO 14001 (Environmental Management), Green Grid Data Center Maturity Model

Table 6. Standards, Labels, and Certifications (Note: ISO, International Organization for Standardization; ITU, International Telecommunication Union.)

Green Procurement Criteria

Green public procurement (GPP) criteria function as a guide, directing the process of selection, technical requirements, awarding procedures, and performance clauses throughout procurement. Selection criteria function as initial filters, aligning potential suppliers with sustainability goals, for example, server use and cooling energy management. Detailed technical specifications designate the required characteristics of servers, data storage, and network equipment, encompassing server active state efficiency and end-of-life management. Award criteria (e.g., idle state power and renewable energy factor), distinguish between suitable suppliers, encouraging surpassing minimum sustainability standards. Lastly, sustainability practices, such as ongoing energy consumption monitoring, are enforced for the duration of the contract via contract performance clauses. Table 7 outlines these components to guide a greener procurement process.

TENDER STAGE	POSSIBLE CRITERIA
Selection criteria for data center ICT equipment	Server use (depends on application that will be running in data center, generally only applicable when procuring a service from a data center owner such as pay-as-you-go cloud computing), control of hazardous substances (Basel Convention), data storage and network equipment, cooling energy management.
Technical specifications	Server active state efficiency (e.g., a computer must offer processing power management that is enabled by default and allows reduced power consumption in times of low use; see Server Efficiency Rating Tool and Energy Star), ICT operating range (temperature and humidity), design for repair and upgrading of servers and data storage, end-of-life management of servers, data storage and network equipment, environmental monitoring, cooling system best practices, waste heat reuse readiness, renewable energy factor, global warming potential of refrigerants, IT room temperature set point, IT availability classes (e.g., uptime tier, International Organization for Standardization/International Electrotechnical Commission 22237 availability class).
Award criteria	Server idle state power, server deployed power demand, server use, end-of-life management of servers, design PUE curve, PUE improvement from baseline, cooling system energy consumption, waste heat reuse (for new data centers), waste heat reuse (for managed services), renewable energy factor, local energy produced by renewable sources, global warming potential of refrigerants.
Contract performance clauses	Monitoring of IT energy consumption, monitoring of IT equipment use and reporting on end-destination of servers, data storage and network equipment, demonstration of PUE at handover, monitoring of PUE input values, implementation of best practice designs, monitoring of cooling system's energy consumption, monitoring of heat supply and connection, renewable energy factor, global warming potential of refrigerants.

Table 7. Possible criteria Possibilities and Sources (Note: ICT, information and communications technology; IT, information technology; PUE, power use effectiveness)

Further Considerations During the Tendering Stage: When a specific technological solution, for example a cooling system, forms part of a data center, the bidder with the best tender might be required to provide proof of their claims. If this proof is satisfactory, the contract can be awarded. Test reports only ensure that a sample has been tested, not necessarily the items delivered under the contract.

Contract Execution Stage: At this stage, the criteria should be related to measuring operational performance, such as PUE input values and other environmental metrics. Operational performance criteria should be set explicitly and linked to contract performance clauses for monitoring. If monitoring shows that the delivered service does not meet the requirements, the contracting authority can apply penalties or work with the supplier to make improvements.

Many resources are available online to provide template criteria for green procurement. Organizations such as the ITU and European Union have developed comprehensive guidelines and criteria lists that can be adapted to suit particular requirements.

Greening the Enabling Environment for Data Centers

As the data center sector globally strives for sustainability, governments can influence this transformation through various instruments, including laws, incentives, and services that can guide the data center sector toward greener outcomes, for example enforce sustainability standards and motivate operators to adopt green technologies.[107] Other parts of the enabling environment evolve in more complex relationship with other stakeholders, for example skills, innovation, and financing.

This chapter covers four areas:

- **Data center policy framework** discusses policies and regulatory tools.
- **Data center public services and utilities** covers sustainable energy, water, and e-waste management.
- **Data center enablers** covers skills, innovation, and financing.
- **Measurement, reporting, and verification** addresses environmental reporting and transparency.

The enabling environment reflects the maturity of the digital sector and other country-specific factors, and measures to influence the enabling environment should consider these. In a country with a weak data center and cloud market, efforts should be focused on strengthening the overall market and inspiring and attracting green investment. In a crowded market, measures might focus on safeguarding shared resources such as water and energy and encouraging sustainable market development.

Data Center Policy Framework

The policy framework that the government establishes at various levels can influence the design and development of green data centers. This influence encompasses multiple policy instruments, from high-level policies and targets to detailed procedures and guidelines. For development of green data centers, an integrated policy framework can guide and support the various components of the data center sector, such as building envelope, ICT equipment, cooling, energy, and e-waste management, as previously outlined.

Policies and Targets

Many countries have introduced national digital strategies and policies to enhance digital access, literacy, innovation, and investment, and many have also recently addressed data centers and green considerations. These policies define what is expected to be achieved, how to achieve these targets, and how green data centers support broader development goals related to digital development and climate action.

In 2020, Chinese authorities launched a plan to build eight computing hubs and 10 data center clusters across China. Fundamental guidelines include optimizing PUE and maintaining internet latency. The plan emphasizes green requirements, energy efficiency, clean energy, and green procurement. Major technology firms such as Tencent, Alibaba, Baidu, Huawei, ByteDance, Kuaishou, and UCloud are building data centers in western China.[108]

Case 15. Eastern Data, Western Computing National Plan: China

The United Kingdom government has committed to achieving net-zero carbon emissions by 2050. The Greening Government Commitments 2020-2025 focus on reducing the environmental impact of ICT infrastructure. The U.K. government has published the HMG Sustainable Technology Strategy 2018-2020 and collaborated with industry to obtain accurate data, establishing a new baseline for 2020-25. This is reflected in the Greening Government: ICT and Digital Services Strategy 2020-2025. To compile the annual Greening Government ICT report, departmental information on the energy footprint of cloud services is collected, which involves collaboration between government departments and suppliers such as Microsoft and AWS. For the 2021/22 annual report, 34 departments and organizations reported figures on their environmental footprint.[109]

Figure 9 is an example of data provided in the 2022 annual Greening Government ICT report showing hosting kWh consumption data from on premises, off premises, and cloud data centers.

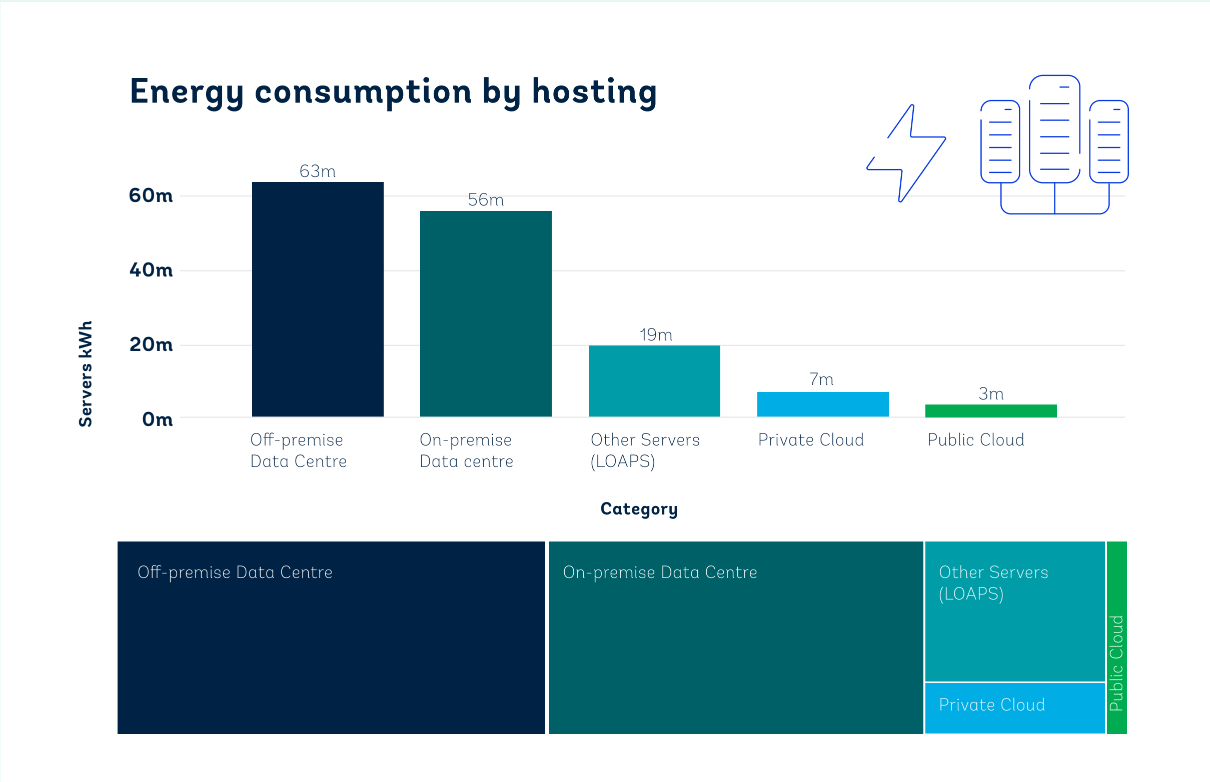


Figure 9. Energy Consumption According to Host (Note: See resources on how the U.K. government is greening its ICT infrastructure)

Case 16. Government Greening ICT Strategy: United Kingdom

Regulation and Industry Standards

Data centers are significant consumers of water and energy, affecting availability of these resources in communities and often necessitating regulatory management. Governments can use regulations to manage resources and implement mechanisms to enable regulatory enforcement.

Standards (Appendix A) offer scientifically and technically evaluated information to enable governments to define rules on constructing and managing green data centers. Although these standards typically emerge from industry, governments have an essential role in facilitating their adoption by agencies and ensuring uniformity across different jurisdictions.

More universally adopted standards for data centers are needed, such as those outlined in Appendix A. Governments can consider setting minimum requirements for green data infrastructure, which allows the data center industry to demonstrate their adherence to good practices, ensures comparability and consistency, and fosters innovation.

In 2021, facing drought-induced energy shortages, Brazil's government issued measures to curb federal agencies' energy use. With hydroelectricity providing 65 percent of the country's power, the drought significantly affected capacity. The new decree mandated technical limits on data center cooling, appropriate air conditioner sizing, power-saving settings on computers, remote cloud access, purchasing of energy-efficient equipment, adherence to energy standards for new or renovated buildings, and regular equipment maintenance.

Case 17. Decree on Data Center Energy Consumption: Brazil

The EU Code of Conduct was established to guide data center operators toward cost-effective energy reduction without disrupting critical operations. It enhances comprehension of data center energy demand, promotes awareness by delivering focused information to managers, owners and investors to enhance efficiency, and provides energy-efficient best practices and objectives. As a voluntary initiative, it expects signatories to honor agreed commitments. The European Union aims to encourage adherence through an awards scheme.

Case 18. Code of Conduct for Energy Efficiency in Data Centers: European Union

Procedures, Guidelines, and Tools

Procedures, guidelines, and tools help answer how when developing green data infrastructure projects. Procedures and manuals outline the specific tasks that data center stakeholders must perform to comply with relevant standards and frameworks, with step-by-step instructions. Most national public policy on green data infrastructure is in this category. Development of these supporting policy instruments should be tailored to solve country-specific challenges and barriers to green data infrastructure development.

Procedures, guidelines, and tools help answer how when developing green data infrastructure projects.

The Indian Green Building Council developed and launched a Green Data Center rating system in 2016 to offer services to the growing data center industry. The system's emphasis is on enabling data center projects to showcase enhanced energy performance through the implementation of energy efficiency measures.

Case 19. Green Data Centers Rating: India

The Malaysian Technical Standards Forum Bhd created a technical code on minimum requirements for specification of green data centers focused on energy efficiency and carbon footprint. The code also outlines best practices that data centers should adopt to achieve a sustainable industry.

Case 20. Specification for Green Data Centers: Malaysia

The German Blue Angel Ecolabel for data centers establishes criteria for sustainable data centers, addressing energy-efficient, climate-friendly data center operation and resource-conserving IT operation. BMZ (the German Federal Ministry for Economic Cooperation and Development), the Environmental Label Jury (which includes consumer organizations, trade organizations, academia, the media), and RAL gGmbH (the awarding body) developed it. It organizes the process for developing the relevant award criteria in independent expert hearings, which involve all relevant interest groups. This approach ensures multi-stakeholder buy-in.

Case 21. Blue Angel Ecolabel for Data Centers, Germany

Tax Incentives and Finance

Limited capital to invest in renewable energy and energy efficiency and lack of reliable carbon monitoring are among the obstacles to promoting green development of data infrastructure. Governments could explore financial and fiscal incentives to address these barriers.

The New South Wales State Government Energy Saver Program provides eligible businesses a 50 percent subsidy for data center energy audits, which promotes cost efficiency. Data centers in Australia receive a 1- to 6-star rating based on PUE from operational data, allowing performance to be compared.

Case 22. CitySwitch Energy Audit Subsidy for Data Centers: Australia

Since 2018, French data centers have been able to reduce their domestic tax on final electricity consumption by adopting an ISO 50001 energy management system and good energy management practices. To assist in obtaining ISO 50001, the Association Technique Énergie Environnement offers a subsidy covering up to 20 percent of annual energy expenses capped at €40,000.[110]

Case 23. Subsidy for ISO Certification: France

Summing up, governments can apply a range of measures (Table 8) that target the components introduced for greening data centres, which encompass sustainable design and construction, sustainable and circular ICT equipment, energy, sustainable cooling, and e-waste management, as well as addressing cross-cutting concerns.

COMPONENT	POLICY ACTION	REGULATIONS	PROCEDURES, GUIDELINES, TOOLS	FINANCIAL AND FISCAL INSTRUMENTS
Building envelope	Develop national strategy with green targets and national connectivity plans considering potential site location of green data centers.	Develop regulations on permission for new data centers in areas with energy and water scarcity.	Guidelines on green design and construction, guidance notes on sustainable building material selection, financial incentives to encourage sustainable solutions.	Grants and investments in research and development, loans, guarantees for risk mitigation.
ICT equipment	Outline expectations for government agencies in ICT, data center, and cloud industry on green data infrastructure development.	Support development of standards on energy-efficient IT requirements and efficient IT infrastructure design. Strengthen compliance of ICT hardware with green regulations.	National guidance on IT equipment transition, eco-design, and energy labeling measures; green public procurement policy for IT equipment and devices.	Tax incentives for decommissioning of energy-intensive legacy equipment.
Energy	Establish accreditation, certification, and inspection schemes to ensure conformity with energy efficiency and sustainability standards.	Develop regulatory framework that encourages systems integration, waste heat reuse, smart heating and cooling, and energy storage. Provide standards for data center backup power supply and power storage.	National indicators to measure decoupling process of energy demand from greenhouse gas emissions in data centers, green procurement policy of cleaner energy for data centers, guidelines on data center energy information system.	Facilitation of thermal networks by allowing flexible energy prices, publicly supported bank guarantees for renewable energy purchasing power agreements, feed-in tariffs, incentives for renewable energy investments.
Cooling	Develop regional regulations for water consumption and wastewater management, regulations on data center cooling energy consumption.	Participate in standards-making process at national, regional, and international levels.	Data collection for cooling energy demand measurement, national guidance on operation and maintenance of innovative cooling methods, guidelines on data center temperature and humidity.	Transparency for energy prices and tariffs and tax credits for adopting efficient cooling technologies.
E-waste	Enhance e-waste regulations to ensure effective enforcement and implementation; and foster the development of e-waste policies or regulations in countries without.	Develop regulations to support sound environmental e-waste disposal.	Guidance notes on ICT equipment refresh cycle and end-of-life management, regulations on environmentally sound management of e-waste.	Extended producer responsibility (manufacturers and importers responsible for entire product lifecycle), environmental taxes, subsidies, grants to establish recycling facilities, deposit-refund systems, and tax incentives to businesses engaged in e-waste recycling.

Table 8. Green Data Infrastructure Policy Framework

Data Center Public Services and Utilities

Energy and water resources are critical for the operation of data centers. Services such as e-waste disposal are also essential to support sustainable industry development.

Sustainable Energy

Increasing data center demands strain energy resources, requiring a balance between data center energy needs and other national and regional energy demands. Shifting power consumption from fossil fuels to renewable energy is the most critical part of reducing a data center's carbon footprint. The ICT sector is the largest purchaser of renewable energy globally, and data centers can be anchor tenants or developers for renewable energy projects.[111] Most large, global data center players have ambitious commitments to use renewable energy sources. This means that access to renewable energy is an important criterion for these companies when choosing countries for data center investments. Governments should engage the digital sector as an ally in national efforts to move toward renewable energy.

In 2019, Google signed a contract with AES Chile to build 23 wind turbines in Chile's Biobío region. The project is part of a hybrid wind and solar project that is generating clean energy for Google's first data center in Latin America. The wind farm is operational and is expected to ensure that the data center runs on 80 percent carbon-free energy.[112]

Case 24. Solar and Wind Powering Data Centers: Chile

There is a range of barriers the private sector and governments might face when deploying renewable energy for data centers:

- Incompatible, inadequate grid capacity for renewable energy expansion
- Shortage of transmission and distribution infrastructure
- Inadequate regulatory support of PPAs linked to independent power producers, limiting renewable energy investments
- Lack of a level playing field for renewable electricity and major power suppliers such as coal and natural gas
- General lack of knowledge and inability to keep pace with a fast-moving industry

Governments play a significant role in reducing these barriers and supporting the green energy transition.

In addition, data centers generate excess heat, which can be used in buildings or centralized district heating.[113][114] For this to be done efficiently, it will require government planning and provision of incentives.

In the Netherlands, there is increasing discussion about developing new data centers, but the fast-growing data center market is increasing national and regional energy consumption, so the Dutch government has restricted establishment of hyperscale data centers. Regional strategies are being developed to ensure that data center growth is balanced with local energy supply.[115]

Case 25. Rules for Establishing Hyperscale Data Centers: The Netherlands

Renewable energy providers such as NextEra Energy, Invenergy, and Ørsted are vital players in the green data center space. They collaborate with governments and technology companies to develop renewable energy projects, ensuring a sustainable and dependable power supply for data centers.

Water Management

Water is a critical resource for green data infrastructure development. A 15-MW mid-size data center uses as much water as three average-size hospitals or more than two 18-hole golf courses.[116] When data centers consume significant amounts of water, they compete with other local users for access to water resources. For example, as much as 57 percent is sourced from potable water. Many data center operators source their water from reservoirs because access to rainfall, gray water, and surface water is seen as unreliable.[117] Additionally, fewer than one-third of data center operators measure water consumption.

Water is a critical resource for green data infrastructure development.

Effective water governance through integrated water resource management is imperative for developing green data infrastructure, especially in countries and regions with water scarcity.

The U.S. Federal Energy Management Program offers strategies for water efficiency in cooling systems that feature cooling towers in new and existing federal data centers and provides agencies with resources to identify potential water-saving opportunities for these water-intensive applications.

Case 26. Federal Energy Management Program for Cooling Water Efficiency: United States

In Hong Kong, the Water Supplies Department approves freshwater supplies for cooling purposes. Data center projects and participating businesses using freshwater cooling towers for water-cooled air conditioning systems must apply for participation in the scheme. The government also created a thematic website with a code of practice for the lifecycle of water-cooled air conditioning systems.[118]

Case 27. Voluntary Freshwater Cooling Tower Scheme: Hong Kong

E-Waste Management

From a cost and lifecycle perspective, management, and disposal of e-waste from data centers is difficult because of the frequent refresh cycles of ICT components, particularly in regions with inadequate e-waste management infrastructure. Governments have a crucial role in addressing these difficulties by understanding the e-waste challenges specific to data centers, implementing regulatory policies for electronic stewardship, establishing country-specific services and capacity-building initiatives, and fostering collaboration among multiple stakeholders, for example credible IT asset disposition providers. Such measures are essential for effectively managing data center e-waste and minimizing its environmental impact.

Nigeria is investing $15 million in collaboration with the Global Environment Facility and United Nations Environment Program to initiate a circular electronics system. The project is designed to promote eco-friendly recycling practices, improve e-waste worker conditions, and generate safe jobs.[119]

Case 28. Circular Electronics System: Nigeria

Policy Instruments for Public Services and Utilities

Renewable energy

- Offer feed-in tariffs, facilitate PPAs between data centers and renewable energy providers, and establish renewable energy certificate programs.
- Identify and remove barriers to data centers' access to renewable energy and offer tax credits, exemptions, or grants to operators that adopt and invest in renewable energy technologies.
- Incorporate the renewable energy requirements of data centers into the framework of national grid policies, ensuring seamless integration. Additionally, establish and implement net energy metering policies to facilitate the efficient management of renewable energy generation and consumption within data centers, ultimately contributing to a more sustainable energy ecosystem.
- Support renewable energy generation aligned with national renewable energy targets.
- Implement green procurement policies that give preference to data centers using renewable energy.
- Encourage reduced use and reuse of energy.
- Develop supportive policies for waste heat reuse.
- Facilitate public-private collaboration to increase renewable energy use and investment.

Water

- Understand water demand and supply in the context of data center growth.
- Clarify water ownership for better administration.
- Raise awareness of pollution and downstream effects caused by data center water use.
- Address community concerns and data center water demand.
- Establish water footprint benchmarks for resource efficiency and conduct regular audits to ensure monitoring of consumption.
- Promote free cooling technology and potable water sources for data center cooling.
- Develop water efficiency standards and regulations, set targets for water use reduction, and promote adoption of water-efficient technologies.
- Establish collaboration between operators, water utilities, and relevant stakeholders to exchange best practices for sustainable water use.

E-waste

- Establish or strengthen regulations and standards for e-waste management, including specific requirements for data centers. These regulations can cover proper disposal, recycling, and documentation of e-waste and use of certified recyclers. Impose fines on or prosecute illegal operations or noncompliance.
- Establish extended producer responsibility regulations to shift responsibility for end-of life management of electronics to producers, which will encourage them to design products that are more easily recyclable and facilitate establishment of collection and recycling infrastructure.
- Adhere to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal.
- Support e-waste recycling facility development and establish certification programs and standards for facilities to meet environmental and safety requirements, recognizing good practices in e-waste management.
- Assess the environmental performance of IT suppliers regularly and stay informed about environmentally friendly options in the marketplace.
- Establish an index of certified e-waste management companies and their compliance with specific standards. Facilitate supply chain coordination and partnerships between various stakeholders, including manufacturers, recyclers, and consumers.
- Address data security concerns for ICT equipment reuse to minimize e-waste generation.
- Facilitate collaboration and partnerships between industry associations, recycling organizations, and other stakeholders to promote knowledge sharing, best practice exchange, and development of innovative solutions for e-waste management.

Data Center Enablers: Skills, Innovation, and Financing

Governments need to focus on enhancing engagement and skill development to create secure, stable, and sustainable frameworks, systems, and institutions that promote the advancement or development of green data centers:

- Facilitate development of green technology and innovation.
- Strengthen knowledge, skills, and training related to data centers and sustainable practices.
- Build a supportive financing and investment environment.

Innovation and Technology

Data center technology is evolving rapidly. Numerous prominent technology companies and organizations are driving innovation and contributing substantially to the advancement of green data centers.[120] Below are some examples of the extensive range of private sector innovations.

Examples of data center innovations in the private sector

- Google has made significant commitments to renewable energy and operates on 24/7 carbon-free energy; has achieved carbon neutrality across its global operations; and has introduced advanced cooling techniques, optimal server efficiency, and innovative modular data center designs.[121 122]
- Microsoft is committed to attaining carbon-negative operations by 2030 and has invested significantly in renewable energy and immersive cooling. It has developed data centers powered entirely by renewable energy sources, prioritizes energy efficiency through artificial intelligence-driven optimization, and launched a circular centers program as part of its zero-waste sustainability efforts to facilitate the reuse and recycling of servers and hardware within its data centers.[123]
- Facebook is recognized for its pioneering data center designs and energy efficiency measures. It has committed to sourcing 100 percent renewable energy and has made substantial investments in solar and wind projects.[124] Facebook's Open Compute Project promotes collaboration and open-source sharing of energy-efficient data center designs.[125]
- Apple data centers have been powered by 100 percent renewable energy since 2014, and it has formed partnerships with renewable energy suppliers to ensure sustainability.[126]
- AWS has committed to achieving 100 percent renewable energy for its global infrastructure. The AWS Cold Storage Data Center uses less energy than traditional data centers by using a cold storage system to store data instead of using heaters to keep the servers cool. This approach uses 90 percent less energy than traditional approaches.[127] AWS also offers services to help customers optimize their energy consumption.
- Intel, a prominent chip manufacturer, participates in green data center initiatives. It designs energy-efficient processors and collaborates with data center operators to enhance server efficiency and is investing in research and development on innovative data center technologies and addressing areas such as heating, cooling, and water use.[128]

The industry is continuously evolving, and numerous other companies, large and small, are working toward green data center solutions. Although strides have been made, developing solutions tailored to the needs of LMICs is still crucial. This involves not only developing locally created solutions, but also fostering technology transfer. Policy makers should encourage innovative, affordable technologies suitable for their regions.

Collaborative efforts and knowledge sharing among these key players and the broader technology industry contribute to ongoing innovation and advancement of green data centers. Research and development in renewable technologies must be supported, and cross-border knowledge sharing with industry and universities should be facilitated to promote adoption of green IT, efficient cooling, and smart data center management.

Global initiatives and alliances are useful starting points for inspiration and potential collaboration, including:

- The Green Grid
- The Global e-Sustainability Initiative (GeSI)
- The Sustainable Digital Infrastructure Alliance (SDIA)

Skills and Training

Highly technical skills are needed to manage and operate data centers, with additional skills required for green data center development, and the demand for skilled green data center staff outweighs the supply worldwide, with many data center owners and operators unable to hire qualified personnel. Demand is projected to increase to about 300,000 engineers worldwide by 2025, with at least half of current data center engineers retiring.[129]

Demand is projected to increase to about 300,000 engineers worldwide by 2025.

This challenge is even greater in LMICs, where staffing requirements are expected to increase unevenly across regions. Most of the demand will be in Asia-Pacific, driven by expected cloud and Internet giants and colocation capacity growth in China and Southeast Asia. Market demand in Europe, the Middle East, and Africa is foreseen to exhibit comparably aligned trends among these regions.. In Latin America, growth is expected to be driven by several markets, including Brazil, Chile, Colombia, and Mexico.[130] The available pool of qualified engineers in these regions is limited.

By implementing sustainable standardized designs, data centers can streamline the construction and deployment process, reducing the need for highly specialized skills and labor. Modular designs allow for pre-engineered components that can be easily assembled, making it more feasible to build and operate sustainable data centers in regions where skilled workforce availability is limited.

Laos' first state-run data center opened in 2016 with support from Japanese partners. The data center's servers were housed in shipping containers for easy transport and setup. Containerized data centers consume less power than facilities housed in self-standing structures. The container was designed to use an indirect outside air cooling system. The setup involved transporting the containers to the desired site and connecting the equipment and was completed in seven months.

Case 29. Containerized Data Center: Laos

Governments and the private sector should work together to enhance educational efforts and provide training programs that include sustainability topics. This could be achieved by integrating these subjects into existing curricula, establishing short courses on best practices, and increasing awareness of green solutions and materials.

Financing

As the demand for data storage and processing continues to grow worldwide, various regions are recognizing the economic and technological opportunities presented by establishing sustainable and green data center ecosystems. International investors and industry leaders are often keen to engage in partnerships and initiatives that support the development of sustainable data centers, leveraging their financial resources, technological insights, and operational know-how to drive innovation and growth in this evolving sector. Thus, establishing a sustainable data center sector can greatly leverage global capital and expertise, although cultivating an environment conducive to business is essential to attract this investment. This involves understanding the key factors that developers and investors consider when making investment decisions. It may be necessary to reduce restrictions on foreign direct investment, increase the ease of doing business, protect intellectual property rights, and de-risk green digital and energy investments.

Although LMICs are investing in data centers and the digital economy, there is a financing gap when it comes to greening efforts. Globally, and especially in LMICs, there is a need to de-risk and encourage green investments. Governments and development financing institutions should consider financing models and incentives that factor in the costs and expertise needed to build and operate sustainable data centers.

Although LMICs are investing in data centers and the digital economy, there is a financing gap when it comes to greening efforts.

IFC, for example, offers guidance on EDGE certification and rewards interested companies with access to finance.

The Digital Investment Facility (DIF), co-funded by the European Commission, the Finnish Ministry of Foreign Affairs, and the German Federal Ministry for Economic Development and Cooperation (BMZ), is a mechanism to enhance investments in data infrastructure such as data centers and Internet exchange points. The DIF will focus on green, secure data infrastructure in sub-Saharan Africa and is designed to facilitate integrated partnerships between key stakeholders, including the public sector, the private sector, and development finance institutions, to boost investments in digital connectivity under global gateway partnerships.

Case 30. The Digital Investment Facility

Supporting Policies for Technology Development and Innovation, Skills, and Training Capital

To foster the growth of sustainable data centers, a range of supportive policies can be implemented, spanning technology development and innovation, skills enhancement, training initiatives, and financing strategies. These policies collectively contribute to creating an environment conducive to the advancement of green data centers and their integration into national infrastructure:

Technology development and innovation

- Encourage market development of innovative, affordable technologies tailored to LMICs.
- Support research into renewable technologies.
- Facilitate technology transfer and regional knowledge sharing.
- Provide funding for green solution development.
- Increase fiber optic cable deployment.

Skills and training

- Increase knowledge and awareness of sustainable design and construction, circular ICT equipment, renewable energy solutions, sustainable cooling, and e-waste management.
- Integrate sustainability topics into engineering curricula.
- Provide short courses for data center managers.
- Develop apprentice programs.
- Enhance government practitioner knowledge about green procurement.
- Establish partnerships with industry experts and organizations to deliver training to government employees.

Financing

- Ease limitations on foreign direct investment in green data centers while forging public-private collaborations. Prioritize regional stakeholders and proprietors to enhance oversight of national and vital infrastructure. This approach also promotes an environment where regional expertise and insights are harnessed to drive innovation and address national sustainability concerns.
- De-risk green energy investments.
- Reduce energy taxes and taxes on imported energy-efficient equipment.
- Invest in renewable energy projects or offer subsidies for renewable technology installations.
- Implement green procurement policies and align with sustainable investment practices/requirements.

Measurement, Reporting, and Verification

To ensure the environmental responsibility of data centers, governments and operators must measure, document, and verify their environmental footprint accurately. This accountability hinges on consistent, transparent reporting.[131] [132] [133] [134] For example, the new EU Energy Efficiency Directive highlights that owners and operators of data centers greater than 500 kW must publish their environmental performance at least once a year, increasing transparency. This includes energy consumption, power use, temperature, heat use, and renewable energy use based on CEN/CENELEC EN 50600.[135]

Several steps can be taken to establish this foundation and help regulate transparency.

- **Integrate reporting requirements** and sustainable ICT strategies into government sustainability reporting and establish core sustainability key performance indicators for performance along the supply chain. This initial step promotes accountability and demonstrates a clear commitment to sustainability within the government and its operations.
- **Enhance data transparency in supply chains**, focusing on carbon emissions, environmental impacts, materials, and chemicals. Governments can promote innovative technologies such as digital product passports and blockchain that help track and validate this data.
- **Adopt common international reporting frameworks and standards**, allowing key performance indicator monitoring and ensuring alignment with global best practices. Departments and agencies can be required to report relevant metrics, for example annual GHG emissions, energy use, and waste related to ICT and digital services.
- **Establish a robust measurement infrastructure** and use suitable tools for metric collection. An independent evaluation and auditing system can be considered to verify data collected from various systems and platforms.
- **Ensure transparency and disseminate data**. Data should be made public and accessible to relevant stakeholders annually.[136] Forming collaborations between the public and private sectors can improve the efficiency of sharing data within data center contexts.
- **Establish internal and external benchmarks**, including key performance indicators, to assess performance and progress. Agreement on suitable measures and standards for measurement and data collection is required to ensure accurate, meaningful comparisons.

Best practices for greenhouse gas emission reporting

As highlighted in the Introduction, reporting plays a crucial role in promoting the environmental sustainability and climate resilience of data centers by fostering awareness, transparency, and accountability. The Greenhouse Gas Protocol has become a widely used standard for measuring and reporting emissions which are categorized into three 'scopes' (Figure 10). These scopes offer a worldwide framework to quantify and control GHG emissions across diverse organizations and industries. This structure effectively addresses the issue of "double-counting" emissions in corporate reporting. ISO 14064 also classifies GHG emissions into these categories.

Many companies use science-based targets developed by the Science-Based Targets Initiative, whose guidelines stipulate that organizations must account for and set measurable targets. GHG emissions are broken down into the following three categories:

- Scope 1: emissions from corporate internal operations, including direct emissions
- Scope 2: emissions related to energy use for their operation
- Scope 3: value chain emissions (if they exceed 40 percent of their total emissions footprint)[138]

Organizations can set emissions reduction targets or customer engagement targets for these categories. Not addressing scope 3 emissions could present investment risks for companies, because it is likely that reporting on these will become mandatory.[138 139 140] ITU, together with GSMA and GeSI published Scope 3 Guidance for Telecommunication Operators and is developing similar guidance for data centers.

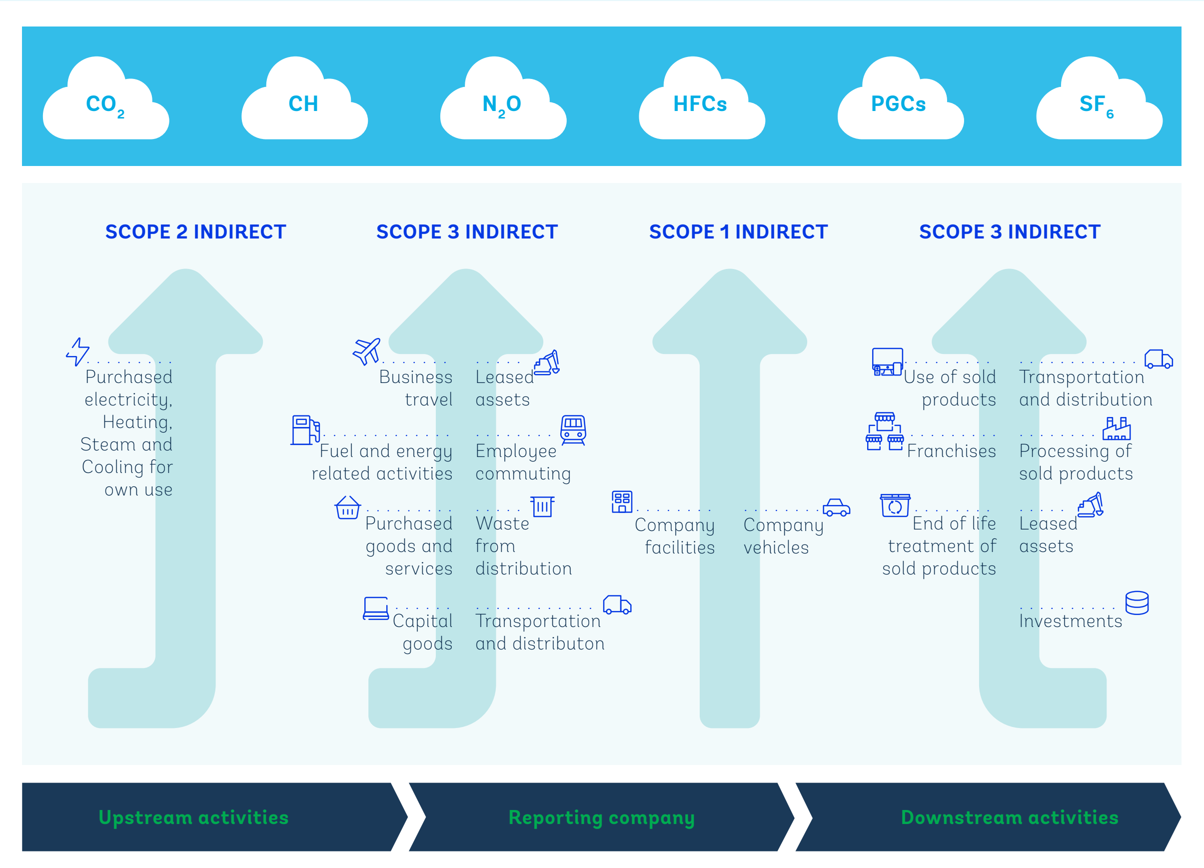


Figure 10. Greenhouse Gas Emission Scopes (Source: Adapted from this website)

If an organization operates in multiple subsectors (e.g., a mobile operator also running fixed networks and data centers), it can split emissions and add subsector targets to achieve a company-wide target. Geographic differences between ICT operators, such as differences in electricity grid factors and availability, must also be recognized. Figure 11 shows a typical process that can be followed to reduce data center GHG emission scopes.[141]

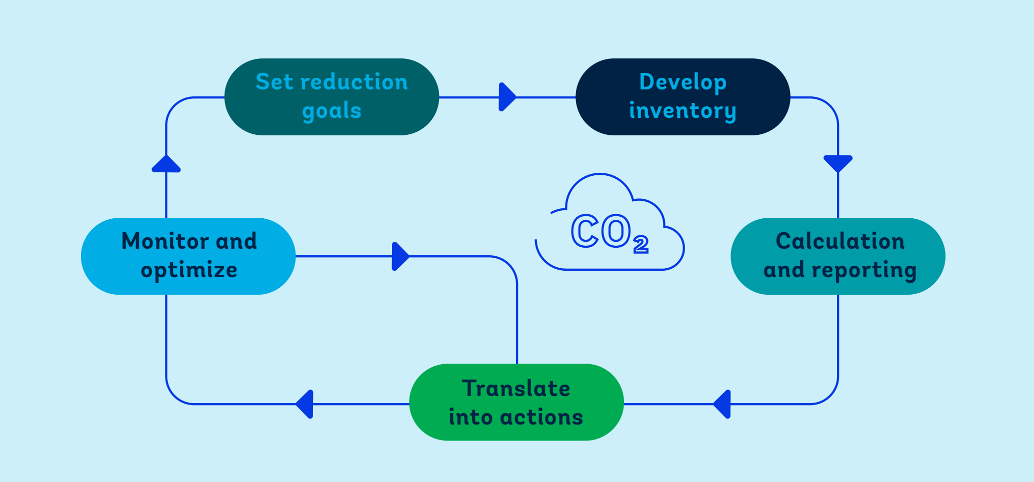


Figure 11. Steps to Reduce Data Center Greenhouse Gas Emission Scopes

Organizations are encouraged to consider the trajectories in Recommendation ITU-T L.1470[142] as references to define a level of ambition for scope 3 emissions reduction targets. These targets should align with the objectives of the Paris Agreement, specifically the 1.5°C target, and employ methods consistent with the necessary decarbonization efforts to limit global temperature rise within this threshold. Resources such as Guidance for ICT Companies Setting Science Based Targets[143] and Recommendation ITU-T L.1470 can provide helpful guidance. Organizations should also use suppliers committed to or setting science-based targets. In addition to carbon reporting, it is important to report on all environmental impacts, as previously discussed, including e-waste metrics, actual power use, water use, and other environmental indicators outlined in the LCA environmental impact indicators. See EN 50600 for details.

Challenges and Opportunities in Implementing Policy Instruments

Challenges and opportunities arise when implementing policy instruments for sustainable data centers.

Opportunities

Implementing policies can increase sustainability and significantly reduce the environmental impact of data centers. Given ever-increasing digital demand, this is vital for mitigating climate change. Meeting growing market demand for green data centers positions a country or region as a sustainable hub for data center operations, attracting investment and enhancing economic competitiveness.

Financial incentives such as tax credits, grants, and subsidies can motivate data center operators to adopt green technologies and practices, fueling economic growth, creating jobs in renewable energy, and attracting investment in sustainable data center infrastructure.

There is substantial potential for innovation and cost savings. Implementing efficient, sustainable technology can decrease energy consumption and waste, ultimately reducing operational costs, and can spark innovation, creating new products, services, and methods of operation and fostering a resilient, future-ready industry.

Challenges

Resistance from data center operators can be anticipated. They may view new regulations as burdensome or disruptive to their current operations. The task is to help them understand that long-term benefits outweigh initial inconveniences. Existing regulations and policies may not be conducive to adoption of green practices in data centers; outdated frameworks should be revised.

Costs associated with compliance can pose a significant challenge. Implementing energy-efficient technologies or transitioning to renewable energy sources can involve significant upfront costs, including expenses for adopting new technologies, adjusting operational processes, and investing in skill development for staff. This can be particularly difficult for small operators with tight budgets. Operators may be hesitant to invest without clear financial incentives or support. It is important to balance the need for sustainability with market competitiveness and profitability.

The complexity of implementing and enforcing specific policy instruments should be considered. These policies often involve numerous stakeholders and intricate technical elements. Ensuring clear understanding, compliance, and enforcement across sectors can be challenging and resource intensive. It is important for governments to establish robust monitoring mechanisms to track progress and enforce compliance.

Appendix A. Key Cross-Cutting Industry Standards and Certifications

STANDARD, CERTIFICATION, OR RECOMMENDATION	DESCRIPTION
Greenhouse Gas Protocol Corporate Accounting and Reporting Standard	Outlines requirements and provides guidance for companies and other organizations preparing corporate-level GHG emissions inventories
International Organization for Standardization	Includes ISO 14001 (environmental management), ISO 50001 (energy management), and ISO/IEC 22237-1:2021 (classifies data centers based on energy efficiency and other criteria)
ITU-T L. Series Recommendations	ITU-T Study Group 5 on Environment, EMF and Circular Economy is responsible for developing methodologies to evaluate the impacts of ICT on climate change. ITU-T Recommendations provide guidance on using ICT in an eco-friendly manner and methodologies to reduce the adverse environmental effects of ICT • Recommendation ITU-T L.1471: Guidance and criteria for information and communication technology organizations on setting net zero targets and strategies • Recommendation ITU-T L.1470: GHG emissions trajectories for the ICT sector compatible with the UNFCCC Paris Agreement • Recommendation ITU-T L.1450: Methodologies for the assessment of the environmental impact of the information and communication technology sector • Recommendation ITU-T L.1420: Methodology for energy consumption and greenhouse gas emissions impact assessment of information and communication technologies in organizations • Recommendation ITU-T L.1300: Best practices for green data centres • Recommendation ITU-T L.1304: Procurement criteria for sustainable data centers • Recommendation ITU-T L.1320: Energy efficiency metrics and measurement for power and cooling equipment for telecommunications and data centres • Recommendation ITU-T L.1302: Assessment of energy efficiency on infrastructure in data centre and telecom centre • Recommendation ITU-T L.1301: Minimum data set and communication interface requirements for data centre energy management • Recommendation ITU-T L.1305: Data centre infrastructure management system based on big data and artificial intelligence technology
Global Reporting Initiative Standards	Sets standards for sustainability reporting
Uptime Institute	Provides green certification and standards for data centers, offering programs to optimize energy use; includes Efficient IT Assessment and Tier Standard for resilience levels
Telcordia GR-3160	Provides guidelines on environmental protection for equipment, fire safety, and space planning
Certified Energy Efficient Data Centre Award (CEEDA)	Global framework that increases data center energy efficiency, improves performance, and decreases operational costs
Science Based Targets Initiative (SBTi)	Drives ambitious climate action in private sector by enabling organizations to set science-based emissions reduction targets, with specific guidance developed for the ICT sector

STANDARD, CERTIFICATION, OR RECOMMENDATION	DESCRIPTION
EDGE certification	Green building certification system for emerging markets created by the International Financial Corporation that enables developers to optimize designs; promote sustainability; and create marketable, cost-effective projects
Leadership in Energy and Environmental Design (LEED)	Global certification program that evaluates sustainability and efficiency of buildings, including data centers, based on criteria such as energy and water use, site selection, materials, and indoor environmental quality
TCO Certified servers	Leading global sustainability certification for information technology products addressing environmental and social factors throughout the product lifecycle, including supply chain responsibility, hazardous substances, and circular criteria
Green Grid Data Center Maturity Model (DCMM)	Framework and tool that increases data center energy efficiency and improves performance, focusing on areas such as power use effectiveness, cooling efficiency, equipment use, and monitoring systems
Certified Green Computing Facility (CGCF) certification from Green Climate Initiative	Provides proof that an organization has not only adopted green computing facility best practices, but has also implemented them effectively
American National Standards Institute/ Building Industry Consulting Service International 002-2019 Data Center Availability Class Methodology	Comprehensive guide for data center design worldwide covering various types of data centers that includes design concepts, site selection, building architecture, core systems, facility systems, security, and commissioning and provides requirements, guidelines, and best practices for all aspects of data center design
National and regional examples	• Code of Conduct for Energy Efficiency in Data Centres (European Union): to encourage data center operators and owners to reduce energy consumption while maintaining critical functions of data centers by promoting energy-efficient practices and fostering collaboration among stakeholders • European standard (CSN EN 50600): general concepts, building construction, power distribution, environmental control, telecommunications cabling infrastructure, security systems, management, and operational information systems • ETSI EN 303 470 (European Standard): energy efficiency measurement methodology and metrics for servers • Energy Star certification (United States): provided by Environmental Protection Agency, recognizes energy-efficient products and buildings, including data centers, that meet Environmental Protection Agency energy efficiency criteria • Building Research Establishment Environmental Assessment Method (United Kingdom): sustainability assessment method and certification for buildings, including data centers, that evaluates criteria such as energy efficiency, water use, materials, and waste management • SS 564 Part 1 (Singapore): focuses on data center sustainability, covering energy and water use, consumption, and efficiency; includes best practices for sustainable data center design and management of electrical systems, mechanical systems, and ICT equipment

GHG, greenhouse gas; ICT, information and communications technology; ISO, International Organization for Standardization; ITU, International Telecommunication Union.

Appendix B. Resiliency Measures for Data Centers[144 145 146]

Site Selection for resilience

- Data centers
  - Engage resilience and risk experts early in project assessment process to benefit from their expertise in evaluating and mitigating climate-related risks.
  - Prioritize site selection that minimizes exposure to environmental risks such as flooding, landslides, subsidence, and adverse weather conditions.
  - Prioritize flood risk factors when evaluating potential data center sites or sea-level rise or storms in vulnerable regions such as small island developing states.
  - Consider local risks such as political instability, previous underground mining activities, and distance from polluting sites when choosing a data center location.
  - Ensure sufficient distance between primary data center and sites such as flood plains and earthquake fault lines to mitigate concurrent losses from events.

- Small server rooms
  - Place server room in a separate building to mitigate potential resilience risks such as fire and plumbing leaks from bathrooms or kitchens. Avoid basements and top floors to reduce risks of condensation or water damage.
  - Ensure that server room has sufficient space for potential expansion of server system.

Design and Build

- Adopt industry standards for data center design and construction such as EN 50600 and International Organization for Standardization/International Electrotechnical Commission 22237 series.
- Encourage adoption of sustainability certifications and frameworks such as EDGE certification, Leadership in Energy and Environmental Design, or Building Research Establishment Environmental Assessment Method to promote climate resilience in data centers.
- Use building materials and construction practices that minimize risk of water damage.
- Install fire suppression systems to mitigate fire hazard, adhering to pressure-relief venting requirements.
- Prioritize continuity of power, communications, and cooling, integrating redundancy at every level.
- Ensure reliable, sufficient backup power to withstand extended grid power outages.
- Install uninterruptible power supply systems to provide emergency power during sudden outages.
- Incorporate onsite backup power generators to extend uninterruptible power supply functionality for prolonged periods.
- Use socket strips with voltage filters when using a single power supply for the entire IT system.

Operations

- Strategy and planning
  - Develop resilience strategy and action plan for data center operations.
  - Refresh resiliency strategy regularly based on latest weather and storm models.
  - Establish baseline of service resiliency, including considerations for climate change impacts.
  - Continuously apply resilience measures to mitigate climate-related risks.
  - Regularly assess climate risks.

- Server room operations and management
  - Ensure proper climate control in server room, maintaining recommended temperature and humidity levels in accordance with the American Society of Heating, Refrigerating and Air-Conditioning Engineers' 2021 Equipment Thermal Guidelines for Data Processing Environments.
  - Install monitoring systems such as video surveillance and sensors to detect problems such as overheating, fire, and water damage. Use alarm management systems and incident reporting tools.

Resources

- Studies, guides, and methodologies
  - Data Center Tier Certification
  - Microsoft: Datacenter Threat, Vulnerability, and Risk Assessment Methodology, 2023
  - No Broken Link: The Vulnerability of Telecommunication Infrastructure to Natural Hazards, World Bank, 2019
  - Uptime Institute: The Gathering Storm: Climate Change and Data Center Resiliency, 2020
  - The UK's Core Digital Infrastructure: Data Centres: Climate Change Adaptation and Resilience, 2016
  - The Coalition for Climate Resilient Investment
  - European Union: A Europe Fit for the Digital Age Initiative

- Climate risk tools
  - World Bank climate and disaster risk screening tools
  - United Nations Environment Program: A Practical Guide to Climate Resilient Buildings and Communities, 2021
  - Think Hazard
  - Sustainable Digital Infrastructure Alliance
  - Green Grid
  - Climate-Neutral Data Centre Pact, European Data Centre Association

Appendix C. Mitigation Measures for Data Centers

BUILDING ENVELOPE-MITIGATION STRATEGIES

Design and Build

- Planning
  - Site selection to access cleaner energy and water resource
  - Brownfield and retrofit construction as a carbon-reduction solution[147]
  - Containerized modular data center design to reduce use of concrete and construction waste and cooling demand
  - Use of prefabricated materials and off-site manufacturing as a carbon- and waste-reduction solution[148]
  - Use of lean manufacturing to reduce operational losses and promote a low-carbon strategy
  - Plan for circularity and minimized waste generation; plan early to optimize reduction of carbon emissions through alternative layout and substitute materials based on comparative analysis of materials and their impact on carbon emissions
  - Initiating collaboration with the design and construction team at an early stage to incorporate sustainability measures for constructing green data centers
  - Inspiration from resources such as Open Standard for Data Center Availability for good practices on data center design
  - Local renewable energy production (solar/wind) on data center premises

- Design
  - Energy-efficient data center architectural design[149]
  - Design of building orientation with respect to sun path to control thermal loss and save energy[150 151]
  - Multi-story data centers for greater land availability, cost effectiveness of the investment

- Construction
  - Use of environmentally friendly, locally available materials where possible
  - Sustainable transportation of building materials (construction transport can account for up to 10 percent of project carbon dioxide emissions[152])
  - Climate-responsive building materials to reduce greenhouse gas emissions and reduce thermal loss from the structure[153]
  - Recycled building materials, especially steel and metal
  - Good practice and innovations in building technologies, for example:
    - Steel-reinforced concrete structures to reduce waste and capture carbon over their lifecycles[154]
    - CarbonCure, which injects waste carbon dioxide into concrete to help decarbonize[155]
    - Nature-based solutions for greening buildings to decrease energy and cooling demand[156]
  - Financial instruments to support adoption of sustainable technology and equipment (e.g., sustainability-linked finance)

Resources

- Overview of ANSI/BICSI 002-2019, Data Center Availability Class Methodology
- EDGE certification
- Leadership in Energy and Environmental Design
- Green Globe
- Embodied Carbon in Construction Calculator
- EU Buildings as Material Banks: material tracing passport enabling tracking of materials throughout supply chain
- Building Research Establishment Environmental Assessment Method
- Country examples
  - German Sustainable Building Council System: Global Benchmark for Sustainability
  - Japan: Comprehensive Assessment System for Building Environmental Efficiency
  - United States: Green Globes Building Certification
  - France: High-quality environmental standard

CIRCULAR AND SUSTAINABLE INFORMATION AND COMMUNICATIONS TECHNOLOGY (ICT) EQUIPMENT

Hardware and Equipment Selection

- Select equipment suitable for the data center power density to avoid overtaxing cooling system.
- Use energy efficiency-certified equipment and products such as Energy Star and TCO Certified servers, storage devices, and other network hardware.
- Consider installed devices' embodied energy and environmental impact relative to their refresh and replacement frequency.
- Promote provision of power and cooling based on actual power draw capability of equipment instead of power supply unit or nameplate rating.[157]
- Use equipment that includes mechanisms for external control of energy use.
- Encourage audits of existing physical equipment and services.

Data and Storage Management

- Implement effective data storage management to reduce server requirements, including removing dark data.
- Reconfigure virtual machines to improve resource use and reduce energy demand.
- Be aware of fluctuating workloads from applications and software developments when considering type of workloads during design and operation.

Operational Strategies

- Regularly check usage rate of servers to identify unused servers or servers with low usage and redundant applications for server management improvement.
- Consolidate multiple applications without conflicting software requirements on one server to reduce hardware use and energy consumption.
- Implement server virtualization to improve equipment use and reduce cost, material waste, electricity use, server sprawl, and cooling loads.
- Decommission unused servers and consider removing low-use services (verifying impact of service before doing so). Put idle equipment into low-power sleep mode or shut it down.
- Maximize system performance through balanced memory configuration to reduce energy use.
- Monitor and report use and energy consumption of equipment.
- Implement automation solution for real-time infrastructure, device, and function coordination to optimize energy balance.
- Audit existing ICT environmental requirements.
- Choose remote power control according to operational needs.
- Implement power-monitoring system for racks and infrastructure to increase energy efficiency and support better capacity planning.

Refresh

- Assess power use data to strengthen server room operation and refresh needs.
- Refresh servers with higher energy-efficiency levels.
- Refresh power distribution equipment (uninterruptible power supplies, power distribution units) and power supplies to ensure greater efficiency gains.

Resources

- Standards, Codes, and Guidelines:
  - European Union: Data Centres Energy Efficiency Code of Conduct
  - EU eco-design directives
  - Recommendation ITU-T L.1300-Best practices for green data centers
  - Recommendation ITU-T L.1303-Functional requirements and framework of green data center energy-saving management system
  - International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 30134-4:2017 Information technology-Data centers-Key performance indicators-Part 4: IT Equipment Energy Efficiency for servers
  - ETSI-EN 303 470 Environmental Engineering; Energy efficiency measurement methodology and metrics for servers
  - Framework for the Assessment of Environmental Performance Standards and Ecolabels for Federal Purchasing
  - ICT Standard by International Federation of Global and Green Information and Communication Technology
  - National Resources Defense Council: Utility Energy Efficiency Program Design: Server Room Assessments and Retrofits
  - European Union Energy label
  - China Energy Label

- Product Guides and Fact Sheets:
  - European Union: The Product Environmental Footprint Guide - Uninterruptable power supply
  - Electronic Product Environmental Assessment Tool Ecolabel
  - Fact Sheet: Improving Energy Efficiency for Server Rooms and Closets
  - Energy Efficiency in Small Server Rooms: Field Surveys and Findings

- Certification and Labeling Programs:
  - Green-e certification program
  - Light Certification Scheme (ICTFOOTPRINT.eu)
  - Energy Star data center equipment
  - Energy Star Score for Data Centers
  - Green Information Technology Professional
  - Electronic Product Environmental Assessment Tool

ENERGY SYSTEM INTEGRATION

Energy Management Plan

- Audit energy savings to identify opportunities for increasing energy efficiency in specific areas.[158 159]

Backup Power Storage

- Explore alternatives to diesel backup generators.
- Consider microgrids to leverage a wide array of green power technologies.
- Use gas or hydrogen fuel cells.
- Use lithium-ion batteries.
- Eliminate 90 percent of emissions over the fuel's lifecycle by using hydrotreated vegetable oil-powered backup generation instead of diesel.[160]
- Apply energy-efficient Energy Star label uninterruptible power supply to reduce energy waste by up to 52 percent compared to conventional uninterruptible power supply battery backups[161] or apply European Code of Conduct on Energy Efficiency of air conditioning uninterruptible power supplies.
- Evaluate the backup frequency and security levels concerning power distribution and backup power technology.
- Use redundant uninterruptible power supply systems to provide grid support. Due to the need for redundancy, data centers usually possess significant backup power capacity, which can be fed back into the power grid.

Renewable Energy

- Position data centers in areas conducive to their integration with renewable or cleaner energy sources, thereby enhancing the availability and accessibility of such sustainable energy options.
- Encourage data center power purchase through renewable or cleaner energy via power purchase agreements (PPAs) or energy purchase agreements
- Explore onsite renewable energy sources.
- Develop cross-border transmission infrastructure and open up existing networks to increase transmission capacity allocation.
- Support system flexibility (e.g., demand response; storage such as pump storage, hydro, batteries, thermal storage) for data center renewable energy demand.
- Use portable scale approach to handle megawatt growth and avoid overprovisioning. Use technology readiness level scale.
- Encourage open access to PPA market.
- Facilitate long-term fixed pricing for renewables.

Waste Heat Use and Sector Coupling

- Evaluate technical and economic feasibility of heat recovery.
- Consider implementing cogeneration, also known as combined heat and power, which utilizes both heat and electricity for practical applications. Such systems can reach an efficiency of 80 percent.[162]
- Convert waste heat to easier-to-transport electricity.
- Integrate waste heat into district energy system.
- Use waste heat for cooling through absorption refrigerators.
- Incorporate waste heat use into design phase of cooling system.
- Use waste heat for cooling in high-temperature regions such as subtropical areas.

Resources

- Measurement and management standards
  - Power use effectiveness
  - Energy reuse effectiveness
  - ISO 50001 Energy Management
  - EU Renewable Energy Factor (e.g., CSN EN 50600-4-3)
- Renewable energy commitments and initiatives
  - RE100
  - 24/7 Carbon-Free Energy Compact
  - Clean Energy Buyers Association
  - Global System for Mobile Communications Association policy note on access to renewable energy
  - Southern African Renewable Energy Investment and Growth Programme
  - Africa Renewable Energy Initiative
  - U.S. Environmental Protection Agency Green Power Partnership
- Renewable energy policies and regulations
  - PPAs and energy purchase agreements, World Bank
  - Regulatory indicators for sustainable energy
  - International Energy Agency renewable energy policy database
  - International Renewable Energy Agency renewable energy policies
  - Renewable technology innovation indicators, International Renewable Energy Agency
  - Association of Southeast Asian Nations renewable energy policies

COOLING

Design

- Natural cooling strategies
  - Use free cooling (naturally cool air or water) to lower data center air temperature. Free cooling resources include geothermal, thermal reservoirs, low-temperature ambient air, and evaporating water.
- Mechanical cooling systems
  - Install air conditioner or computer room air handler units to remove hot air from surrounding area.
- Airflow management: hot and cold aisle containment
  - Separate cold and hot air within the room and remove hot air from cabinets to prevent cold and hot air from mixing inside server rooms; implementation via blank panels, curtaining, equipment configuration, and cable entrance and exit ports.
- Innovative cooling techniques
  - Adopt innovative cooling solutions such as liquid cooling to increase cooling performance efficiency.
  - Considering modular cooling plants for growing demand for heat loads.
- Water supply
  - Encourage use of reclaimed water where available to minimize use of potable water.
  - Encourage transition to waterless or connect to water-cooled systems and improve adaptation of data center cooling systems.

Operation

- Information technology (IT) equipment management
  - Reorganize IT equipment and remove unnecessary servers. Virtualize idle servers to reduce cooling energy demand.
  - Prevent exhaust air from leaking into intake area.
- Temperature and humidity control
  - Prioritize supply air sensors for monitoring and control, given the better control point setting and the benefits of a consistent supply air temperature for all underfloor air.
  - Assess chilled water temperature for dehumidification processes and avoid overcooling the water.[163]

- Choose equipment with power and inlet temperature monitoring capabilities to optimize cooling.
- Cooling system optimization
  - Identify the cooling units with the lowest sensible load i.e. the load neglecting the effects of humidity, estimate the number of required cooling units by dividing the IT load by the smallest sensible cooling unit capacity, and reduce the number of operating cooling units by shutting units off.
  - Raise the operating temperature, which shortens the cooling period and decreases energy consumption.
- Fan control and monitoring
  - Upgrade fan monitoring and controls. Use variable-speed controls to slow fan speeds. Fan energy consumption is a function of the cube of fan speed, so slowing the fans brings an immediate measurable reduction in energy consumption of approximately 24 percent.[164]
- Use of artificial intelligence and advanced technologies
  - Draw on artificial intelligence and neural networks to regulate the data center's cooling system.
- Staff management and planning
  - Make changes in computer environment in a methodical, planned, well-communicated way.
  - Perform energy audit to review and report preparatory metrics of cooling system.
  - Consider cooling system with economizers for new-build server rooms.

Monitoring and Automation

- Data center automation
  - Facilitate data center automation process by installing an energy management system that monitors and controls data center system cooling power consumption and cooling efficiency in real time.
- Liquid cooling monitoring system
  - Install a monitoring system for liquid cooling to check the electrical and chemical stability of the coolant regularly, the state of the IT equipment, the state of the power equipment, the data center's energy consumption, and the safety of the liquid for employees and the environment.[165]
- Refrigerant monitoring
  - Use quality monitoring equipment to examine the chemical composition of additives in the refrigerant, as well as electrical conductivity, pH, corrosion rate, and turbidity.[166]

Resources

- Guidelines and standards
  - Liquid Cooling Guidelines for Datacom Equipment Centers- American Society of Heating, Refrigerating and Air-Conditioning Engineers
  - New Guideline for Data Center Cooling-American Society of Heating, Refrigerating and Air-Conditioning Engineers
  - Recommendation ITU-T L.1320 : Energy Efficiency Metrics and Measurement for Power and Cooling Equipment for Telecommunications and Data Centres
  - Cooling Efficiency Ratio-ISO
- Research reports
  - Innovative Data-Centre Cooling Technologies in China - Liquid Cooling Solution
  - Chilling Prospects: Providing Sustainable Cooling for All
- Metrics
  - Water use effectiveness
- Information and educational resources
  - Questions and Answers on Data Center Cooling Issues
  - Artificial Intelligence and Machine Learning Applications: Google DeepMind AI Cooling
  - Innovative Cooling Projects: Microsoft Project Natick-subsea data center

E-WASTE

Design

- Consider reuse potential when designing servers to increase possibility of easy repair and refurbishing.
- Incorporate materials that can be recycled without residual materials going to landfill.
- Enhance the server refresh cycle by replacing servers with remanufactured and refurbished units that prioritize energy efficiency and environmental impact. Additionally, extend the operational lifespan of servers to maximize their usage duration.

Decommissioning

- Strengthen industry commitment to sustainable end-of-life management with transparent published goals for enforced accountability. Adopt extended producer responsibility principles.
- Divert e-waste from landfills by recycling and reusing materials and equipment, including repurposing or redeploying elsewhere in the organization.
- Establish an IT asset recovery service with a certified provider.
- Reuse processing and memory components, such as hard disk drives.
- Replenish products or sell in second-hand markets or through wholesale channels.
- Reassign IT equipment for refurbishment and remanufacturing if environmentally and economically more viable.
- Recover materials for remanufacturing.
  - Sustainably source recyclable materials.
  - Divert materials from irresponsible recycling.
  - Ensure that recycled materials are responsibly managed and that disposition vendors do not dispose of them in low- and middle-income countries.

Resources

- E-waste standards and certification
  - ITU-T Recommendations on e-waste
  - ISO 14001:2015
  - WEEELABEX - pan-European requirements
  - R2:2013 standard (Sustainable Electronics Recycling International)
  - TCO certified
- E-waste reports and monitoring
  - ITU's work to combat e-waste, including through ITU Telecommunication Development Sector, to create a circular economy for electronics
  - Global E-waste Monitor 2020 (United Nations Institute for Training and Research and ITU)
  - Global E-waste Statistics Partnership
- International agreements and conventions
  - Basel Convention (international treaty on control of transboundary movements of hazardous waste and its disposal)
- Organizations and initiatives
  - E-waste Coalition
  - Regional cooperation on e-waste management in Latin American countries (United Nations Industrial Development Organization)
  - Solving the E-waste Problem Initiative
  - Circular Electronics Partnership
  - Global Electronics Council
  - Platform for Accelerating the Circular Economy
  - WEEE Forum
  - International E-Waste Management Network
  - e-Stewards

CIRCULARITY TOOLS

Tools have been developed for transitioning to a circular economy, such as LCA for monitoring environmental impact and lifecycle costing for calculating economic impact.

Lifecycle Costing

- ISO 15686-5:2017 provides requirements and guidelines for performing lifecycle cost analyses of buildings and constructed assets and their parts, whether new or existing.

Lifecycle Assessment

- ISO 14040:2006 sets out the principles and framework for conducting a life cycle assessment (LCA), detailing its stages and limitations but not specifying methodologies.
- ITU-T L.1410 addresses environmental LCAs of ICT goods, networks, and services. This LCA standard is based on ISO 14040:2006 and tailored for ICT LCA.

Material Passports

- Involves sharing information about materials used in a product throughout its lifecycle, including physical properties, safety data, logistics, and recyclability. Multiple parties are developing the material passport concept in mainly European countries, for example, through the BAMB2020 project. As a tool to create transparency and unlock circularity, the European Commission has proposed digital product passports that share product information throughout the product lifecycle. The European Commission is drafting a regulation on digital product passports, with final approval expected in 2024.[167] ITU is also developing a global digital ICT product passport to achieve a circular economy.

Material Circularity Indicator

- The material circularity indicator is a decision-making process designed to evaluate how well an organization or product does as it transitions from a linear to a circular economy by measuring use of virgin material and resultant waste sent to landfills or energy recovery.

Circular Scoring Assessment

- ITU-T L.1023 provides an assessment method for circularity scoring of ICT goods consisting of three steps:
  - 1) Set the relevance and applicability of each criterion for circular product design for the ICT goods.
  - 2) Assess the margin of improvement of each criterion.
  - 3) Calculate the circularity score (0 to 100 percent) for the ICT goods at hand for all three circular design guideline groups (product durability; ability to recycle, repair, reuse, and upgrade from equipment level; and ability to recycle, repair, reuse, and upgrade from manufacturer level).

References

[1] **Project Drawdown. 2020.** "Alternative Refrigerants @ ProjectDrawdown #ClimateSolutions." https://drawdown.org/solutions/alternative-refrigerants

[2] **World Bank. 2022.** "Catalyzing Green Digital Transformation, 2022." World Bank, Washington, DC. https://www.digitaldevelopmentpartnership.org/knowledge.html?ddp=kn-pb-22-t1-10

[3] **International Energy Agency. 2022.** World Energy Outlook 2022. "Executive Summary-World Energy Outlook 2022-Analysis." International Energy Agency, Paris, France. https://www.iea.org/reports/world-energy-outlook-2022/executive-summary

[4] **International Telecommunication Union. 2014.** "L.1300: Best Practices for Green Data Centres." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/rec/T-REC-L.1300-201406-I/en

[5] **Jeff Vogel, Julia Palmer, Michael Hoeck, Jerry Rozeman, and Joseph Unsworth. 2022**/ "2022 Strategic Roadmap for Storage." Gartner, Inc.

[6] Rwanda, for example, has a public-private partnership model. https://aos.rw/about/

[7] **VMware. 2017.** "Modernize Government Data Centers." VMware, Palo Alto, CAß. https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/solutions/industry/government/vmware-modernize-government-data-centers-solution-overview.pdf.

[8] **International Telecommunication Union. 2021.** "Digital Trends Reports 2021." International Telecommunication Union, Geneva, Switzerland. www.itu.int/en/ITU-D/Conferences/WTDC/WTDC21/Pages/RPM/Digital-Trends-Reports-2021.aspx

[9] **Vivien. Foster, Niccolò, Comini, Sharada Srinivasan. 2021.** "Improving Data Infrastructure Helps Ensure Equitable Access for Poor People in Poor Countries." World Bank, Washington, DC. https://blogs.worldbank.org/opendata/improving-data-infrastructure-helps-ensure-equitable-access-poor-people-poor-countries

[10] The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of ITU or the World Bank concerning the legal status of any country, territory, city, or area or of its authorities or concerning the delimitation of its frontiers or boundaries.

[11] **International Telecommunication Union. 2021.** "Digital Trends in Asia and the Pacific 2021." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/hub/publication/d-ind-dig_trends_asp-01-2021/

[12] **Australian Strategic Policy Institute. 2020.** ICT For Development in the Pacific Islands. An Assessment of E-Government Capabilities in Fiji, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu." Australian Strategic Policy Institute, Barton, Australia. https://s3-ap-southeast-2.amazonaws.com/ad-aspi/2020-02/ICT%20for%20development%20in%20the%20Pacific%20islands.pdf?x_oS.r8OVVfTlxxgNHI58k_VL45KC83H

[13] **International Telecommunication Union. 2018.** "Thematic Report: ICTs, LDCs and the SDGs Achieving Universal and Affordable Internet in the Least Developed Countries" International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/dms_pub/itu-d/opb/ldc/D-LDC-ICTLDC-2018-PDF-E.pdf

[14] **International Telecommunication Union. 2014.** "L.1300: Best Practices for Green Data Centres." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/rec/T-REC-L.1300-201406-I/en

[15] **McKinsey Global Institute. 2020.** "Climate Risk and Response: Physical Hazards and Socioeconomic Impacts. Will Infrastructure Bend or Break under Climate Stress? Case Study." McKinsey & Company. https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/will%20infrastructure%20bend%20or%20break%20under%20climate%20stress/will-infrastructure-bend-or-break-under-climate-stress-case-study-old.pdf

[16] **Andy Lawrence. 2020.** "UI Intelligence Report 41. The Gathering Storm: Climate Change and Datacenter Resiliency." Uptime Institute. https://uptimeinstitute.com/the-gathering-storm-climate-change-and-data-center-resiliency

[17] **Uptime Institute. 2022.** "The Uptime Institute Global Data Center Survey 2022." https://uptimeinstitute.com/resources/research-and-reports/uptime-institute-global-data-center-survey-results-2022

[18] **International Energy Agency. 2022.** "Data Centers and Data Transmission Networks." International Energy Agency, Paris. https://www.iea.org/reports/data-centers-and-data-transmission-networks, License: CC BY 4.0

[19] Figures from the Central Statistics Office show that data centers accounted for more than 5,200 GWh of use in 2022 out of total metered consumption of 29,500 GWh. www.cso.ie/en/

[20] **International Energy Agency. 2022.** "Data Centers and Data Transmission Networks." International Energy Agency, Paris. https://www.iea.org/reports/data-centers-and-data-transmission-networks, License: CC BY 4.0

[21] **Jonathon Koomey.** "Growth in Data Center Electricity U2005 to 2010." Analytics Press, Oakland, CA. https://alejandrobarros.com/wp-content/uploads/old/4363/Growth_in_Data_Center_Electricity_use_2005_to_2010.pdf

[22] **Junaid Shuja, Abdullah Gani, Shahaboddin Shamshirband, Raja Wasim Ahmad, Kashif Bilal. 2016.** "Sustainable Cloud Data Centers: A Survey of Enabling Techniques and Technologies." Renewable and Sustainable Energy Reviews 62: 195-214. https://www.sciencedirect.com/science/article/pii/S136403211630051X

[23] **Green Business Certification Inc. 2023.** "EDGE Is a Green Building Certification System Focused on Making Buildings More Resource-Efficient." https://edge.gbci.org/

[24] **Copenhagen Center on Energy Efficiency. 2020.** "Environmental Sustainability of Data Centers: A Need for a Multi-Impact and Life Cycle Approach." Copenhagen Center on Energy Efficiency, Copenhagen, Denmark. https://c2e2.unepccc.org/wp-content/uploads/sites/3/2020/02/environmental-sustainability-of-data-centers-a-need-for-a-multi-impact-and-life-cycle-approach-brief-1-uk.pdf

[25] **David Eckstein, Vera Künzel, Laura Schäfer. 2021.** "Global Climate Risk Index 2021. Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2019 and 2000-2019." Germanwatch e.V., Bonn & Berlin, Germany. https://germanwatch.org/sites/germanwatch.org/files/Global%20Climate%20Risk%20Index%202021_1.pdf

[26] **Andy LawrenceA. 2020.** "UI Intelligence Report 41. The Gathering Storm: Climate Change and Data Center Resiliency." Uptime Institute. https://uptimeinstitute.com/uptime_assets/1d430c1fe0846e5c3ca4ac58a18c10126d6d4b2918d5d1960e794cecc52d230d-the-gathering-storm-climate-change-and-data-center-resiliency.pdf

[27] **Sotirios A. Argyroudis, Stergios Aristoteles Mitoulis, Eleni Chatzi, Jack W. Baker, Ioannis Brilakis, Konstantinos Gkoumas, Michalis Vousdoukas, William Hynes, Savina Carluccio, Oceane Keou, Dan M. Frangopol, Igor Linkov. 2022.** "Digital Technologies Can Enhance Climate Resilience of Critical Infrastructure." Climate Risk Management 35: 100387. https://doi.org/10.1016/j.crm.2021.100387

[28] **TechUK. 2016.** "ICT ARP Response to DEFRA 2016 the UK'S Core Digital Infrastructure: Data Centres - Climate Change Adaptation and Resilience." https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/620924/climate-adrep-tech-uk.pdf

[29] **Sotirios A. Argyroudis, Stergios Aristoteles Mitoulis, Eleni Chatzi, Jack W. Baker, Ioannis Brilakis, Konstantinos Gkoumas, Michalis Vousdoukas, William Hynes, Savina Carluccio, Oceane Keou, Dan M. Frangopol, Igor Linkov. 2022.** "Digital Technologies Can Enhance Climate Resilience of Critical Infrastructure." Climate Risk Management 35: 100387. https://doi.org/10.1016/j.crm.2021.100387

[30] **Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, Carter Powis. 2020.** "Climate Risk and Response: Physical Hazards and Socioeconomic Impacts." McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/climate-risk-and-response-physical-hazards-and-socioeconomic-impacts

[31] **Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, Carter Powis. 2020.** "Climate Risk and Response: Physical Hazards and Socioeconomic Impacts." McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/climate-risk-and-response-physical-hazards-and-socioeconomic-impacts

[32] **Equinix. 2023.** "Design for Data Center Resiliency to Reduce Downtime Risk." https://blog.equinix.com/blog/2023/06/08/design-for-data-center-resiliency-to-reduce-downtime-risk/

[33] **Rafael Sacks, Marak Girolami, Ioannis Brilakis. 2020.** "Building Information Modelling, Artificial Intelligence and Construction Tech." Developments in the Built Environment 4: 100011. https://www.sciencedirect.com/science/article/pii/S2666165920300077?via%3Dihub

[34] **Asian Development Bank. 2021.** "Digital Technologies for Climate Action, Disaster Resilience, and Environmental Sustainability." Mandaluyong, Philippines: Asian Development Bank. https://www.adb.org/sites/default/files/publication/700396/digital-technologies-climate-action.pdf

[35] **Google. 2022.** "Incident Affecting Google Compute Engine." Google Cloud Service Health. https://status.cloud.google.com/incidents/XVq5om2XEDSqLtJZUvcH

[36] **Daniel BizoD. 2022.** "Extreme Heat Stress-Tests European Data Centers-Again." Uptime Institute. https://journal.uptimeinstitute.com/extreme-heat-stress-tests-european-data-centers-again/

[37] **National Association of Software and Service Companies. 2020.** "Recommendations for Data Centre Policy - NASSCOM." New Delhi, India: Community Nasscom. https://community.nasscom.in/sites/default/files/report/25264-nasscom-recommendations-data-center-policy.pdf

[38] **Serverfarm. 2020.** "Modernization versus New Build Data Centers." Los Angeles, CA: Serverfarm Data Centers. https://www.serverfarmllc.com/sustainability/modernization-vs-new-build-data-centers/

[39] **Schneider Electric. 2020.** "Why Rightsizing Your UPS Should Be Part of Your Data Center Modernization Plan." https://blog.se.com/datacenter/architecture/2020/09/29/why-rightsizing-ups-data-center-modernization-plan/

[40] **Pierre Delforge. 2014.** "America`s Data Centers Are Wasting Huge Amounts of Energy." https://studylib.net/doc/18077239/america-s-data-centers-are-wasting-huge-amounts-of-energy.

[41] **Sabey Data Centers. 2015.** "Yahoo to Double Quincy Data Center Capacity Using Computing Coop Design." https://sabeydatacenters.com/news/yahoo-to-double-quincy-data-center-capacity/

[42] **Edgar G. Hertwich, Saleem Ali, Luca Ciacci, Tomer Fishman, Niko Heeren, Eric Masanet, Farnaz Nojavan Asghari, Elsa Olivetti, Stefan Pauliuk, Qingshi Tu, Paul Wolfram. 2019.** "Material Efficiency Strategies to Reducing Greenhouse Gas Emissions Associated with Buildings, Vehicles, and Electronics-a Review." Environmental Research Letters 14: 043004. https://iopscience.iop.org/article/10.1088/1748-9326/ab0fe3

[43] **International Finance Corporation. 2017.** "Green Buildings for a Smarter World." International Finance Corporation, Washington, DC.

[44] **Eric Lamendour. 2022.** "Will Decarbonization Impact Future Data Center Design?" Data Center Dynamics, London, UK. https://www.datacenterdynamics.com/en/marketwatch/will-decarbonization-impact-future-data-center-design/

[45] **Rack Centre. 2022.** "Rack Centre Becomes the First IFC EDGE Certified Data Centre in Europe, Middle East and Africa." Rack Centre. https://rack-centre.com/rack-centre-becomes-the-first-ifc-edge-certified-data-centre-in-europe-middle-east-and-africa/

[46] **International Telecommunication Union, Waste from Electrical and Electronic Equipment Forum. 2020.** "Internet Waste." https://www.itu.int/en/ITU-D/Environment/Documents/Publications/2020/Internet-Waste%202020.pdf?csf=1&e=iQq5Zi

[47] **Huigui Rong, Haomin Zhang, Sheng Xiao, Canbing Li, Chunhua Hu. 2016.** "Optimizing Energy Consumption for Data Centers." Renewable and Sustainable Energy Reviews 58: 674-691. https://doi.org/10.1016/j.rser.2015.12.283.

[48] **International Telecommunication Union. 2014.** "L.1300: Best Practices for Green Data Centres." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/rec/T-REC-L.1300-201406-I/en

[49] **International Telecommunication Union. 2015.** "L.1302: Assessment of Energy Efficiency on Infrastructure in Data Centres and Telecom Centres." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/rec/T-REC-L.1302-201511-P/en

[50] **Uptime Institute. n.d. "Efficient IT Assessment & Stamp of Approval."** https://uptimeinstitute.com/professional-services/efficient-it

[51] **Paolo Bertoldi, John Booth, Mark Acton. 2022.** "2022 Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy Efficiency." European Commission, Brussels, Belgium. https://e3p.jrc.ec.europa.eu/publications/2022-best-practice-guidelines-eu-code-conduct-data-centre-energy-efficiency

[52] **MIT Technology Review. 2016.** "Moore's Law is Dead. What Now?" https://www.technologyreview.com/2016/05/13/245938/moores-law-is-dead-now-what/

[53] **Belen Bermejo, Carlos Juiz. 2022.** "Performance and Energy Consumption Tradeoff in Server Consolidation." BenchCouncil Transactions on Benchmarks, Standards and Evaluations 2 (2): 100060. https://doi.org/10.1016/j.tbench.2022.100060

[54] **David Meisner, Brian T. Gold, Thomas F. Wenisch. 2009.** "PowerNap: Eliminating Server Idle Power." ACM SIGARCH Computer Architecture News 37 (1): 205–216. https://doi.org/10.1145/2528521.1508269

[55] **Microsoft. 2023.** "Session Host Virtual Machine Sizing Guidelines." Microsoft Learn Article 06 https://learn.microsoft.com/en-us/windows-server/remote/remote-desktop-services/virtual-machine-recs

[56] **Eric Masanet, Arman Shehabi, Nuoa Lei, Sarah Smith, Jonathan Koomey. 2020.** "Recalibrating Global Data Center Energy-Use Estimates." Science 3676481. doi: 10.1126/science.aba3758

[57] **John Roach. 2018.** "Under the Sea, Microsoft Tests a Datacenter That's Quick to Deploy, Could Provide Internet Connectivity for Years." Microsoft Features. https://news.microsoft.com/features/under-the-sea-microsoft-tests-a-datacenter-thats-quick-to-deploy-could-provide-internet-connectivity-for-years/

[58] **Data Center Dynamics. 2022.** "Guinness World Records Confirms Dubai's Moro Hub is World's Largest Solar Data Center." https://www.datacenterdynamics.com/en/news/guinness-world-records-confirms-dubais-moro-hub-is-worlds-largest-solar-data-center/

[59] **Max Schulze. 2022.** "Why PPAs Don't Make Data Centers More Sustainable." Sustainable Digital Infrastructure Alliance. https://sdialliance.org/blog/why-ppas-dont-make-data-centers-more-sustainable/

[60] **Energy Star. n.d.** "Reduce Energy Losses from Uninterruptable Power Supply (UPS) Systems." https://www.energystar.gov/products/reduce_energy_losses_uninterruptable_power_supply_ups_systems

[61] **Alan R. Earls. 2020.** "Data Center Backup Power Systems, Standards to Address Downtime." SearchDataCenter. Newton, MA. https://www.techtarget.com/searchdatacenter/tip/Data-center-backup-power-systems-standards-to-address-downtime

[62] **Energy Star. n.d.** "Reduce Energy Losses from Uninterruptable Power Supply (UPS) Systems." https://www.energystar.gov/products/reduce_energy_losses_uninterruptable_power_supply_ups_systems

[63] **Paolo Bertoldi, John Booth, Mark Acton . 2022.** "2022 Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy Efficiency." European Commission, Brussels, Belgium. https://e3p.jrc.ec.europa.eu/publications/2022-best-practice-guidelines-eu-code-conduct-data-centre-energy-efficiency

[64] **Scala Data Centers. 2023.** "Sustainability." https://scaladatacenters.com/en/sustainability/

[65] **Josephine Walbank. 2022.** "Top 10 Data Centres Using Green Energy." Data Centre Magazine https://datacentremagazine.com/articles/top-10-data-centres-using-green-energy

[66] **Meta Sustainability. 2020.** "Denmark Data Center to Warm Local Community." https://sustainability.fb.com/wp-content/uploads/2020/12/FB_Denmark-Data-Center-to-Warm-Local-Community.pdf

[67] **Verative. 2022.** "A Beginner's Guide to Data Center Cooling Systems." https://www.vertiv.com/en-emea/about/news-and-insights/articles/educational-articles/a-beginners-guide-to-data-center-cooling-systems/

[68] **X. Zhang, T. Lindberg, N. Xiong, V. Vyatkin, A. Mousavi. 2017.** "Cooling Energy Consumption Investigation of Data Center IT Room with Vertical Placed Server." ResearchGate, Berlin, Germany. https://www.researchgate.net/publication/317308758_Cooling_Energy_Consumption_Investigation_of_Data_Center_IT_Room_with_Vertical_Placed_Server

[69] **Duc Van Le, Yingbo Liu, Rongrong Wang, Rui Tan, Lek Heng Ngo. 2022.** "Air Free-Cooled Tropical Data Center: Design, Evaluation, and Learned Lessons." IEEE Transactions on Sustainable Computing 7 (3). https://ieeexplore.ieee.org/document/9645228

[70] **Tony Day. 2017.** "Improvements in Cooling of a Data Centre."Google Patents, Mountain View, CA. https://patents.google.com/patent/EP2189875A2/en

[71] **Wen-Xiao Chu, Chi-Chuan Wang. 2019.** "A Review on Airflow Management in Data Centers." Applied Energy 240: 84–119. https://www.sciencedirect.com/science/article/pii/S0306261919303381?via%3Dihub

[72] **M&M Carnot. 2020.** "Refrigerant Restrictions: Is Your Data Center Ready for the Transition?" https://r744.com/wp-content/uploads/sites/3/2022/05/MM-Carnot-CRAC-report.pdf

[73] **Project Drawdown. 2020.** "Alternative Refrigerants @ ProjectDrawdown #ClimateSolutions." Project Drawdown. https://drawdown.org/solutions/alternative-refrigerants

[74] **EK Water Blocks, Sustainable Digital Infrastructure Alliance. 2022.** "The Cooling Requirements of Data Centers." Sustainable Digital Infrastructure Alliance, Berlin, Germany. https://sdialliance.org/resources/the-cooling-requirements-of-data-centers/

[75] **Meng Zhang, Zhongbin Zhang, Yu Hu, Yun Geng, Hu Huang, Yi Huang. 2017.** "Effect of Raised Floor Height on Different Arrangement of Under-Floor Air Distribution Performance in Data Center." Procedia Engineering 205: 556–64. https://doi.org/10.1016/j.proeng.2017.10.425

[76] **American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2021.** "2021 Equipment Thermal Guidelines for Data Processing Environments: ASHRAE TC 9.9 Reference Card." American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA. https://www.ashrae.org/file%20library/technical%20resources/bookstore/supplemental%20files/referencecard_2021thermalguidelines.pdf

[77] **European Telecommunications Standards Institute. 2015.** "Environmental Engineering (EE); European Telecommunications Standard for Equipment Practice; Thermal Management Guidance for Equipment and Its Deployment." ETSI, Sophia Antipolis, France. https://www.etsi.org/deliver/etsi_tr/102400_102499/102489/01.04.01_60/tr_102489v010401p.pdf

[78] **European Telecommunications Standards Institute. 1992.** "Equipment Engineering (EE); Environmental Conditions and Environmental Tests for Telecommunications Equipment Part 1-3: Classification of Environmental Conditions Stationary Use at Weather Protected Locations." ETSI, Sophia Antipolis, France. https://www.etsi.org/deliver/etsi_i_ets/300001_300099/3000190103/01_60/ets_3000190103e01p.pdf

[79] **International Telecommunication Union. 2014.** "L.1300: Best Practices for Green Data Centres." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/rec/T-REC-L.1300-201406-I/en

[80] **International Telecommunication Union. 2020.** "L.1381 : Smart Energy Solutions for Data Centres." Geneva, Switzerland: International Telecommunication Union. https://www.itu.int/rec/T-REC-L.1381

[81] **Brien Posey. 2022.** "Data Center Temperature and Humidity Guidelines-TechTarget.com." TechTarget. https://www.techtarget.com/searchdatacenter/tip/Data-center-temperature-and-humidity-guidelines

[82] **American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2021.** "2021 Equipment Thermal Guidelines for Data Processing Environments ASHRAE TC 9.9 Reference Card." American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA. https://www.ashrae.org/file%20library/technical%20resources/bookstore/supplemental%20files/referencecard_2021thermalguidelines.pdf

[83] **European FluoroCarbons Technical Committee, European Chemical Industry Council. n.d.** "Data Centres." https://www.fluorocarbons.org/applications/data-centres/

[84] **M&M Carnot. 2020.** "Refrigerant Restrictions: Is Your Data Center Ready for the Transition?" https://r744.com/wp-content/uploads/sites/3/2022/05/MM-Carnot-CRAC-report.pdf

[85] **Pei Huang, Benedetta Copertaro, Xingxing Zhang, Jingchun Shen, Isabelle Löfgren, Mats Rönnelid, Jan Fahlen, Dan Andersson, Mikael Svanfeldt. 2020.** "A Review of Data Centers as Prosumers in District Energy Systems: Renewable Energy Integration and Waste Heat Reuse for District Heating. Applied Energy 258: 114109. https://www.sciencedirect.com/science/article/pii/S0306261919317969

[86] **Caiqing Zhang, Hongxia Luo, Zixuan Wang. 2022.** "An Economic Analysis of Waste Heat Recovery and Utilization in Data Centers Considering Environmental Benefits." Sustainable Production and Consumption 31: 127-138. https://www.sciencedirect.com/science/article/pii/S2352550922000409

[87] **Equinix. 2016.** https://blog.equinix.com/blog/2016/03/21/equinix-offers-new-access-to-opportunity-in-brazil-with-sp3-data-center/

[88] **World Bank. 2022.** "Greening Digital in Korea: Korea Case Study for Greening the ICT Sector." World Bank Group Korea Office Innovation and Technology Note Series, No. 6. World Bank Group Korea Office.

[89] **Federal Energy Management Program. n.d.** "Cooling Water Efficiency Opportunities for Federal Data Centers." https://www.energy.gov/femp/cooling-water-efficiency-opportunities-federal-data-centers

[90] **U.S. Department of Energy. 2011.** "Federal Energy Management Program Best Practices Guide for Energy-Efficient Data Center Design." U.S. Department of Energy, Washington, DC. https://www.energy.gov/femp/articles/best-practices-guide-energy-efficient-data-center-design

[91] **Urs Hölze. 2022.** "Our Commitment to Climate-Conscious Data Center Cooling." Google. https://blog.google/outreach-initiatives/sustainability/our-commitment-to-climate-conscious-data-center-cooling/

[92] **David MyttonD. 2021.** "Data Centre Water Consumption." Npj Clean Water 4 (11). https://www.nature.com/articles/s41545-021-00101-w

[93] **Md Abu Bakar Siddik, Arman Shehabi, Landon Marston. 2021.** "The Environmental Footprint of Data Centers in the United States." Environmental Research Letters 16: 064017. https://iopscience.iop.org/article/10.1088/1748-9326/abfba1/pdf

[94] **Amazon Web Services. 2023.** "Water Stewardship in Data Centres." https://sustainability.aboutamazon.co.uk/environment/the-cloud/water-stewardship

[95] **Google. 2022.** "Incident Affecting Google Compute Engine." https://status.cloud.google.com/incidents/dS9ps52MUnxQfyDGPfkY

[96] **United Nations Institute for Training and Research, International Telecommunication Union. 2020.** "The Global E-waste Monitor 2020-Quantities, Flows, and the Circular Economy Potential." https://ewastemonitor.info/gem-2020/.

[97] **International Telecommunication Union, Waste from Electrical and Electronic Equipment Forum. 2020.** "Internet Waste." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/en/ITU-D/Environment/Documents/Publications/2020/Internet-Waste%202020.pdf?csf=1&e=iQq5Zi

[98] **International Telecommunication Union. 2021.** "Policy Practices for E-Easte Management." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/en/ITU-D/Environment/Pages/Toolbox/WEEE-Africa-Toolkit.aspx

[99] **International Telecommunication Union, Waste from Electrical and Electronic Equipment Forum. 2020.** "Internet Waste." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/en/ITU-D/Environment/Documents/Publications/2020/Internet-Waste%202020.pdf?csf=1&e=iQq5Zi

[100] **Rich Miller. 2023.** "Meta Will Run Its Servers for up to 5 Years." Data Cener Frontier. https://www.datacenterfrontier.com/hyperscale/article/21548840/meta-will-abandon-some-data-center-builds-run-servers-longer

[101] **Rabih Bashroush, Nour Rteil, Rich Kenny, Astrid Wynne. 2022.** "Optimizing Server Refresh Cycles: The Case for Circular Economy With an Aging Moore's Law." IEEE Transactions on Sustainable Computing 7 (1): 189-200. doi: 10.1109/TSUSC.2020.3035234

[102] **International Telecommunication Union, Waste from Electrical and Electronic Equipment Forum. 2020.** "Internet Waste Thought Paper." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/en/ITU-D/Environment/Pages/Spotlight/Internet-Waste-thought-paper.aspx

[103] **Global E-Waste Statistics Partnership. 2017.** https://globalewaste.org/

[104] **Vusumuzi MaphosaV. 2022.** "Sustainable E-Waste Management at Higher Education Institutions' Data Centres in Zimbabwe." International Journal of Information Engineering and Electronic Business 14 (5): 15-23. https://doi.org/10.5815/ijieeb.2022.05.02

[105] **Circular Economy for the Data Centre Industry. 2023.** "Training." https://www.cedaci.org/training

[106] **Climate Neutral Data Centre Pact. 2023.** "Working Groups-Climate Neutral Data Centre Pact." https://www.climateneutraldatacentre.net/working-groups/#circular-economy

[107] **Jacqueline Davis. 2022.** "Bring on Regulations for Data Center Sustainability, Say Europe and APAC." Uptime Institute Blog. https://journal.uptimeinstitute.com/bring-on-regulations-for-data-center-sustainability-say-europe-and-apac/.

[108] **Arendse Huld. 2022.** "Eastern Data, Western Computing-China's Big Plan to Boost Data Center Computing Power Across Regions." China Briefing News. https://www.china-briefing.com/news/china-data-centers-new-cross-regional-plan-to-boost-computing-power-across-regions/.

[109] **Angelica Mari. 2019.** "UK Government Launches Cloud Sustainability Probe." Computer Weekly Online https://www.computerweekly.com/news/252461582/UK-government-launches-cloud-sustainability-probe

[110] **Digital Sustainability. 2021** "Data Centers: Conditional TICFE (Domestic Tax on Final Electricity Consumption) Reduction as of 1st January 2022." https://www.apl-datacenter.com/en/data-centers-conditional-ticfe-domestic-tax-on-final-electricity-consumption-reduction-as-of-1st-january-2022/

[111] **International Energy Agency. 2022.** "Data Centers and Data Transmission Networks." International Energy Agency, Paris, France. https://www.iea.org/reports/data-centres-and-data-transmission-networks

[112] **Google Cloud. 2022.** "24/7 Carbon-Free Energy: Powering up New Clean Energy Projects Across the Globe." Google Blog, Online. https://cloud.google.com/blog/topics/sustainability/clean-energy-projects-begin-to-power-google-data-centers

[113] **Arianna Tofani. 2022.** "A Case Study on the Integration of Excess Heat from Data Centres in the Stockholm District Heating System." KTH Royal Institute of Technology. http://kth.diva-portal.org/smash/get/diva2:1723944/FULLTEXT01.pdf

[114] **Afry Management Consulting. 2020.** "Overview of the Potential for Waste Heat and Cost - Benefit Analysis of Efficient Heating in Accordance with the Energy Efficiency Directive." Report for the Ministry of Economic Affairs and Employment. https://energy.ec.europa.eu/system/files/2021-03/fi_ca_2020_en_a01_overview_eed_article_14_0.pdf

[115] **Peter Judge. 2022.** "Dutch Government Halts Hyperscale Data Centers, Pending New Rules." https://www.datacenterdynamics.com/en/news/dutch-government-halts-hyperscale-data-centers-pending-new-rules/

[116] **David Mytton. 2021.** "Data Centre Water Consumption." Npj Clean Water 4 (11). https://www.nature.com/articles/s41545-021-00101-w

[117] **World Bank. Forthcoming.** "Sustainability of Cloud and Data Centers Report." World Bank, Washington, DC.

[118] **Developing Data Centers in Hong King. 2021.** "Data Center Development in Hong Kong." Datacenter.gov.hk. 2021. https://www.datacenter.gov.hk/en/watersupply.html.

[119] **United Nations Environment Program. 2019.** "Nigeria Turns the Tide on Electronic Waste." United Nations Environment Program, Nairobi, Kenya. https://www.unep.org/fr/node/25118

[120] **Greenex DC. 2022.** "Green Data Center Innovation from World's Top Companies." Greenex DC, Case Study. https://greenexdc.com/green-data-center-innovation-from-worlds-top-companies/

[121] **Google. 2022.** "Environmental Report 2022." Google, Mountain View, CA, https://www.gstatic.com/gumdrop/sustainability/google-2022-environmental-report.pdf

[122] **Google. 2022.** "24/7 Carbon-Free Energy by 2030." Google Data Centers. https://www.google.com/about/datacenters/cleanenergy/

[123] **Microsoft. 2021.** "Microsoft Circular Centers Program Achieves 83% Reuse, Increasing Supply Chain Efficiency and Resiliency with Dynamics 365 and Power Platform." Microsoft Corporation. https://customers.microsoft.com/en-us/story/1431789627332547010-microsoft-circular-centers

[124] **Facebook.** "Facebook Reaches 100% Renewable Energy." https://sustainability.fb.com/wp-content/uploads/2021/04/Facebook_RenewableEnergy_April2021.pdf

[125] **Mark Roenigk, Omar Baldonado, Dharmesh Jani. 2020.** How the Open Compute Project Revolutionized the Open Hardware Community." Meta. https://tech.facebook.com/engineering/2021/11/open-compute-project/

[126] **Apple. 2018.** "Apple Now Globally Powered by 100 Percent Renewable Energy." Apple. https://www.apple.com/newsroom/2018/04/apple-now-globally-powered-by-100-percent-renewable-energy/

[127] **Greenex DC. 2022.** "Green Data Center Innovation from World's Top Companies." https://greenexdc.com/green-data-center-innovation-from-worlds-top-companies/

[128] **Intel. 2022.** "Intel Makes Key Investments to Advance Data Center Sustainability." Intel. https://www.intel.com/content/www/us/en/newsroom/news/key-investments-advance-data-center-sustainability.html

[129] **Rhonda Ascierto. 2021.** "The People Challenge: Global Data Center Staffing Forecast 2021-2025." Uptime Institute Intelligence. https://uptimeinstitute.com/uptime_assets/f7fdc06fd6dd53d60f4b3a6ea2b75f5a4ab874d6e52bd727833b29426a245d3e-staffing-forecast-2021-2025.pdf.

[130] **Rhonda Ascierto. 2021.** "The People Challenge: Global Data Center Staffing Forecast 2021-2025." Uptime Institute Intelligence. https://uptimeinstitute.com/uptime_assets/f7fdc06fd6dd53d60f4b3a6ea2b75f5a4ab874d6e52bd727833b29426a245d3e-staffing-forecast-2021-2025.pdf.

[131] **Greenhouse Gas Protocol. 2019.** "We Set the Standards to Measure and Manage Emissions." https://ghgprotocol.org/

[132] **Sustainable Digital Infrastructure Alliance. 2021.** "Transparency as a Viable Sustainability Strategy for Data Centers Creating a Competitive Advantage through Open Data on Environmental Impact." https://sdiav2.cdn.prismic.io/sdiav2/2db7b1f7-f216-43bc-bbc2-28fafbb10a11_Business+Strategy+-+changed+subheadline.pdf

[133] **Global Enabling Sustainability Initiative.** https://www.gesi.org/

[134] **The Green Grid. 2023.** https://www.thegreengrid.org/

[135] **Max Schulze. 2023.** "The SDIA Welcomes the Deal of the European Council and Parliament on the Energy Efficiency Directive." Sustainable Digital Infrastructure Alliance. https://sdialliance.org/blog/new-energy-eu-efficiency-directive-targets-data-centers/

[136] **International Telecommunication Union, World Benchmarking Alliance. 2022.** "Greening Digital Companies: Monitoring Emissions and Climate Commitments." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/en/ITU-D/Environment/Pages/Toolbox/Greening-Digital-Companies.aspx

[137] **Science Based Targets Initiative. 2023.** "SBTi Criteria and Recommendations for NEAR-TERM TARGETS Version 5.1." https://sciencebasedtargets.org/resources/files/SBTi-criteria.pdf

[138] **International Telecommunication Union, Global Enabling Sustainability Initiative, Global System for Mobile Communications, Science Based Targets Initiative. 2020.** "Guidance for ICT Companies Setting Science Based Targets Mobile Networks Operators, Fixed Networks Operators and Data Centres Operators." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/en/action/environment-and-climate-change/Documents/20200227-Guidance-ICT-companies-report.PDF

[139] **Wai-Shin Chan. 2022.** "Scope 3 Emissions-the Largest Piece in the Net Zero Jigsaw." https://www.gbm.hsbc.com/en-gb/feed/sustainability/scope-3-emissions

[140] **U.S. Securities and Exchange Commission. 2022.** "SEC Proposes Rules to Enhance and Standardize Climate-Related Disclosures for Investors." https://www.sec.gov/news/press-release/2022-46

[141] **Paul Lin, Robert Bunger. 2022.** "Recommended Inventory for Data Center Scope 3 GHG Emissions Reporting Energy Management Research Center." https://download.schneider-electric.com/files?p_enDocType=White+Paper&p_File_Name=WP53_V1_EN.pdf&p_Doc_Ref=SPD_WP53_EN&_ga=2.153184632.174955548.1681894173-942591495.1681894173

[142] **International Telecommunication Union. 2020.** "L.1470: Greenhouse Gas Emissions Trajectories for the Information and Communication Technology Sector Compatible with the UNFCCC Paris Agreement." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/rec/T-REC-L.1470

[143] **Science Based Targets Initiative. 2023.** "Information and Communication Technology (ICT)." https://sciencebasedtargets.org/sectors/ict

[144] **Andy Lawrence. 2021.** "The Gathering Storm: Climate Change and Data Center Resiliency." Uptime Institute. https://uptimeinstitute.com/uptime_assets/1d430c1fe0846e5c3ca4ac58a18c10126d6d4b2918d5d1960e794cecc52d230d-the-gathering-storm-climate-change-and-data-center-resiliency.pdf

[145] **UK Tech. 2016.** "The UK's Core Digital Infrastructure: Data Centres: Climate Change Adaptation and Resilience." https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/620924/climate-adrep-tech-uk.pdf

[146] **Sotirios A. Argyroudis, Stergios Aristoteles Mitoulis, Eleni Chatzi, Jack W. Baker, Ioannis Brilakis, Konstantinos Gkoumas, Michalis Vousdoukas, William Hynes, Savina Carluccio, Oceane Keou, Dan M. Frangopol, Igor Linkov. 2022.** Digital Technologies Can Enhance Climate Resilience of Critical Infrastructure." Climate Risk Management 35:, 100387. https://www.sciencedirect.com/science/article/pii/S2212096321001169

[147] **Luisa F. Cabeza, Quan Bai, Paolo Bertoldi, Jacob M. Kihila, Andre F.P. Lucena, Érika. Mata, Sebastian Mirasgedis, Aleksandra Novikova, and Yamina Saheb. 2022.** "Buildings." In IPCC. 2022: Climate Change 2022: Mitigation of Climate Change Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by P.R. Shukla, J. Skea, R. Slade, A. Al Kourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Maley, 953-1048. Cambridge University Press, Cambridge, UK and New York. https://doi.org/10.1017/9781009157926.011

[148] **Amazon. 2022.** "AWS Is Partnering with a Concrete Company to Develop a More Sustainable Concrete Mix for Its Data Centers." https://www.aboutamazon.com/news/aws/aws-is-partnering-with-a-concrete-company-to-develop-a-more-sustainable-concrete-mix-for-its-data-centers

[149] **U.S. Department of Energy. 2011.** "Energy Star." https://www.energystar.gov/buildings/tools-and-resources/best-practices-guide-energy-efficient-data-center-design

[150] **Nick Gromicko, Ben Gromicko. 2019.** "Building Orientation for Optimum Energy-InterNACHI®." https://www.nachi.org/building-orientation-optimum-energy.htm

[151] **Izzet Yüksek, I Tülay Tikansak Karadayi. 2017.** Energy-Efficient Building Design in the Context of Building Life Cycle. Www.intechopen.com. IntechOpen. https://www.intechopen.com/chapters/53557

[152] **Ahmet Anil Sezer, Anna FredrikssonA. 2021.** "Environmental Impact of Construction Transport and the Effects of Building Certification Schemes." Resources, Conservation and Recycling 172: 105688. https://doi.org/10.1016/j.resconrec.2021.105688

[153] **European Environment Agency. 2022.** "Cooling Buildings Sustainably in Europe: Exploring the Links between Climate Change Mitigation and Adaptation, and Their Social Impacts." https://www.eea.europa.eu/publications/cooling-buildings-sustainably-in-europe

[154] **Concrete Reinforcing Steel Institute. 2023.** "Safe and Sound Steel Reinforce Concrete." Concrete Reinforcing Steel Institute. https://www.crsi.org/safe-and-sound/#:~:text=Steel%20reinforced%20concrete%20structures%20reduce

[155] **CarbonCure Technologies. 2020.** "CarbonCure's Sustainable Concrete Solution." https://go.carboncure.com/rs/328-NGP-286/images/CarbonCure%27s%20Path%20to%20the%20Decarbonization%20of%20Concrete%20eBook.pdf

[156] **United Nations Environment Program. 2020.** "2020 Global Status Report for Buildings and Construction Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector." United Nations Environment Program, Nairobi, Kenya. https://wedocs.unep.org/bitstream/handle/20.500.11822/34572/GSR_ES.pdf

[157] **IBM. n.d.** "Environmental requirements." https://www.ibm.com/docs/en/flashsystem-5x00/8.2.x?topic=pip-environmental-requirements

[158] **International Energy Agency. 2022.** "Energy System Overview-Analysis." International Energy Agency, Paris, France. https://www.iea.org/reports/energy-efficiency

[159] **International Energy Agency. 2015.** "Policy Pathway Powering SMEs to Catalyse Economic Growth Accelerating Energy Efficiency in Small and Medium-Sized Enterprises." International Energy Agency, Paris, France. https://c2e2.unepccc.org/wp-content/uploads/sites/3/2016/03/sme-2015.pdf

[160] **Amazon. 2023.** "Harnessing the Power of Plants to Decarbonise Our Data Centres." https://www.aboutamazon.eu/news/sustainability/harnessing-the-power-of-plants-to-decarbonise-our-data-centres

[161] **Energy Star. n.d.** "Uninterruptible Power Supplies." https://www.energystar.gov/products/uninterruptible_power_supplies

[162] **U.S. Environmental Protection Agency. 2022.** "CHP Benefits." https://www.epa.gov/chp/chp-benefits

[163] **Pau; Lin. 2016.** "Optimize Data Center Cooling with Effective Control Systems." https://download.schneider-electric.com/files?p_enDocType=White+Paper&p_File_Name=VAVR-A4M82C_R0_EN.pdf&p_Doc_Ref=SPD_VAVR-A4M82C_EN&_ga=2.171081126.789520267.1687080307-942591495.1681894173

[164] **Kevin Heslin. 2014**. "Implementing Data Center Cooling Best Practices." Uptime Institute. https://journal.uptimeinstitute.com/implementing-data-center-cooling-best-practices/

[165] **International Telecommunication Union. 2021.** "Innovative Data-Centre Cooling Technologies in China -Liquid Cooling Solution." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/en/action/environment-and-climate-change/Documents/publications/2021/Innovative_Data-Centre_Cooling_Technologies_in_China_Liquid_Cooling_Solution.pdf?csf=1&e=Wd1YhT

[166] **International Telecommunication Union. 2021.** "Innovative Data-Centre Cooling Technologies in China - Liquid Cooling Solution." International Telecommunication Union, Geneva, Switzerland. https://www.itu.int/en/action/environment-and-climate-change/Documents/publications/2021/Innovative_Data-Centre_Cooling_Technologies_in_China_Liquid_Cooling_Solution.pdf?csf=1&e=Wd1YhT

[167] **World Business Council for Sustainable Development. 2023.** "The EU Digital Product Passport Shapes the Future of Value Chains: What It Is and How to Prepare Now." World Business Council for Sustainable Development, Geneva, Switzerland. https://www.wbcsd.org/Pathways/Products-and-Materials/Resources/The-EU-Digital-Product-Passport

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

9 789261 374914