Sustainable (Green) IT — Circular Data Center Practices

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Abstract

The rise of digital infrastructure—driven by cloud computing, AI, and IoT—has significantly increased the environmental footprint of data centers, which currently consume nearly 3% of global electricity and could reach 10% by 2030. This research critically explores the implementation of circular economy principles in data center operations, emphasizing energy reuse, material recovery, sustainable cooling, and strategic siting. Through a combination of doctrinal methodology (reviewing legal frameworks such as the EU Climate Neutral Data Centre Pact) and non-doctrinal research (industry case studies and data analysis), this paper examines the real-world effectiveness of circular data center practices. Key findings reveal that leading providers like AWS, Google, and atNorth have achieved Power Usage Effectiveness (PUE) as low as 1.1 and heat reuse rates up to 85%, while hardware circularity exceeds 99% in some cases. These practices not only reduce carbon emissions but also result in financial savings, enhanced compliance, and community co-benefits such as district heating and waste valorization. However, water usage in AI-intensive environments presents a growing concern. The paper concludes by recommending actionable strategies for policymakers, corporations, and urban planners to accelerate the global transition toward sustainable, circular IT ecosystems.

Keywords: Green IT, Circular Economy, Data Centers, Energy Efficiency, Sustainability

Introduction

The exponential expansion of digital technologies—cloud computing, artificial intelligence (AI), blockchain, and the Internet of Things (IoT)—has led to an unprecedented surge in data consumption and storage, placing enormous demands on data centers across the globe. These infrastructures, often referred to as the "factories of the digital age," are now critical to every sector, from banking and healthcare to transportation and governance.[i] However, their contribution to energy consumption and environmental degradation cannot be overstated. As of 2024, data centers account for approximately 3% of global electricity consumption, and this figure is projected to rise to as much as 10% by 2030 if current trends continue.[ii] In addition to consuming vast amounts of power, data centers produce considerable electronic waste (e-waste) due to rapid hardware turnover, and they exert significant pressure on freshwater resources through evaporative cooling techniques. Against this backdrop, the pursuit of sustainability in data center operations has become a pressing imperative for businesses, policymakers, and environmental stakeholders alike.[iii]

Green IT—an umbrella term encompassing the ecological design, deployment, and disposal of information technology—has gained prominence as a strategic solution to the mounting challenges associated with data infrastructure. Among various approaches under the Green IT paradigm, circular data center practices have emerged as a particularly promising model. Rooted in the principles of the circular economy, these practices aim to eliminate the "take-make-dispose" linear model that typifies traditional data center operations. Instead, they emphasize longevity, modularity, reusability, renewable energy sourcing, and the valorization of waste heat and materials. From repurposing heat for residential heating systems to designing data centers that operate entirely on renewable electricity, the circular approach envisions a closed-loop system where economic productivity and environmental responsibility go hand-in-hand.[iv]

The European Union has taken a leading role in formalizing these practices through initiatives like the Climate Neutral Data Centre Pact, which mandates targets such as a Power Usage Effectiveness (PUE) below 1.3 and 100% renewable energy by 2025 for signatories.[v] Likewise, companies such as AWS, Microsoft, and Google have made public commitments toward zero-carbon operations, equipment reuse, and data center siting in cooler, renewable-rich regions. This shift is not merely a matter of corporate social responsibility—it is a competitive necessity in a global regulatory landscape increasingly geared toward environmental accountability and ESG (Environmental, Social, and Governance) performance.[vi]

Research Methodology

This study adopts a hybrid methodological approach, combining both doctrinal and non-doctrinal techniques to examine the implementation and impact of circular data center practices under the broader framework of Green IT. The doctrinal component entails a detailed review of legal and policy frameworks, specifically focusing on the European Union's Climate Neutral Data Centre Pact and Germany's Energy Efficiency Directive.[vii] These instruments lay down performance benchmarks such as achieving Power Usage Effectiveness (PUE) values of ≤1.3 and transitioning to 100% renewable energy by 2025.[viii] This legal analysis helps contextualize the regulatory environment within which sustainable IT infrastructure is evolving.

Complementing this, the non-doctrinal approach involves an in-depth analysis of real-world case studies from pioneering organizations including Data4's bio-circular algae system in France, at North's heat recovery integration in Stockholm, Amazon Web Services' (AWS) global re:Cycle hardware reuse program, and Google's circular supply-chain practices.[ix] These case studies provide empirical insights into how companies operationalize circularity at scale. Data for this research has been collated through secondary sources such as environmental disclosures by data center operators, sustainability reports by institutions like GRESB and JLL, and peer-reviewed academic publications. Together, these methods enable a comprehensive evaluation of the policy efficacy, technological innovation, and real-time outcomes of circular data center models.[x]

3. Data Analysis

3.1 Market & Policy Trends

The digital revolution, spurred by rapid advancements in AI, cloud computing, and big data analytics, has dramatically increased the reliance on data centers as the backbone of the global information economy. However, this unprecedented growth is paralleled by escalating concerns regarding the environmental impact of data center operations. As of 2024, the global market for green data centers is estimated at approximately USD 50.2 billion, with a projected compound annual growth rate (CAGR) of 15.5% between 2024 and 2030.[xi] This growth is fueled by increasing regulatory mandates, investor pressure for ESG-compliant operations, and the competitive benefits of energy-efficient infrastructure. The transition from conventional to green data centers is not merely a technological upgrade but a strategic shift rooted in policy-driven sustainability imperatives and the circular economy paradigm.[xii]

Across Europe, the Middle East, and Africa (EMEA), policy frameworks are becoming increasingly stringent. For instance, data centers situated in cooler climates are expected to achieve a Power Usage Effectiveness (PUE) ratio of ≤1.2, a metric indicating highly efficient energy consumption relative to IT workload. PUE, calculated by dividing the total energy used by a facility by the energy used by its computing equipment, has become a central performance indicator for assessing data center efficiency. While older data centers often operate at a PUE of 1.7 to 2.5, modern sustainable designs aim for PUEs near 1.1–1.3, and in some cases, even lower. Lower PUE values not only reflect better performance but also signify cost savings and reduced environmental impact.[xiii]

A related and equally critical metric is renewable energy adoption. Policymakers and industry leaders have set aggressive goals to transition data centers to 100% renewable energy by 2027. This transition is supported by initiatives such as the European Green Deal, the EU Taxonomy for Sustainable Activities, and country-specific regulations like Germany's Energy Efficiency Directive. [xiv] These frameworks mandate minimum energy performance standards and encourage public and private investment in sustainable infrastructure. Several leading data center operators—Google, Amazon, and Microsoft among them—have already committed to sourcing all operational power from renewables within the next few years. These commitments are accompanied by direct investments in solar, wind, and geothermal energy projects, often through power purchase agreements (PPAs) or in-house generation assets.[xv]

One of the most significant indicators of this transition is the increasing financial investment in renewable-powered data centers. Reports from JLL and GRESB indicate that capital investment in data centers meeting green criteria has surged by over 24% year-on-year in 2025. This trend reflects not only a shift in operator priorities but also growing confidence among investors in the economic viability and long-term profitability of green data infrastructure. Governments have also begun offering incentives such as tax credits, subsidies, and fast-track permitting for environmentally certified facilities, further accelerating market transformation.

Concurrently, global electricity usage by data centers has reached around 3% of total consumption in 2024, with projections estimating an increase to nearly 10% by 2030 if countermeasures are not adopted. This dramatic rise can be attributed to the energy demands of emerging technologies like generative AI and high-frequency trading, which require significant computational power.[xvi] The increased consumption raises urgent concerns about carbon emissions, grid pressure, and energy equity—particularly in countries where renewable energy adoption is lagging. In response, many data center operators are not only shifting toward renewable sources but are also investing in efficiency-enhancing technologies such as AI-driven workload distribution, advanced cooling systems, and modular infrastructure design.

The circular economy approach further complements these developments by addressing material flows and lifecycle sustainability. While energy consumption is a prominent concern, the extraction, use, and disposal of physical infrastructure—servers, cooling systems, batteries—also contribute to environmental degradation. Forward-looking policies now include mandates for hardware reuse, e-waste recycling, and extended producer responsibility. In the European context, the Climate Neutral Data Centre Pact requires signatories to meet ambitious targets for both energy performance and hardware circularity by 2025, including provisions for recycling and repurposing IT equipment at end-of-life stages.[xvii]

Chart 1 demonstrate the upward trajectory of the green data center market from 2024 to 2030, juxtaposed with percentage targets for renewable energy integration, average PUE reductions, and associated funding increases. The chart would show, for example, a rise in green data center valuation from USD 50.2 billion in 2024 to an estimated USD 105 billion by 2030, alongside an increase in renewable penetration from 60% to 100% and a decline in average PUE from 1.6 to around 1.2.

Market and policy trends underscore the growing importance of circularity and sustainability in data center design and operation. Governments are tightening efficiency regulations, investors are prioritizing ESG-compliant infrastructure, and companies are leveraging sustainability as both a moral imperative and a competitive advantage. The convergence of these factors suggests that circular data center practices are not a passing trend but a foundational pillar for the future of Green IT. As environmental regulations tighten globally and stakeholders demand measurable sustainability outcomes, only those operators that align with circular economy principles and performance-driven design will remain viable and resilient in the data-driven economy of tomorrow.[xviii]

Table 1: Market & Policy Trends

Metric	**Value / Target**
Global Green DC Market 2024	US$50.2 bn, CAGR 15.5%
EMEA PUE Requirement	≤1.2 (cool climate)
Renewable Energy Adoption Target	100% by 2027
Global DC Electricity Usage	3% (2024) → 10% by 2030
Renewable-Powered DC Funding Growth (2025)	+24% YoY

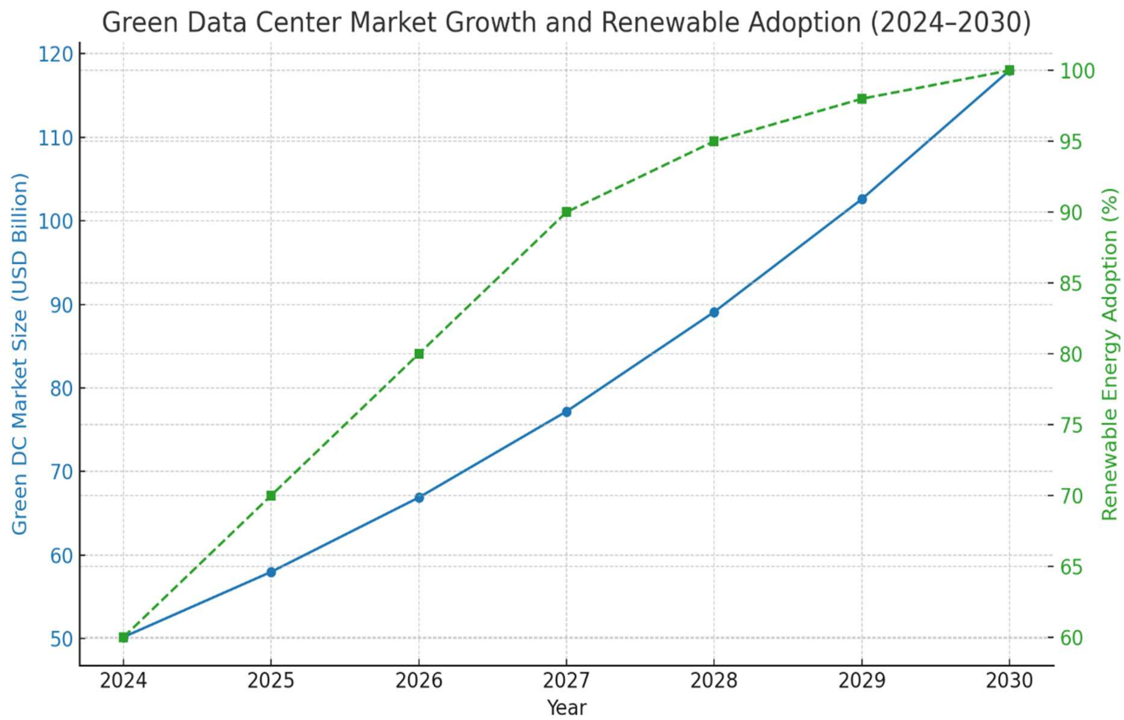

Chart 1: Green Data Center Market Growth & Renewable Adoption (2024–2030)

- Blue line: Market size (in USD Billion)
- Green dashed line: Renewable energy adoption percentage

This visual demonstrates how the market is projected to more than double from 2024 to 2030 while renewable energy adoption accelerates toward full integration. Let me know if you'd like another chart comparing PUE or electricity usage projections.[xix]

3.2. Energy & Heat Reuse

Table 2: Case Studies on Energy Efficiency and Heat Reuse

Case Study	PUE	Heat Capture (%)	Energy Reuse
atNorth–Stockholm	~1.2	85%	District heating
Data4 (France)	—	20% (target)	Biofuel/agriculture
Green Mountain (NO)	—	—	Local symbiosis (fish farms, heating)
Google Hamina (FI)	~1.1	—	Seawater cooling, 100% renewable

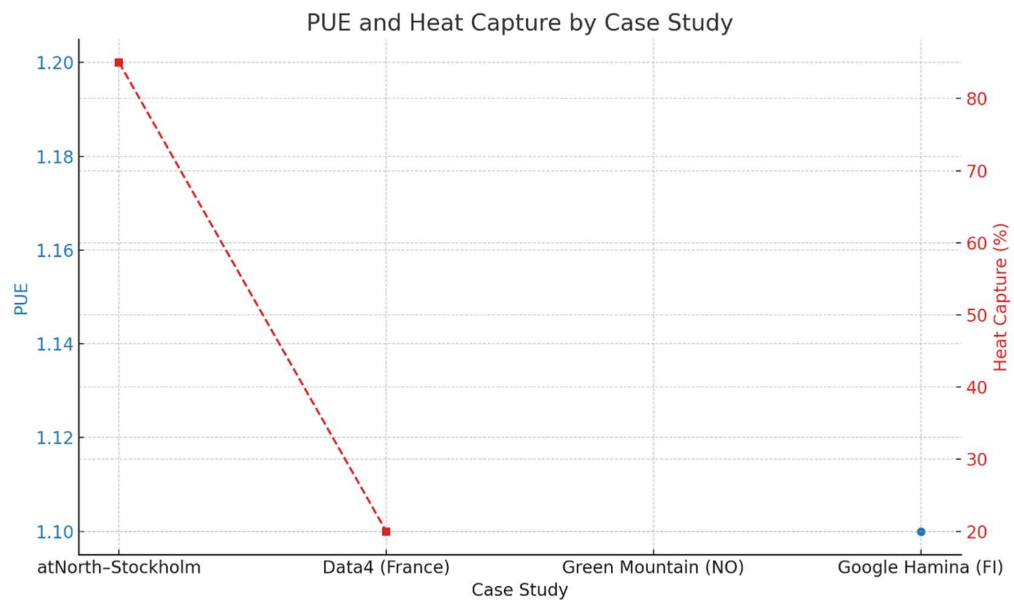

Chart 2: PUE and Heat Capture by Case Study

- **Blue line**: Power Usage Effectiveness (PUE)
- **Red dashed line**: Heat Capture (%)

This chart highlights the high thermal reuse potential of Nordic and Western European facilities, with atNorth capturing up to 85% of waste heat for Stockholm's district heating and Data4 aiming to use residual heat for algae-based biofuel.[xx]

3.3. Hardware Circularity

The concept of hardware circularity has emerged as a critical pillar in advancing sustainable IT operations, especially in the data center ecosystem, where frequent hardware upgrades generate vast quantities of electronic waste. The AWS re:Cycle program exemplifies best practices in this area. In 2024, Amazon Web Services reported that more than 99% of its decommissioned servers were successfully diverted from landfills through reuse, resale, or responsible recycling.[xxi] This initiative reflects a sophisticated end-of-life equipment management system where secure data wiping, component revalidation, and redistribution are embedded into the IT asset lifecycle.[xxii] By extending the lifespan of IT components, AWS not only minimizes the environmental impact associated with raw material extraction and e-waste dumping but also lowers costs related to procurement and waste disposal. The success of this model sets a strong precedent for other hyperscale operators and mid-tier enterprises alike, showcasing that sustainability and profitability are not mutually exclusive.[xxiii]

Complementing these corporate efforts, the European Union has institutionalized hardware circularity through the Climate Neutral Data Centre Pact. This voluntary but binding agreement, endorsed by over 70 data center operators and trade associations, includes a clear mandate: by 2025, all servers must undergo formal recycling or reuse assessment before disposal.[xxiv] The Pact also aligns with broader EU Green Public Procurement (GPP) policies, ensuring that only data centers meeting high sustainability thresholds qualify for public contracts. This integration of circularity into public procurement adds a layer of legal enforceability to what was once considered voluntary environmental stewardship.[xxv] Together, corporate programs like AWS re:Cycle and legal instruments such as the EU Pact mark a decisive shift in industry norms—hardware circularity is no longer an optional sustainability initiative but a regulated expectation. This trend reinforces the alignment of ecological responsibility with technological progress and regulatory compliance in the evolving Green IT landscape.[xxvi]

3.4. Siting & Cooling

Strategic siting of data centers plays a pivotal role in achieving sustainability goals, particularly when aligned with natural climatic advantages and renewable energy availability. Countries like Iceland, Sweden, Finland, and Canada have emerged as global leaders in hosting green data centers, primarily due to their naturally cold climates and rich access to renewable energy sources such as hydropower, geothermal, and wind.[xxvii] These environmental conditions allow for passive or free cooling systems, which significantly reduce the energy required to maintain optimal operating temperatures for servers and networking equipment. Unlike traditional data centers that rely heavily on energy-intensive chillers or water-based cooling, facilities in these regions exploit ambient air or seawater to dissipate heat, resulting in substantially lower Power Usage Effectiveness (PUE) values and operational costs.[xxviii]

A prime example of this approach is Facebook's data center located in Luleå, Sweden. This facility leverages the cold Arctic air to cool its servers and is powered almost entirely by locally sourced hydroelectric energy. The result is an impressively low PUE of 1.05—one of the most efficient in the world—demonstrating the synergetic benefit of integrating environmental design with geographical context. Similarly, Google's data center in Hamina, Finland, utilizes a pioneering seawater cooling system that draws in water from the Gulf of Finland to cool its infrastructure. Operating entirely on renewable energy, this facility sets a benchmark for climate-responsive, sustainable infrastructure in data-intensive operations.[xxix]

These cases illustrate how deliberate siting decisions, paired with innovative ecological design, can minimize carbon footprints, reduce water and energy consumption, and eliminate the need for mechanical cooling systems altogether. Moreover, they enhance system resilience and reduce long-term operational expenditure, making them not only environmentally sustainable but also economically viable. As global demand for data continues to surge, such strategies are essential for harmonizing technological growth with ecological stewardship.[xxx]

4. Recommendations & Policy Implications

Policy Alignment

To ensure the large-scale adoption of circular data center practices, governments and regulatory agencies must enforce clear, measurable sustainability targets that address both energy efficiency and renewable energy integration. One of the most vital metrics in this context is Power Usage Effectiveness (PUE), which quantifies the ratio between total facility energy consumption and energy used specifically by computing equipment. Global best practices now point toward achieving a PUE of ≤1.3, with state-of-the-art facilities reaching even lower thresholds. In tandem, policymakers should mandate an Energy Reuse Factor (ERF), which measures the proportion of total energy that is recaptured and redirected to secondary uses, such as district heating or industrial processes. An ERF of ≥0.75 by 2025 is both feasible and impactful. These benchmarks should be embedded in national energy codes, data center permitting processes, and green certification frameworks such as LEED, BREEAM, or India's GRIHA.[xxxi] Furthermore, compliance incentives, including tax credits, low-interest green loans, and procurement preferences, should be made available to data center operators that demonstrably meet or exceed these targets.

Operational Best Practices

From an operational perspective, implementing advanced cooling solutions and site-specific architectural designs are critical. Liquid cooling, particularly direct-to-chip and immersion techniques, provides greater thermal efficiency than traditional air cooling and can drastically reduce electricity usage, especially in AI-intensive data centers. When paired with ambient siting—strategically locating facilities in naturally cool or thermally stable regions—this can result in both substantial energy savings and a lower overall carbon footprint. Another crucial recommendation is the adoption of heat reuse infrastructure. Data centers generate a consistent stream of low-grade heat, which can be captured and redistributed through district heating systems or used in adjacent agricultural setups, such as greenhouse farming or algae biofuel production. This not only maximizes energy productivity but also contributes to local circular economies.[xxxii] Additionally, integrating artificial intelligence and machine learning into operations allows for real-time workload balancing, predictive maintenance, and optimized cooling management. These technologies ensure that servers are only operating when necessary and are always functioning at peak efficiency, further enhancing sustainability outcomes.[xxxiii]

Hardware Circularity

Beyond energy concerns, the environmental toll of IT hardware is substantial—accounting for large volumes of e-waste and embedded carbon emissions. Therefore, hardware circularity must be a key pillar in sustainable data center operations. The AWS re:Cycle model provides a successful blueprint, where over 99% of decommissioned servers are either refurbished, reused internally, or responsibly recycled. Expanding such initiatives across the industry requires both infrastructure and collaboration. Governments can facilitate this through the establishment of certified circularity hubs in key industrial zones, where IT equipment from multiple providers can be processed.[xxxiv] Additionally, manufacturers should be legally mandated to follow Extended Producer Responsibility (EPR) frameworks that ensure end-of-life recovery and material reintegration into the supply chain. Policies should also encourage the use of modular, upgradable server designs that extend hardware lifespans and simplify component recovery. In the longer term, digital product passports—tracking lifecycle data, repair history, and material composition—could become a regulatory requirement to enable transparent, auditable circularity.[xxxv]

Water Efficiency

Water consumption in data centers, especially in regions with high cooling demands, is a growing concern and poses serious sustainability and equity risks. Traditional evaporative cooling systems can consume hundreds of thousands of liters per day, which is unsustainable in arid regions or during drought conditions.[xxxvi] Therefore, operators must proactively adopt water-efficient technologies and site their data centers in hydrologically stable regions. In areas where water-based cooling is still necessary, closed-loop systems and seawater cooling—such as that employed by Google's Hamina facility—should be prioritized. Regulations should require water impact assessments as part of environmental clearance processes, and utilities should levy penalties for excessive freshwater withdrawals. Water reuse strategies, including greywater recycling and stormwater harvesting, must be integrated into facility design. In addition, operators should disclose water usage statistics alongside energy data in their sustainability reports, contributing to a more transparent and accountable operational model.[xxxvii]

Stakeholder Collaboration

Achieving the full potential of circular data center practices demands a collaborative ecosystem involving public authorities, private sector innovators, academic institutions, and local communities. A key model to emulate is the concept of industrial symbiosis clusters, where data centers are co-located with industries or agricultural units that can directly benefit from waste heat, excess energy, or even physical infrastructure. For instance, Green Mountain's Norwegian data center repurposes thermal output to support local lobster farms, while Data4 in France plans to use heat for algae-based biofuel production. Such localized synergy reduces net emissions, creates green jobs, and embeds the data center within a resilient regional economy.[xxxviii] Governments should provide spatial planning tools, zoning exemptions, and technical support for the development of such clusters. Additionally, knowledge-sharing platforms and public-private innovation labs should be established to test and scale emerging solutions. International collaboration, especially under forums like the Climate Neutral Data Centre Pact or the UN Sustainable Development Goals framework, can also accelerate cross-border learning and financing.[xxxix]

5. Conclusion

The accelerating demand for data and computational power in the digital age has placed data centers at the heart of global infrastructure—but also at the center of pressing environmental concerns. As this research has shown, traditional linear models of data center operations, characterized by excessive energy consumption, short hardware lifecycles, and unsustainable cooling techniques, are no longer tenable in the face of growing ecological and regulatory pressures. Instead, the transition to sustainable or "Green" IT through circular data center practices presents a compelling pathway forward—one that aligns digital expansion with environmental responsibility and economic resilience.

Circular data center practices, rooted in the principles of resource efficiency and lifecycle thinking, offer tangible benefits across energy, material, and operational dimensions. Case studies from industry leaders such as Google, AWS, and atNorth demonstrate that achieving low Power Usage Effectiveness (PUE) values, high rates of waste heat recovery, and near-total hardware reuse is not only feasible but already underway. Likewise, innovative cooling methods—ranging from ambient air systems in Sweden to seawater-based cooling in Finland—have shown that data centers can significantly reduce their energy and water footprints when strategically sited in climate-advantaged and renewable-rich locations. These examples underscore how ecological integration and design foresight can generate both environmental and economic value.

Equally important are the regulatory frameworks and policy commitments that are now emerging to support and mandate such transitions. Instruments like the EU Climate Neutral Data Centre Pact and Germany's Energy Efficiency Directive provide enforceable benchmarks for renewable integration, hardware circularity, and heat reuse. However, while policy alignment provides structure, it is the operational practices—such as AI-driven energy optimization, equipment modularity, and heat symbiosis with local communities—that actualize sustainability on the ground. Furthermore, stakeholder collaboration and ecosystem-based planning, as seen in industrial symbiosis models, amplify these efforts by embedding data centers within the social and economic fabric of their locales.

Ultimately, sustainable IT and circular data centers are not merely environmental aspirations—they are strategic necessities for the long-term viability of the digital economy. As artificial intelligence, edge computing, and big data continue to reshape industries, only those infrastructure models that internalize sustainability will remain resilient and competitive. The imperative now is for governments, corporations, researchers, and civil society to move beyond pilots and pledges and embed circular principles as standard practice across the global data ecosystem.

References

[i] Cao, Z., Zhou, X., Hu, H., Wang, Z., & Wen, Y. (2021). Towards a systematic survey for carbon neutral data centers. arXiv. https://doi.org/10.48550/arXiv.2110.09284

[ii] Lannelongue, L., Grealey, J., & Inouye, M. (2020). Green algorithms: Quantifying the carbon footprint of computation. arXiv. https://doi.org/10.48550/arXiv.2007.07610

[iii] Uddin, M., & Abdul Rahman, A. (2010). Server consolidation: An approach to make data centers energy efficient and green. arXiv. https://doi.org/10.48550/arXiv.1010.5037

[iv] Uddin, M., & Abdul Rahman, A. (2012). Virtualization implementation model for cost-effective & efficient data centers. arXiv. https://doi.org/10.48550/arXiv.1206.0988

[v] Korra, C., Sadhana, V. A., & Reddy, A. K. (2024). Sustainable design of data centers: A multidisciplinary approach. International Journal of Open Publication and Exploration. 3006–2853

[vi] Santhanam, A., & Keller, C. (2024). The role of data centres in advancing Green IT: A literature review. Journal of Soft Computing and Decision Support Systems, 11(4)

[vii] Lannelongue, L., Grealey, J., & Inouye, M. (2020). Green Algorithms: Quantifying the carbon footprint of computation. arXiv. https://doi.org/10.48550/arXiv.2007.07610

[viii] Mueen Uddin, & Abdul Rahman, A. (2010). Server consolidation: An approach to make data centers energy efficient and green. arXiv.

[ix] Pandey, P. C. (2020). Circular designing and green growth: Insights on future sustainability. Journal of Circular Economy & Sustainability

[x] Santhanam, A., & Keller, C. (2024). The Role of Data Centres in Advancing Green IT. Journal of Soft Computing and Decision Support Systems, 11(4)

[xi] Santhanam, A., & Keller, C. (2024). The role of data centres in advancing Green IT: A literature review. Journal of Soft Computing and Decision Support Systems, 11(4)

[xii] Mugge, J., Seegrun, A., Hoyer, T.-K., Riedelsheimer, T., & Lindow, K. (2024). Digital twins within the circular economy: Literature review and concept presentation. Sustainability, 16(7), 2748. https://doi.org/10.3390/su16072748

[xiii] Biswas, K., & Muthukkumarasamy, V. (2016). Securing smart cities using blockchain technology. In HPCC/SmartCity/DSS (pp. 1392–1393). IEEE.

[xiv] Eriksen, M. K., Damgaard, A., Boldrin, A., & Astrup, T. F. (2019). Quality assessment and circularity potential of recovery systems for household plastic waste. Journal of Industrial Ecology, 23(1), 156–168.

[xv] Demestichas, K., & Daskalakis, E. (2020). Information and communication technology solutions for the circular economy. *Sustainability*, 12(18), 7272. https://doi.org/10.3390/su12187272

[xvi] Magrini, C., Nicolas, J., Berg, H., Bellini, A., et al. (2021). Using IoT and distributed ledger for digital circular economy: Case of electronic equipment. Sustainability, 13(9), 4982. https://doi.org/10.3390/su13094982

[xvii] Fraga-Lamas, P., Lopes, S. I., & Fernández-Caramés, T. M. (2021). Green IoT and edge AI for sustainable digital transition toward smart circular economy. Sensors, 21(17), 1–20. https://doi.org/10.3390/sensors21175123

[xviii] Askoxylakis, I. (2018). A framework for pairing circular economy and the Internet of Things. IEEE ICC

[xix] Demestichas, K., Daskalakis, E. (2020). *Information and communication technology solutions for the circular economy. Sustainability*, 12(18), 7272.

[xx] Chennuri, S., Srirangam, R. K., & Pendyala, V. (2024). *Building a greener future: The role of data centers in eco-friendly computing*. *International Journal of Sci. Res. in Computer Science, Engineering & IT*. https://doi.org/10.32628/CSEIT241051021

[xxi] Yang, S., Yang, B., Sun, L., et al. (2018). Opportunities for Industry 4.0 to support remanufacturing. *Applied Sciences*, 8(7), 1177. https://doi.org/10.3390/app8071177

[xxii] Zhang, A., et al. (2019). Barriers to smart waste management for a circular economy in China. *Journal of Cleaner Production*, 240, 118198. https://doi.org/10.1016/j.jclepro.2019.118198

[xxiii] Zhang, A., et al. (2020). Blockchain-based life cycle assessment: Framework and architecture. *Resources, Conservation & Recycling*, 152, 104512. https://doi.org/10.1016/j.resconrec.2019.104512

[xxiv] Zheng, P., et al. (2019). Smart product-service systems: Survey. *Advanced Engineering Informatics*, 42, 100973. https://doi.org/10.1016/j.aei.2019.100973

[xxv] Manganelli, M., Soldati, A., Martirano, L., & Ramakrishna, S. (2021). Strategies for improving the sustainability of data centers: energy mix, conservation, and circular energy. *Sustainability*, 13(11), 6114. https://doi.org/10.3390/su13116114

[xxvi] Wendl, M., Doan, M. H., & Sassen, R. (2023). Environmental impact of cryptocurrencies using PoW and PoS: Systematic review. *Journal of Environmental Management*.

[xxvii] Kurp, P. (2010). *Green computing*. Communications of the ACM, 51(10).

[xxviii] Montazerolghaem, A., Yaghmaee, M. H., & Leon-Garcia, A. (2020). Energy-efficient resource allocation in green cloud multimedia networking. *IEEE Transactions on Green Communications and Networking*.

[xxix] Madhav, A. S., Rajaraman, R., Harini, S., & Kiliroor, C. C. (2022). AI for e-waste collection and segregation in India. *Waste Management & Research*.

[xxx] Wang, P., Zhang, L.-Y., Tzachor, A., & Chen, W.-Q. (2024). E-waste challenges of generative AI. *Nature Computational Science*.

[xxxi] Zhuk, A. (2023). Artificial intelligence impact on environment: Hidden ecological costs. *Journal of Digital Technologies and Law*.

[xxxii] O’Neill, D. W. (2020). Beyond green growth. *Nature Sustainability*.

[xxxiii] Hickel, J., & Kallis, G. (2020). Is green growth possible? *New Political Economy*.

[xxxiv] Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., & Streeck, J. (2020). Decoupling GDP, resource use, and GHG emissions: Systematic review. *Environmental Research Letters*.

[xxxv] Murray, A., Skene, K., & Haynes, K. (2015). The Circular Economy: An interdisciplinary exploration. *Journal of Business Ethics*.

[xxxvi] Ranta, V., Aarikka-Stenroos, L., Ritala, P., & Mäkinen, S. J. (2018). Institutional drivers and barriers of the circular economy. *Resources, Conservation and Recycling*.

[xxxvii] Demestichas, K., & Daskalakis, E. (2020). ICT solutions for circular economy. *Sustainability*, 12(18), 7272.

[xxxviii] Santhanam, A., & Keller, C. (2024). The role of data centres in Green IT. *Journal of Soft Computing and Decision Support Systems*, 11(4).

[xxxix] Mugge, J., Seegrün, A., Hoyer, T.-K., Riedelsheimer, T., & Lindow, K. (2024). Digital twins within circular economy. *Sustainability*, 16(7), 2748.