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REVIEW ARTICLE

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SUSTAINABLE DATA CENTERS: A SYSTEMATIC REVIEW OF TECHNOLOGIES AND PRACTICES FOR CARBON EMISSION REDUCTION

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***Abstract*—**The digital economy around the world relies on data centres which are crucial today. Since cloud computing, AI and data are now needed more than ever, energy consumption has risen rapidly and sustainability has become extremely important. Data centres use an unreasonable amount of electricity on a global scale, which has put their carbon emissions in the spotlight of environmental concerns. This review covers new technologies and ways of operating data centers that help reduce greenhouse gas emissions from these major digital service providers. The massive amount of energy used by data centres globally highlights the essential need of sustainable practices in this industry. The article covers important measures that reduce environmental consequences and increase energy efficiency. Virtualisation, energy-efficient gear, renewable energy integration, and advanced cooling systems are all part of these initiatives. Additionally, it highlights the role of performance metrics like Power Usage Effectiveness (PUE), Carbon Usage Effectiveness (CUE), and Water Usage Effectiveness (WUE) in guiding sustainable operations. Though there has been progress, the absence of standard evaluation tools and slow adoption of best practices is still holding back the full achievement of carbon-neutral data centers. The paper stresses the need for collaboration, openness and innovative design in improving the sustainability of data centers.

***Keywords*—**Sustainable data centers, carbon emission reduction, renewable energy, green computing, environmental sustainability, data center optimization.

I. INTRODUCTION

In recent times, data centers have become crucial for tasks such as cloud services, AI, social media and many other types of enterprise applications [1]. Still, energy use is rising sharply because of how popular these techs have become and this is causing major environmental issues. Data centres are already responsible for around one percent of the world's electrical consumption, and unless there are major advancements in energy efficiency and carbon mitigation measures, that percentage is only going to rise.

Data centers produce negative effects on the environment from their increase in energy use as well as their dependence on unclean energy and large air conditioning systems. The industry has begun to use sustainable methods and innovative architecture to solve these problems[2]. These steps feature dynamic energy optimization, renewable energy usage, advanced cooling technologies and strategies that move tasks to high-efficiency machines. For example, the GEECO model automatically reorganizes cloud workloads according to the present atmosphere and work needs, greatly decreasing both energy use and emissions.

Meanwhile, the move towards a circular economy in the data center sector is gaining speed. There is a growing emphasis on infrastructure reuse, using modular designs, checking carbon emissions over the whole project's life and green purchasing[3]. The purpose of these initiatives is to lower waste, increase the life of infrastructure components and cut embodied carbon during the entire supply chain process. It's important to focus on both technical and regulatory sides of sustainability in data centers[4]. Environmental performance of datacenters is evaluated and optimized using industry metrics such as PUE, CUE and WUE.

Despite these advancements, a critical gap remains in the quantitative evaluation of sustainability impacts, particularly in high-availability architectures. The environmental footprints of data centre designs with comparable performance levels might vary greatly[5]. However, due to the lack of standardized evaluation frameworks, sustainability considerations are often overlooked in architectural decision-making processes[6]. To promote sustainable innovation, it is essential to develop methodologies that quantify the environmental trade-offs associated with various design choices.

A. Structure of the paper

This paper is organised in the following way: **Section II** provides an overview of data center sustainability. **Section III** discusses the technologies for reducing carbon emissions. **Section IV** explores best practices and operational strategies for carbon emission reduction. **Section V** presents a review of recent literature and comparative analysis. Finally, **Section VI** concludes with future research directions.

II. OVERVIEW OF DATA CENTER SUSTAINABILITY

A data centre is defined as "a department within an enterprise (organisation) that houses and maintains the organization's mainframes, servers, databases, and other back-end IT systems and data stores." This is how a data centre is defined physically (in terms of infrastructure) [7]. The operational definition of a data centre is a facility that handles financial information, processes and stores intellectual property, hosts websites, processes and processes commercial transactions, and routes e-mails. A data centre, therefore, is like the cerebral cortex of an organisation.

The ever-growing need for digital services has led to data centres becoming integral components of modern infrastructure[8]. However, there are growing worries regarding their environmental effect because to their energy-intensive nature [1]. The concept of sustainability in data

centers encompasses designing, operating, and managing facilities in a manner that minimizes resource consumption and greenhouse gas emissions while maintaining performance, scalability, and reliability. Climate change and increasing energy prices have made sustainability a commercial and regulatory need in addition to an environmental one.

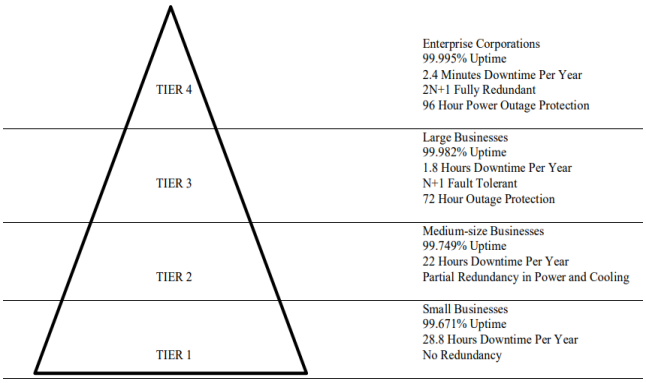

Fig. 1. Data Center Tiers

The data centre tiers, or types of data centres, provide a more accurate picture of the industry's development. Figure 1 is the most effective tool for illustrating this point.

A. *Importance of Data Center Sustainability*

"Data centre sustainability" refers to the practice of intentionally reducing environmental consequences via the use of renewable energy sources, energy-efficient technologies, and resource optimisation [9]. The significance of this approach lies in its potential to curb the carbon emissions of a sector that already contributes to nearly 1–2% of global electricity consumption[10]. In light of the growing digitisation of services, data centre sustainability is crucial to bringing the IT sector into line with international environmental goals like the Sustainable DevelopmentGoals of the UN and the ParisAgreement.

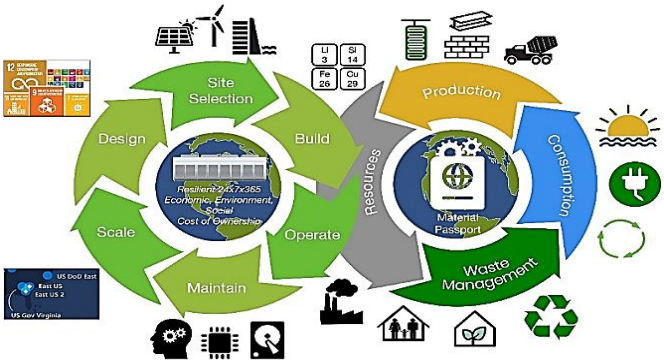

Fig. 2. Lifecycle and Circular Economy Framework for Sustainable Data Centers

The figure 2 displays the importance of data center sustainability by presenting a lifecycle and circular economy framework that integrates environmental responsibility into every stage of a data center's existence[11]. Every step in the process, including picking a site, designing, building, operating, scaling and maintaining, has guidelines to help minimize the use of energy and reduce carbon emissions [12]. A circular economy seeks to conserve and reinforce resources by measures such as improved waste management, renewable energy, and material passports. Implementing this approach makes data centers strong, efficient and environmentally and socially responsible, emphasizing their place in helping the world reduce carbon emissions and develop sustainably.

B. *Core Pillars of Sustainable Data Centers*

Sustainable data centers rely on various principles to help protect the environment while ensuring their performance, reliability and ability to handle increasing needs. These areas are important for growth and improvements that help us reach our sustainable goals.

1) *Energy Efficiency*

Energy efficiency is one of the main factors in making a data center more sustainable. Here, the strategy involves making IT equipment more efficient, setting up power management and better designing the facility to limit energy waste [13]. Methods like combining servers, monitoring PUE and smart workload distribution help to cut both energy use and costs in operations.

2) *Renewable Energy Integration*

It is critical to change from using fossil fuels to using renewable energy. Now, many sustainable data centers rely on solar, wind, hydro or geothermal energy or gain renewable energy credits (RECs). This allows us to reduce our carbon footprint and contribute to the transition to an economy that uses less carbon.

3) *Efficient Cooling Systems*

A data center's cooling system is a major power hog. In order to lessen their need on conventional HVAC systems, sustainable buildings use cutting-edge cooling methods such as liquid cooling, free-air cooling, and hot/cold aisle containment. These methods enhance thermal efficiency and significantly cut down electricity usage.

4) *Hardware Optimization and Lifecycle Management*

It is critical to use storage devices, servers, and network equipment that are energy efficient in order to decrease power consumption. Efficient resource utilisation and e-waste minimisation are additional benefits of controlling the whole hardware lifetime, from purchase to recycling. Virtualization and containerization also play key roles by reducing the physical hardware footprint.

5) *Resource and Waste Management*

Sustainable data centers adopt practices that minimize water usage, reduce electronic waste, and encourage recycling. This includes the use of water-efficient cooling technologies and responsible disposal or repurposing of retired equipment[14]. Monitoring and managing resources across IT and facility infrastructure helps ensure minimal environmental impact.

6) *Intelligent Monitoring and Automation*

Real-time data analytics and AI-driven management systems enable proactive control over energy usage, cooling, and workload distribution. Automation tools help identify inefficiencies and optimize operations dynamically, contributing to smarter, more sustainable performance.

C. *Key Performance Indicators (KPIs) for Sustainability*

To assess and enhance a sustainability of data centers, several KPIs are widely used across the industry:

- **Power Usage Effectiveness (PUE):** PUE measures the efficiency of data centres' energy use in relation to

the electricity consumed by IT equipment. Decreases in PUE are indicators of improved energy efficiency [15]. This is the proportion of the building's total energy usage that comes from information technology equipment. The optimal PUE is 1. indicating all energy is used directly for computing. Lower PUE values reflect greater energy efficiency.

$$PUE = \frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy} \quad (1)$$

- **Data Centre Infrastructure Efficiency (DCiE):** DCiE, which stands for the ratio of IT power usage to overall power consumption, is the inverseof PUE. It shows the proportion of overall energy consumption that is attributable to IT equipment; the inverse of PUE.

$$DCiE = \left(\frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy}\right) \times 100\% \quad (2)$$

- **Carbon Usage Effectiveness (CUE):** Greenhouse gas emissions per unit of energy consumed by IT equipment may be quantified using CUE, which allows one to assess the data center's carbon footprint. This measure calculates carbon emissions for each unit of energy used by IT devices[16]. Data centre operations' carbon intensity may be better understood with its help.

$$CUE = \frac{Total\ CO2\ Emissions}{IT\ Equipment\ Energy} \quad (3)$$

- **Water Usage Effectiveness (WUE):** The WUE ratio quantifies the amount of water used in relation to the amount of energy used by data centre IT equipment. Represents the amount of water used per kWh of IT energy[3]. It measures the long-term sustainability of air conditioning strategies, mostly in water-short countries.

$$WUE = \frac{Annual\ Water\ Usage\ (liters)}{IT\ Equipment\ Energy(kWh)} \quad (4)$$

III. Technologies For Reducing Carbon Emissions

As data centers need more energy, the adoption of new technologies that reduce carbon emissions is becoming necessary. This part explores the main technological developments that sustain the functions of data centers.

A. Virtualization and Containerization

Applications may now operate in a containerised or virtualised environment on a single physical server, which greatly reduces hardware requirements and maximises resource utilisation. Minimizing energy use and related carbon emissions is possible by using these approaches to combine several tasks into one workload. Containerized microservices have been shown to manage more processes at once, while also decreasing response times and energy costs[17]. Server and storage virtualisation, as well as effective resource utilisation, are some of the tactics being used by data centres to increase their efficiency. A physical device can be made to run as several virtual servers or storage devices by using the right software. This technique is known as server and storage virtualisation[18]. This approach might greatly enhance resource utilisation by enabling a single physical device to perform the tasks of several virtual ones. Less space and energy consumption and fewer servers and storage devices are required as a result of this improved utilisation of the data center's resources [19]. It is possible to see improvements in energy usage, a reduced environmental impact and lower costs for operations. Improving the way available resources are used is a key way to increase data centre efficiency. In order to cut down on power use and garbage creation, it is important to keep an eye on and optimise how IT equipment is being used. Monitoring equipment use on a regular basis may help data centre operators spot cases of resource wasting or inefficiency.

B. Energy-Efficient Hardware

Green data centres use energy-efficient technology as one of their key concepts in their quest of sustainability within data centre operations [20]. The way hardware is used in a data center can greatly influence its power consumption, so it plays an important role in decreasing the carbon footprint. Having energy-efficient hardware, checking if aging servers, storage systems and network equipment need changing and choosing virtualization, low-power processors and memory modules[21]. The data center landscape has evolved greatly over the years as new technologies created a need for even greater processing power and storage[22]. However, this pursuit of performance has often resulted in the deployment of hardware that is not optimized for energy efficiency. A bigger carbon footprint and higher energy usage are the two outcomes. There are a lot of older data centres that are still using servers that aren't very energy efficient.

C. Advanced Cooling Systems

Maintaining ideal operational conditions inside data centres is greatly aided by cooling systems. The conventional air-cooling systems used in data centres are effective, but require a lot of energy. Data centres that prioritise environmental sustainability investigate various cooling solutions to maximise efficiency while keeping server temperatures consistent. This section elaborates on the significance of cutting-edge cooling methods, including liquid immersion, hot aisle containment, and free air cooling[23]. The processing power of servers generates heat, and effective cooling is paramount to prevent overheating and ensure the reliable operation of hardware. Nonetheless, traditional air-conditioning and ventilation are major contributors to how much energy data centers use. Air-cooling means moving cool air throughout the data center to reduce the heat made by the servers[24]. The systems are not energy efficient, despite their widespread usage; this is especially true in data centres, where precise temperature control is a major challenge. Cutting-edge cooling technologies are used in green data centers to fix the energy issues seen with conventional air cooling.

D. Renewable Energy Integration

To be environmentally responsible, data centers need to focus on using renewable energy during the climate crisis and fossil fuel shortages [25]. It examines how many green data centers rely on renewables like solar, wind and geothermal to keep their operations more environmentally friendly and dependable for the future[26]. A significant cause of environmental concerns comes from using fossil fuels in data centers. Burning fossil fuels increases pollution in the air, pollutes the water and causes greenhouse gases to be released[27]. To reduce their environmental effects, green data centers are now using new energy sources that focus on sustainable practices. Solar and wind energy have the potential to deliver significant sustainability results for data centres. Using renewable energy sources, rather than fossil fuels, means we emit much less carbon into the atmosphere.

E. Resource Optimization

Resource optimization is at the center of making green data centers energy efficient. The examination of energy-saving opportunities spans every area of data center operations. Green data centers know that achieving energy efficiency isn't only about the components; it should include every aspect of their processes [26]. Resource optimization refers to caring for both energy and other materials to waste as little as possible and make the whole process more environmentally friendly.

IV. Best Practices For Sustainable Data Centers In Carbon Emission Reduction

Good management is necessary to make data centers more sustainable. This section discusses major strategies that help cut emissions and enhance efficiency at the facility.

A. Collaboration and Transparency

Finally, sustainability goals can best be met and shared with others when the company is transparent and collaborative. Data centers are starting to share their energy and carbon data with people, customers and regulators. Being involved in industry groups helps data centres follow the best standards, drive innovation and encourage everyone to increase their green efforts.

B. Smart Automation and AI Optimization

The use of artificial intelligence and automation is rapidly transforming energy management in data centers. AI-powered systems can dynamically balance workloads based on real-time energy efficiency metrics. Predictive maintenance tools look at equipment to spot possible failures early, schedule maintenance and prevent both interruptions and energy losses. Because of these systems, data centers can keep up their efficiency with little human supervision.

C. Data Center Design

Building data centers with sustainable design principles in mind, such as utilizing natural cooling methods, efficient layout to minimize energy wastage, and selecting locations with access to renewable energy.

D. Green Data Center Certification

The vast majority of the services, apps, and communication networks that we use on a daily basis are powered and enabled by data centres, which serve as the central nervous systems of our ever-growing digital world [28]. The goal of environmentally friendly Green Data Centres is to effectively manage massive volumes of data and computational activities while reducing energy usage[29]. LEED and ENERGY STAR certifications demonstrate that a data center is dedicated to sustainability. Such certificates examine important factors such as energy, water use and the effect on the environment. For example, getting LEED certification supports using power-saving solutions and methods which helps control carbon emissions.

E. Carbon Monitoring and Reporting

Sustainable businesses must practice strong monitoring and reporting of carbon. Currently, things like Data Center Infrastructure Management (DCIM) are being used in data centers to examine PUE and spot areas where the system is not working efficiently. A carbon accounting system makes it easy to keep records of emissions which is now expected by clients and officials in most places. Regular sustainability audits make it possible for organizations to improve their operations to match emissions-reduction goals.

F. Strategic Data Center Siting

A center's cooling system is directly affected by its position in the country which can have an effect on energy efficiency. Big savings in energy can be found by moving data centres to locations with moderate weather or an abundance of sustainable energy sources [30]. Research shows that data centres in colder regions, when using less energy for cooling, produce fewer carbon emissions.

V. Literature Review

It provides a review of what's been written on sustainability technology and methods to lessen carbon emissions in data centers. It covers key tactics, reviews recent improvements and explains new difficulties in running data centers in an environmentally responsible way.

Cao et al. (2024), now turn to the matter of data centre sustainability and draw up a plan for the future that will help keep data centres sustainable. They maintain that achieving the best possible data centre sustainability involves more than just improving energy efficiency. To begin, it will give you a rundown of the five main categories of sustainability measurements. They next show how up-to-date data centres stack up in terms of sustainability by analysing publicly accessible data centre sustainability ratings. In addition, they pinpoint a number of emerging trends by analysing the development of Singapore's data centre sustainability requirements[31].

Fatima and Ehsan (2023), examine the effects of datacenters on the environment, determine what factors lead to CO2 emissions, review the literature on previous attempts to address these issues, develop performance metrics to gauge datacenter sustainability, and finally, propose common strategies for reducing CO2 emissions. Finally, they offer a framework based on our research into a small number of purportedly environmentally friendly datacenters, which hope will shed light on the specific ways in which these facilities accomplish their sustainability goals, such as lowering their carbon emissions, increasing the diversity of their energy sources, and decreasing their e-waste output[32].

Deng, Cao and Li (2023), centres on a supply chain where a producer with little capital and a merchant with plenty of cash are involved. Stackelberg game theory may help manufacturers and merchants figure out the best way to reduce carbon emissions percentage-wise when it comes to bank financing, zero-interest early payment, and in-house factoring. At last, they discover that the best profit for the retailer (maker) is shaped like a U when it comes to the price sensitivity of commodities. The proportion of carbon emissions reduction and the financial decisions made by supplier chains are related in a quadratic fashion. Options for funding the equilibrium of a supply chain are monotonically affected by carbon emission trading pricing. An rise in the carbon emission trading price makes internal financing more attractive when carbon emissions are within the norms[33].

Zhang et al. (2023), contributes to advancing the accounting and management of carbon emission data for power grid enterprises, while offering research methodologies and insights to aid power grid enterprises in their pursuit of carbon peak and carbon neutrality. Therefore, this paper first establishes a decarbonization model grounded in changes in

physical quantities before and after the application of diverse technologies, alongside their associated carbon emission reduction factors. The research revolves around methods used to measure carbon emission reductions resulting from diverse carbon emission reduction measures, such as the enhancement of building energy efficiency and clean energy utilization, the control of SF6 emissions, and the adoption of clean energy within the transportation sector[34].

Zhang, Xia and Yang (2022), a methodology for computation that is appropriate for assessing the carbon emissions of Chinese power grid firms' supplier chains. This method can determine the true carbon emissions from power grid companies' supply chains, which can improve their green transformation capabilities, lead to more efficient energy supply chain green transformation, and support the national double carbon strategy[35].

Ji et al. (2022), suggests measures such as carbon emissions per kilowatt-hour and the energy carbon neutralisation index, develops a model to maximise carbon emissions by the regional power grid, and maximises unit production using the primordial dual interior point method. Optimisation of the self-owned power plant and the unified dispatching unit are the two main components of a regional power grid's daily operations that contribute to the calculation of carbon emission reductions. The results demonstrate that the carbon emission indicators suggested in this paper accurately represent the regional power grid's carbon emission level, that the optimisation model for carbon emissions is accurate and dependable, and that the optimisation strategy's outputs can serve as a valuable guide for power grid regulators aiming to reduce carbon emissions[36].

TABLE I. SUMMARY OF LITERATURE REVIEW BASED ON CARBON EMISSION REDUCTION

Reference	Study Focus / Approach	Key Findings	Challenges	Future directions
Cao et al., 2024	Holistic approach to data center sustainability, evaluation using multi-faceted metrics and real-world data center ratings.	Propose 5-dimensional sustainability metrics, review evolving standards (e.g., Singapore), and emphasize a forward-looking sustainable vision.	Standardization of sustainability metrics; lack of global benchmarks.	Propose a multi-dimensional framework using sustainability metrics and public data; suggest evolving standards like those in Singapore.
Fatima and Ehsan, 2023	Environmental impact analysis of data centers, literature survey, and proposal of a sustainability framework.	Identified CO_2 emission sources, reviewed sustainability performance metrics, analyzed green data centers.	Complexity in tracing all environmental factors and sustainability indicators.	Recommend a framework for sustainable design based on case studies of green data centers; emphasize strategies for CO_2 and e-waste reduction.
Deng, Cao and Li, 2023	Supply chain financing under carbon reduction regulations using Stackelberg game theory.	U-shaped profit relationship with price sensitivity; internal financing favored as carbon trading prices rise.	Modeling real-world financial decisions with theoretical assumptions.	Suggest exploring the dynamic impact of carbon pricing on financing decisions; highlight complex, non-linear decision patterns.
Zhang et al., 2023	Decarbonization modeling for power grid enterprises using physical changes and emission reduction factors.	Provides a practical carbon accounting model; supports strategies for energy efficiency, clean energy, and SF_6 emission control.	Complexity in modeling multiple reduction technologies accurately.	Recommend development of decarbonization models using physical-technical relationships; emphasize role of technology deployment.
Zhang, Xia and Yang, 2022	Carbon emission calculation method for power grid enterprise supply chains in China.	Developed accurate emission tracking to support green transformation strategies.	Data collection and integration across large supply chains.	Call for robust carbon tracking systems to support green transformation and alignment with national climate strategies.
Ji et al., 2022	Regional power grid carbon optimization model using carbon emission per kWh and dual interior point method.	Proved effectiveness of carbon emission indicators; optimized dispatching to reduce emissions.	Real-time optimization under dynamic grid conditions.	Encourage deeper integration of carbon indicators into grid dispatch models for effective regulatory planning and emissions control.

VI. CONCLUSION AND FUTURE WORK

As data centers continue to underpin global digital infrastructure, their escalating energy demands and environmental impact present critical sustainability challenges. Reducing carbon emissions in data centre settings has been the objective of this paper's rigorous assessment of modern technology and operational tactics. There is significant opportunity to improve energy efficiency and decrease the sector's carbon footprint via the implementation of critical interventions including virtualisation, energy-efficient hardware, integration of renewable energy, and improved cooling systems. Additionally, performance metrics like PUE, CUE, and WUE, along with best practices including

green certifications and carbon monitoring, offer practical frameworks for evaluating and guiding sustainable operations. A number of obstacles still stand in the way of attaining carbon-neutral data centre operations, notwithstanding notable advancements. A number of obstacles still stand in the way of attaining carbon-neutral data centre operations, notwithstanding notable advancements. However, the lack of standardized evaluation frameworks and insufficient industry-wide adoption of best practices limit the full realization of these sustainability goals.

Future work should focus on the integration of AI-driven energy management systems, real-time sustainability analytics, and the development of globally harmonized carbon reporting standards. Furthermore, interdisciplinary research combining computer science, environmental science, and economics is needed to assess the long-term trade-offs between performance, cost, and environmental impact. Policymaker engagement and industry-wide collaboration will also be crucial in driving the adoption of sustainable practices.

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