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Sustainable Energy Data Centres: A Holistic Conceptual Framework for Design and Operations

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Abstract: Data Centres serve as the foundation for digital technologies in the energy sector, enabling advanced analytics, optimization, and automation. However, their rapid growth can exert a substantial influence on the environment due to their energy consumption, water utilization, and production of electronic waste. This research begins with an energy overview of the setup and operations of data centres, highlighting their key components and infrastructure, and emphasizing their crucial role in managing energy resources and driving the energy sector's digital technologies. Building upon this understanding, a holistic framework is proposed to tackle energy sustainability concerns in data centres, with a focus on energy-related aspects. The framework places emphasis on three primary sustainability metrics, namely energy efficiency, water consumption, and waste management. It underscores the significance of green building design principles and energy-efficient equipment as crucial constituents of sustainable data centre infrastructure. The framework delineates optimal energy operational best practices encompassing virtualization and consolidation, effective cooling tactics, and energy management and monitoring, all aimed at reducing energy consumption and enhancing energy performance. Furthermore, the framework emphasizes the significance of incorporating energy-related sustainability metrics into decision-making procedures and adhering to regulatory standards for energy efficiency. Through adherence to this framework, data centres' environmental impact can be mitigated and a positive contribution towards a sustainable future can be made, particularly in the realm of energy conservation and optimization.

Keywords: data centres; sustainable IT infrastructure; sustainability; digitalization; energy efficient design; advanced sustainability metrics

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1. Introduction

In recent years, the energy industry has faced significant challenges related to climate change, increasing energy demand, and the growing need to ensure security and reliability in energy supply. These challenges have led to a radical transformation in the structure of the energy sector, with an increasing emphasis on sustainability and the integration of innovative and renewable technologies [1]. As the energy system evolved, it encompassed power generation, transmission, and distribution, with Transmission System Operators (TSOs) delivering energy to customers and Distribution System Operators (DSOs) serving end-users [2]. Traditional electricity grids had limited capabilities, allowing only one-way communication and energy exchange, minimal storage, and passive loads. However, modern technology has given rise to smart grids, which integrate information and communication technology (ICT) for enhanced efficiency, resilience, and intelligence. These smart grids utilize real-time data for intelligent analysis, increasing reliability and facilitating the incorporation of renewable sources into the grid [3]. In response to the urgency of climate change, the European Commission introduced the European Green Deal (EGD), an ambitious strategy aimed at cutting carbon emissions by 55% by 2030 and achieving carbon neutrality by 2050 [4]. The energy transition focuses on substituting fossil fuels with renewable energy sources (RES) and is guided by the "3 D's" concept: decarbonization, decentralization, and digitalization. Digitalization plays a crucial role in supporting electrification and decentralization within the energy sector [5]. Consumer expectations from energy suppliers are evolving, with an emphasis on sustainability, reliability, simplicity, customization, and control. Therefore, the increasing demand for energy and shifting customer preferences make the energy sector more complex, competitive, and uncertain. By embracing digital transformation and integrating digital technologies, energy companies can overcome these challenges and enhance sustainability. These technologies optimize the operation of renewable and other energy sources, improving efficiency and dependability.

In [6], critical digital technologies have been identified that contribute to increased renewable energy use, including the Internet of Things (IoT), artificial intelligence and big data, and blockchain. Additionally, Lyu et al. [7] have highlighted emerging digital technologies that impact the energy sector, such as robotics and cloud computing. By leveraging these digital solutions, the energy sector can transition to a more sustainable and efficient future.

The growth of digitalization in the energy sector, as well as other sectors such as telecommunications, e-commerce, cloud computing, and IoT (Internet of Things), has resulted in a significant increase in data generation and storage requirements. This, in turn, has driven the demand for data centres to accommodate the expanding digital infrastructure. However, data centres are power-intensive facilities as they require a continuous supply of electricity to operate their equipment and maintain optimal conditions for data storage. The energy consumption of data centres has become a focus of attention due to environmental concerns and the need for energy-efficient solutions. Thus, the expansion of data centres has raised concerns regarding their impact on environmental sustainability, as they can lead to high greenhouse gas emissions and a negative impact on water resources and air quality. Therefore, it is essential to ensure that data centres are designed and managed sustainably to minimize environmental impact and maximize energy efficiency [8].

This study aimed to deepen our understanding of the environmental impacts of data centres and identify existing best practices by conducting a comprehensive literature review. The analysis enabled us to identify key challenges and opportunities associated with data centre sustainability and determine the most promising solutions to address them. Strategies and measures such as incorporating renewable energy sources, improving energy efficiency, reducing ecological footprints, and adopting sustainable design and management approaches have been implemented to promote data centre sustainability. However, to effectively tackle this challenge, it is crucial to adopt a holistic and systemic approach that considers all aspects of data centre sustainability and their interconnectedness.

The primary contribution of this research is centred around the creation of a comprehensive conceptual framework that incorporates best practices and operational guidelines to facilitate the implementation of sustainable data centres. Throughout the development of this framework, an extensive review and analysis of the existing literature was conducted to identify and select relevant metrics specifically pertaining to sustainable data centres. Importantly, our framework distinguishes itself by providing an integrated approach that effectively incorporates and synthesizes these metrics, setting it apart from other existing frameworks in the field. To better clarify the differences between the framework proposed in this research compared to the previous models, Table 1 offers a comprehensive comparison of the different metrics considered. The proposed framework embraces a variety of sustainability aspects within data centres, making it more extensive and integrative than the ones before. Each of the metrics, while individually valuable, contributes to a nuanced understanding of data centre sustainability when considered as part of a cohesive framework. These include critical areas such as energy efficiency, water consumption, waste management, and renewable energy utilization. By encapsulating a wider range of sustainability metrics, our framework promotes the exploration and application of innovative strategies and best practices. The aim is to reduce the environmental footprint of data centres significantly while upholding, if not enhancing, their operational efficiency. This framework, by integrating these diverse and vital sustainability metrics, provides a more holistic approach to appraise and augment the sustainability of data centres.

Table 1. Comparison of existing frameworks with the proposed framework, based on sustainability metrics.

Reference	PUE	DCiE	CUE	WUE	WRecR	ERR	WRedR	WHRE	WHP
Green Grid 2007 [9]	Yes	Yes	No	No	No	No	No	No	No
Green Grid 2010 [10]	Yes	No	Yes	No	No	No	No	No	No
Green Grid 2011 [11]	Yes	No	No	Yes	No	No	No	No	No
Capozzoli et al. [12]	Yes	Yes	Yes	Yes	No	No	No	No	No
Da Costa et al. [13]	Yes	No	Yes	No	No	Yes	No	No	No
Sivathanu et al. [14]	Yes	No	No	No	Yes	No	Yes	No	No
This study	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

This comprehensive approach to sustainability not only delivers valuable insights for data centre operators and policymakers but also establishes a foundation for further research and development in the field of sustainable data centre design and management. By considering a wider array of metrics within a single framework, stakeholders can more effectively evaluate and prioritize their efforts to create greener and more sustainable data centres, ultimately contributing to a more environmentally responsible energy sector.

The remainder of the paper is structured as follows: Section 2 introduces the relationship between the use of digital technologies and environmental sustainability. In Section 3, the main issues concerning the energy expenditure of data centres are highlighted. Section 4 presents the developed framework and its characteristics. Finally, discussion and concluding remarks are provided in Section 5.

2. Impacts of Digital Technologies on Environmental Sustainability

Considering the holistic concept of sustainability encompassing social, economic, and environmental aspects, our research specifically emphasizes the environmental dimension within the context of data centres. By narrowing our scope to environmental sustainability, we aim to tackle the challenges and seize the opportunities associated with reducing ecological footprints, enhancing energy efficiency, and fostering sustainable practices within the data centre industry. Environmental sustainability involves maintaining a high level of environmental quality over the long term by ensuring that resource exploitation and pollution emissions occur at a pace that does not exceed the environment's capacity to regenerate and process them. In a sustainable human system, the rate of renewable resource exploitation must be lower than their regeneration rate, and the intake of pollutants and waste should not surpass the environment's carrying capacity—its ability to absorb and process these contaminants [15]. In the context of the energy sector, achieving environmental sustainability means offsetting the depletion of nonrenewable resources by replacing them with renewable resources, thus maintaining a balanced and sustainable relationship with the environment. By prioritizing sustainable development policies and practices, the energy sector can contribute to a greener and more sustainable future. The negative impacts of digital technologies on the environment, particularly within the energy sector, remain inadequately examined and understood. Extensive energy resource consumption has resulted in significant ecological consequences, such as acid rain, environmental pollution, and global warming. Furthermore, the utilization of sensors, supercomputers, data analysis, and cloud-based AI has facilitated the extraction and processing of fossil fuels [16]. It is crucial to consider potential adverse environmental effects, as the increased efficiency of fossil-fuel power plants may inadvertently hinder the transition to sustainable power sources. This challenge poses an additional obstacle in reducing CO2 emissions and achieving environmental sustainability [17]. Considering these concerns, this study will concentrate on the data centres that support these digital technologies. Through an in-depth analysis of their roles and impacts on the energy sector and the environment, the research aims to offer a comprehensive understanding of the relationship between data centres and sustainability. Ultimately, this investigation will lay the groundwork for developing a robust framework that addresses and mitigates the environmental challenges associated with data centre operations.

3. Data Centres and Energy Consumption

The International Energy Agency (IEA) reported that data centres accounted for approximately 1% of global electricity consumption in 2020, with projections to rise to 1.2% by 2025. Furthermore, data centres were responsible for 0.3% of global greenhouse gas (GHG) emissions in 2020, which is expected to increase to 0.4% by 2025. However, these estimates vary depending on the methodology and assumptions made, with some studies suggesting higher or lower energy consumption and GHG emissions. Data centres' environmental impacts also differ based on factors such as location, energy sources, and efficiency measures [18,19]. Energy efficiency is a critical consideration in designing data centres, driven by the cost of electricity consumed by IT equipment and cooling and power supply systems. Data centres, built specifically to accommodate high-density computing equipment, can have considerable energy consumption and carbon emissions due to the sheer number of devices. The United States data centres, in 2007, consumed approximately 1.5% of total energy, costing around USD 4.5 billion and resulting in high carbon emissions. It is crucial to note that computing and storage devices are not the sole energy consumers in data centres. Essential subsystems include IT infrastructure, cooling infrastructure, electricity infrastructure, security and compliance, edge computing, and micro data centres [20]. Modern data centres have witnessed significant advancements in IT, cooling, and electricity infrastructures, with virtualization, cloud computing, software-defined networking (SDN), network function virtualization (NFV), and hyper-converged infrastructure (HCI) being adopted. Modelling IT equipment is essential for thermal and flow simulations in air-cooled data centres. This study explores a porous zone model for accurate pressure loss calculations in server components, which is vital for data centre design safety [21]. Cooling technologies have evolved to be more energy-efficient, utilizing outside air and liquid cooling. In data centre cooling, studies highlight thermal management as a key area for reducing energy consumption. It is found that maintaining uniform hot and cold air distribution in air cooling systems and adjusting tile porosity can conserve energy. For liquid and free cooling systems, optimization of factors like climate conditions, system design, coolant type, and flow rate are vital. Such considerations can notably improve the Power Usage Effectiveness (PUE) of these systems [22]. Data centre infrastructure management (DCIM) tools help monitor and optimize cooling systems in real-time, while electricity infrastructure improvements include power distribution, backup systems, and renewable energy sources. Security, compliance, edge computing, and micro data centres also play crucial roles in data centre operations [23]. Examples of technological advancements that improve energy efficiency can be found in other industries. For instance, a study at the National Centre of Excellence for Food Engineering reported that a continuous flow ohmic heater (CFOH) significantly reduced energy consumption compared to traditional heating methods. The CFOH reached an energy efficiency conversion of up to 87.9%, with the potential for further improvement using advanced process controls [24]. Analogously, innovative technologies in data centres can significantly enhance energy efficiency and sustainability. Additional energy consumption is caused by lights, power distribution losses, and other electrical devices such as an uninterruptible power supply (UPS). In other words, the bulk of energy consumption within a data centre is not utilized to power genuine IT services. To achieve optimum efficiency in power consumption and CO2 emissions, each of these devices must be built and utilised in a manner that minimizes their carbon footprint. Minimizing energy consumption in data centres requires an examination of each device's carbon footprint and the energy used for cooling and other overheads. By calculating energy consumption and evaluating its effective use against waste, data centres can optimize their efficiency, reducing their environmental impact and contributing to a more sustainable future [25].

4. The Proposed Framework

The structure of the framework for Environmental Sustainability Metrics for data centres (Figure 1) is organized as follows. Firstly, the framework outlines four key environmental sustainability metrics, which are energy efficiency, water usage, waste heat, and waste management. Secondly, it presents two components of data centre infrastructure, green building design principles and energy-efficient equipment, that are critical for achieving sustainability goals. Thirdly, the framework provides operational best practices, including virtualization and consolidation, efficient cooling strategies, and energy management and monitoring. Fourthly, the framework emphasizes the importance of integrating sustainability metrics in decision-making processes, such as performance tracking and reporting, and continuous improvement. Lastly, the framework includes regulatory compliance and certifications as a key component to ensure that data centres meet environmental sustainability standards.

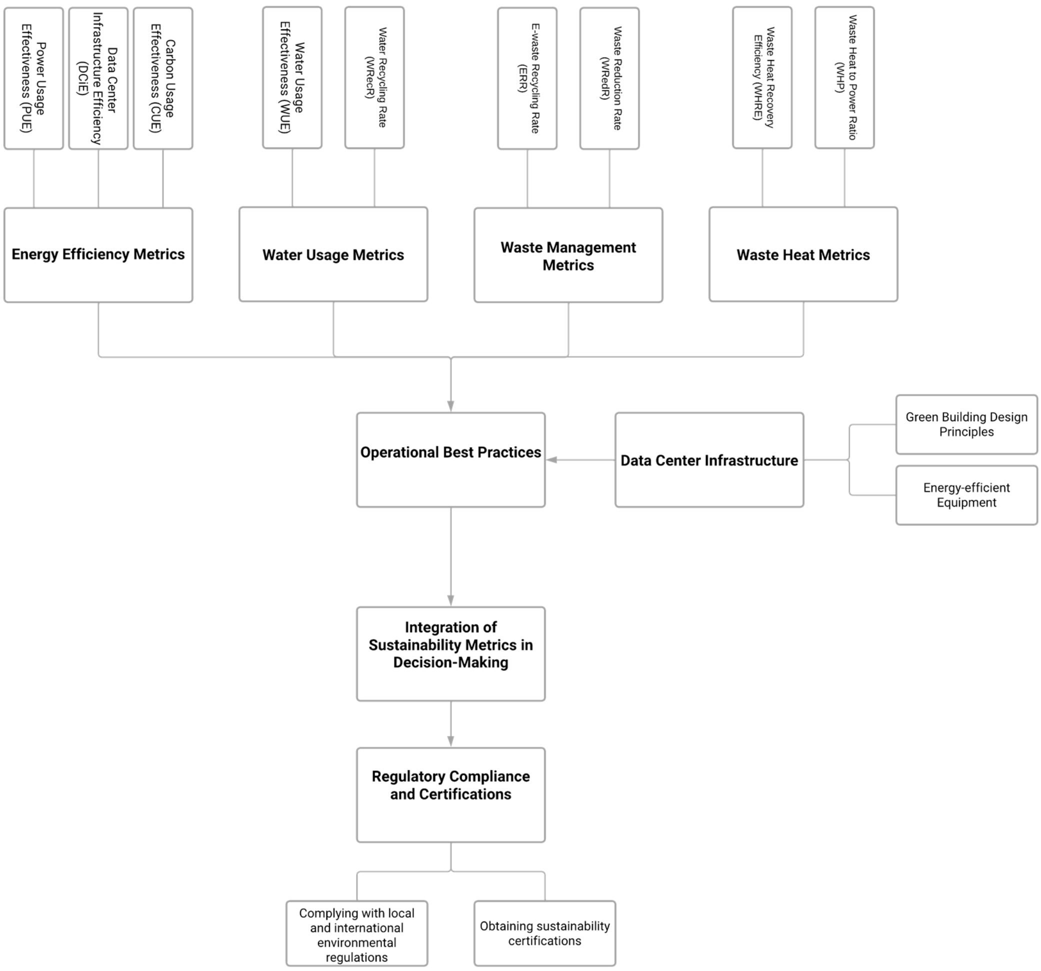

Figure 1. Framework for Environmental Sustainability Metrics for Data Centres.

Below are all the elements of the framework, including the concepts already mentioned regarding not only energy but also environmental impact. The elements of the framework are thus listed and displayed for better understanding.

4.1. Key Environmental Sustainability Metrics

Key Environmental Sustainability Metrics for a data centre are quantitative measures used to track and evaluate the environmental impact of data centre operations. These metrics can include energy consumption, water usage, greenhouse gas emissions, waste generation, and other environmental indicators. By monitoring these metrics, data centre operators can identify areas for improvement and make informed decisions that prioritize sustainability. The selection of key environmental sustainability metrics is critical for effective sustainability management in data centres.

According to the International Energy Agency (IEA), data centres consumed about 1% of the world's total electricity consumption in 2020, which amounts to approximately 200–210 TeraWatt-hours (TWh) of electricity [18]. Water is often used in data centres for cooling purposes. A 2019 report by the National Renewable Energy Laboratory (NREL) estimated that U.S. data centres consumed about 628 billion litres (166 billion gallons) of water in 2014. Globally, water consumption by data centres is difficult to quantify due to the lack of comprehensive data, but it is likely to be significantly higher [26]. Electronic waste, or e-waste, is a significant concern for data centres, as they frequently replace and upgrade equipment. The Global E-Waste Monitor 2020 report estimated that the world generated 53.6 million metric tons of e-waste in 2019, with the data centre industry contributing to a portion of this figure. However, the exact amount of e-waste generated specifically by data centres is difficult to determine [27].

The metrics proposed in the Table 2 are specific, measurable, and relevant to the data centre's operations, goals, and regulatory requirements. They should also be regularly monitored, analyzed, and reported to stakeholders, such as clients, regulators, and investors, to ensure transparency and accountability.

Table 2. Holistic Framework Metrics for Sustainable data centres.

	Metrics	Formula	Function
Energy Efficiency Metrics	PUE	$PUE = \frac{Total\ facility\ consumption}{IT\ equipment\ energy}$	Compare the energy consumption of computing applications and infrastructure equipment with the energy consumption of IT equipment.
	DCiE	$DCiE = \frac{IT\ equipment\ energy}{Total\ facility\ energy}$	Determine the proportion of data centre power consumption.
	CUE	$CUE = \frac{Total\ GHG\ emissions}{IT\ equipment\ energy}$	Assess the data centre's overall GHG emissions and IT equipment energy usage.
Water Usage Metrics	WUE	$WUE = \frac{Annual\ site\ water\ usage}{IT\ equipment\ energy}$	Measure the data centre's water efficiency.
	WRecR	$WRecR = \frac{Total\ recycled\ fresh\ water}{Total\ recycled\ freshwater\ withdrawal}$	Measure the percentage of water that is recycled or reused within the data centre, reducing freshwater consumption.
Waste Management Metrics	ERR	$ERR = \frac{Total\ weight\ of\ all\ recycled\ materials}{Total\ weight\ of\ e - waste\ treated}$	Measure the percentage of electronic waste generated by the data centre that is recycled or properly disposed of, reducing environmental pollution.
	WRedR	$WRedR = \frac{Wasted\ raw\ material\ (period\ a)}{Wasted\ raw\ material\ (period\ b)}$	Measure the reduction in waste generation over time, indicating the effectiveness of waste management practices.
Waste Management Metrics	WHRE	$WHRE = \frac{Recovered\ Waste\ Heat}{Total\ Waste\ Heat\ Generated} \times 100$	Measure the percentage of waste heat generated by the data centre's IT equipment that is captured and reused for other purposes.
	WHP	$WHP = \frac{Energy\ Generated\ from\ Waste\ Heat}{Energy\ Used\ by\ IT\ Equipment}$	Measure the ratio of energy generated from the waste heat recovery process to the energy used by IT equipment

4.1.1. Energy Efficiency Metrics

1. Power Usage Effectiveness (PUE) measures the ratio of total data centre energy consumption to the energy used by IT equipment [28]. A lower PUE indicates better energy efficiency;
2. Data Centre Infrastructure Efficiency (DCiE) is the inverse of PUE, representing the percentage of energy used by IT equipment compared to the total energy consumption [29];
3. Carbon Usage Effectiveness (CUE) measures the greenhouse gas emissions generated per unit of IT equipment energy consumption [29], helping to quantify the data centre's carbon footprint.

4.1.2. Water Usage Metrics

1. Water Usage Effectiveness (WUE) measures the ratio of total data centre water consumption to the energy used by IT equipment [30]. A lower WUE indicates better water efficiency;
2. Water Recycling Rate (WRecR) measures the percentage of water that is recycled or reused within the data centre, reducing freshwater consumption [31].

4.1.3. Waste Management Metrics

1. E-waste Recycling Rate (ERR) measures the percentage of electronic waste generated by the data centre that is recycled or properly disposed of, reducing environmental pollution [32];
2. Waste Reduction Rate (WRedR) measures the reduction in waste generation over time, indicating the effectiveness of waste management practices [33].

4.1.4. Waste Heat Metrics

1. Waste Heat Recovery Efficiency (WHRE) measures the percentage of waste heat generated by the data centre's IT equipment that is captured and reused for other purposes, such as heating adjacent buildings or preheating water [34]. A higher WHRE indicates better utilization of waste heat, reducing energy consumption and improving overall efficiency;
2. Waste Heat to Power Ratio (WHP) measures the ratio of energy generated from the waste heat recovery process to the energy used by IT equipment [35]. A higher WHP indicates a more effective conversion of waste heat into usable energy, contributing to a more sustainable and efficient operation of the data centre.

4.2. Data Centre Infrastructure

A data centre infrastructure is the physical and virtual infrastructure that supports the operation of a data centre. It includes all the hardware, software, and network components necessary to support the processing, storage, and delivery of data and applications. Data pertaining to this infrastructure necessitates an intricate understanding of the data centre's configuration, coupled with detailed operational information. These data can be procured through various avenues. Initial data can be drawn from specifications and performance metrics provided by hardware and software vendors. Organizations running data centres typically employ monitoring systems, capturing operational data such as power usage, cooling needs, and equipment performance metrics, in real-time. This information forms a bedrock of insight into the actual functioning of the data centre. Additionally, external audits or assessments can yield significant data, particularly pertaining to compliance with environmental and energy efficiency standards. Some instances also allow data procurement from published case studies or industry reports. It must be acknowledged, however, that data privacy and security considerations may influence the accessibility of certain data types. Hence, the acquisition of such data could potentially necessitate collaboration with data centre operators.

4.2.1. Green Building Design Principles

When choosing a location for a data centre, it is essential to consider the ecological impact of the site. Site selection and ecology involve choosing sites that minimize the data centre's impact on the environment. This can include selecting previously developed land or brownfield sites rather than pristine greenfield sites. Brownfield sites, in particular, can be ideal for data centre development as they have already been developed and have existing infrastructure in place, reducing the need for additional construction and infrastructure development. By choosing a suitable site, data centre developers can minimise the environmental impact of their operations. Another key consideration when designing a data centre is the use of energy-efficient building materials. Energy-efficient building materials can include insulation, low-emissivity windows, and other materials that reduce energy consumption. By using these materials, data centres can reduce their energy consumption, thereby minimising their carbon footprint and reducing operating costs. In addition, energy-efficient materials can also contribute to a more comfortable and healthier working environment for staff. Finally, natural lighting and ventilation are important considerations when designing a data centre. By maximising the use of natural daylight and airflow, data centres can reduce their energy consumption for lighting and cooling. This can be achieved using skylights, windows, and other design features that maximise natural light and ventilation. By taking advantage of natural lighting and ventilation, data centres can create a more sustainable and energy-efficient operating environment [36–39].

4.2.2. Energy-Efficient Equipment

As the demand for technology and data storage continues to grow, data centres are becoming an increasingly important part of our digital infrastructure. However, data centres also consume a significant amount of energy and contribute to greenhouse gas emissions. In response to these challenges, data centre operators are adopting a range of strategies to improve their energy efficiency and reduce their environmental impact. Three key strategies are the use of high-efficiency servers and storage systems, efficient cooling systems, and renewable energy sources. High-efficiency servers and storage systems are designed to consume less energy while maintaining the same performance as traditional equipment. This is achieved through the use of more efficient components, such as low-power processors and solid-state drives. By using high-efficiency equipment, data centres can significantly reduce their energy consumption, which not only reduces their carbon footprint but also lowers operating costs. Another important consideration for data centres is cooling. Traditional air conditioning systems can be extremely energy-intensive, consuming a significant portion of a data centre's total energy usage. However, there are several alternative cooling systems that are more energy-efficient. For example, evaporative cooling uses water to cool the air and can be much more efficient than traditional air conditioning. Free cooling is another option that takes advantage of cooler outdoor temperatures to cool the data centre without the need for air conditioning. By adopting these more efficient cooling systems, data centres can reduce their energy consumption and lower their carbon footprint. Renewable energy sources, such as solar or wind power, are another key strategy for reducing the environmental impact of data centres. By using renewable energy sources, data centres can reduce their reliance on fossil fuels and decrease their greenhouse gas emissions. In addition to reducing their carbon footprint, using renewable energy sources can also help data centres to achieve energy independence and reduce their exposure to fluctuating energy prices [40–43].

4.3. Operational Best Practices

Operational best practices for a data centre refer to the set of guidelines, procedures, and policies that are designed to optimize the performance, efficiency, and reliability of a data centre. These best practices are developed based on industry standards, practical experience, and proven methodologies, and are aimed at ensuring that data centres operate at their best, meeting the needs of users and customers. The implementation of operational best practices for a data centre involves a wide range of activities, including maintenance and monitoring of the physical infrastructure, management of the IT equipment, and implementation of security measures. It also involves developing and implementing procedures for managing power and cooling, handling equipment failures, and managing changes to the IT environment.

4.3.1. Virtualization and Consolidation

Data centres are adopting various strategies to improve their efficiency, including server and storage virtualization and efficient use of resources. Server and storage virtualization involves using software to simulate multiple virtual servers or storage devices on a single physical device. This technology can significantly improve resource utilization by allowing a single physical device to function as multiple virtual devices. By doing so, the data centre can make more efficient use of its resources, reducing the number of physical servers and storage devices required, and lowering energy consumption and space requirements. This can result in lower operating costs, reduced carbon footprint, and increased efficiency. Another key strategy for improving data centre efficiency is the efficient use of resources. This entails monitoring and optimizing IT equipment usage to minimize energy consumption and waste generation. By regularly monitoring equipment usage, data centre operators can identify areas where resources are being wasted or used inefficiently. This information can be used to develop strategies to optimize resource utilization, such as adjusting cooling systems to match actual equipment loads or consolidating equipment to reduce power usage. Efficient resource utilization not only reduces the environmental impact of data centres but can also improve the bottom line. By optimizing the use of resources, data centres can reduce operating costs, improve performance, and extend the life of their equipment. Furthermore, by adopting these best practices, data centres can position themselves as leaders in sustainability and attract environmentally conscious customers [44,45].

4.3.2. Efficient Cooling Strategies

One of the key considerations when designing a data centre is cooling, as this can consume a significant amount of energy. Two popular cooling technologies that are gaining traction in the industry are free cooling systems and liquid cooling systems. Free cooling systems are designed to use outside air or water to cool the data centre when ambient conditions allow, reducing energy consumption. These systems work by taking advantage of the cooler temperatures outside to cool the data centre, instead of relying solely on traditional air conditioning systems. By using outside air or water, free cooling systems can reduce the amount of energy required to cool the data centre and can significantly lower operating costs. In addition to being energy-efficient, free cooling systems are also environmentally friendly, as they reduce the carbon footprint of the data centre. Another cooling technology that is gaining popularity is liquid cooling systems. Liquid cooling systems use liquids like water or dielectric coolants to absorb and dissipate heat more efficiently than air-based systems. Liquid cooling can be used to cool both the IT equipment and the data centre infrastructure itself, such as the power distribution units and batteries. By using liquid cooling systems, data centres can significantly reduce their energy consumption, lower their operating costs, and improve their overall performance. Both free cooling systems and liquid cooling systems are viable options for data centres looking to improve their energy efficiency and reduce their carbon footprint. While each technology has its own unique benefits and challenges, they both represent important steps towards creating more sustainable and energy-efficient data centres [46–51].

4.3.3. Energy Management and Monitoring

Two key strategies for achieving energy efficiency in data centres are real-time energy monitoring and energy efficiency benchmarks. Real-time energy monitoring involves tracking energy consumption throughout the data centre in real-time, identifying inefficiencies and opportunities for improvement. This can be achieved through the use of energy management software and hardware, which can monitor and analyze data on energy usage across the entire data centre infrastructure. By monitoring energy usage in real-time, data centre operators can identify areas where energy is being wasted or used inefficiently and take corrective action. This can include measures such as adjusting cooling systems or optimizing the use of IT equipment. Another key strategy for achieving energy efficiency in data centres is the use of energy efficiency benchmarks. These benchmarks provide performance targets for data centres, encouraging continuous improvement in energy efficiency. Benchmarks can be developed based on industry standards, best practices, or the data centre's own historical performance. By setting benchmarks and regularly monitoring performance against them, data centre operators can identify areas for improvement and measure progress towards their energy efficiency goals. By adopting these best practices, data centre operators can significantly reduce their energy consumption and carbon footprint, while also improving their profitability [46,52–54].

4.4. Integration of Sustainability Metrics in Decision-Making

The integration of sustainability metrics in decision-making for a data centre involves incorporating environmental and social factors into the decision-making process. This can include assessing the environmental impact of data centre operations, identifying opportunities for improvement, and making decisions that prioritize sustainability.

Performance Tracking and Reporting

Data centre operators are adopting various strategies, including regular monitoring of sustainability metrics and transparent reporting of these metrics to stakeholders.

Regular monitoring of sustainability metrics involves collecting and analyzing data on energy consumption, water usage, and waste management performance over time. By monitoring these metrics, data centre operators can identify trends, identify areas for improvement, and track progress towards sustainability goals. This can include measures such as tracking energy consumption in real-time, analyzing water usage patterns, and implementing waste reduction initiatives. By regularly monitoring sustainability metrics, data centre operators can identify opportunities for improvement and make informed decisions that prioritize sustainability. Transparent reporting of sustainability metrics to stakeholders is another important strategy for improving sustainability performance in data centres. This involves communicating sustainability performance to stakeholders such as clients, regulators, and investors. Transparent reporting helps demonstrate the data centre's commitment to sustainability, facilitates informed decision-making, and enhances accountability. It can also help to establish trust with stakeholders, as they can see the data centre's performance over time and assess its sustainability efforts [55].

4.5. Regulatory Compliance and Certifications

Complying with local and international environmental regulations ensures that data centres meet minimum environmental performance standards and avoid potential penalties. Obtaining sustainability certifications, such as LEED (Leadership in Energy and Environmental Design), ENERGY STAR, or ISO 14001, demonstrates a data centre's commitment to sustainability and provides a competitive advantage in the market [55].

5. Discussion and Conclusions

Digital infrastructure has become a vital part of modern society, enabling us to communicate, work, and socialize on a scale never seen before. However, this growth has come with significant environmental costs, and data centres are increasingly being recognized as major contributors to greenhouse gas emissions and other forms of pollution due to their significant energy consumption, high water usage, and generation of electronic waste. In this context, the framework proposed in this study is of crucial importance. It offers a holistic and integrative approach that seeks not only to improve energy efficiency but also to promote a more sustainable and responsible operation of data centres. It transcends the conventional focus on technological solutions and incorporates broader environmental dimensions, encouraging a shift in how we perceive and manage these infrastructures. To address these issues, adopting environmental sustainability metrics in data centres has become essential for managing and reducing their environmental impact while meeting the growing demand for digital services. One innovative approach to further enhance sustainability is to consider establishing data centres in brownfields, repurposing underutilized or contaminated sites for new development, which can lead to additional environmental and economic benefits. Implementing the framework can lead to several benefits, such as reduced operating costs, enhanced corporate reputation, and compliance with environmental regulations.

By adopting sustainability metrics, data centres can gain insights into their environmental performance and identify opportunities for improvement. This can help them reduce their energy consumption, water usage, and waste generation, leading to lower operating costs and improved profitability. Moreover, adopting sustainability metrics can also enhance a data centre's reputation, positioning it as a leader in sustainability and attracting environmentally conscious customers. This can improve market share, increase customer loyalty, and create new business opportunities. Compliance with environmental regulations is another benefit of adopting sustainability metrics, ensuring that data centres are operating in accordance with local, regional, and national environmental laws. Encouraging data centres to continuously strive for improvement in sustainability performance is crucial to contributing to a greener and more sustainable future for the industry.

Incorporating brownfield development into data centre planning can bring additional advantages, such as reducing the need for new land, minimizing urban sprawl, and revitalizing contaminated or underutilized areas. This can be achieved through regular monitoring of sustainability metrics, implementation of best practices and new technologies, and collaboration with industry partners and stakeholders. Moreover, the framework's significance lies in its potential to drive systemic change within the industry. It encourages a proactive approach towards sustainability, fostering a culture of continuous improvement and innovation. It can guide data centres in their transition towards more sustainable operations, contributing to the mitigation of climate change and the promotion of a greener economy.

Therefore, the developed framework offers a comprehensive and all-encompassing approach to tackling sustainability issues in data centres. The framework presented places emphasis on four primary sustainability metrics, highlights the importance of incorporating green building design principles and utilizing energy-efficient equipment, and delineates operational best practices. This approach provides data centre operators with a lucid path towards achieving sustainable operations. Furthermore, the framework emphasizes the significance of incorporating sustainability metrics into decision-making procedures, adhering to regulatory norms, and considering brownfield development as a strategic option for sustainable growth. Through adherence to this framework, operators of data centres can mitigate their environmental impact and make a positive contribution towards a sustainable future.

In conclusion, it is important to acknowledge the limitations of this study, which will help guide future research and enhance the practical applicability of the proposed framework. Firstly, the study primarily focuses on the environmental aspects of sustainability within data centres, while recognizing the broader social and economic dimensions. This limitation stems from the intention to provide a focused analysis of the environmental impact of data centres and lay the groundwork for future exploration of other dimensions of sustainability. Secondly, the lack of specific use cases or empirical data is another limitation. The study is based on a conceptual analysis rooted in the existing literature, prioritizing the development of a comprehensive framework. While this approach provides valuable insights and a foundation for further research, future studies incorporating practical use cases can enhance the framework's applicability and validate its effectiveness in real-world scenarios. Additionally, the generalizability of the framework may be constrained due to the diverse nature of data centres and regional variations in regulatory environments and industry practices. Future research should consider tailoring the framework to specific contexts and conducting empirical studies to address this limitation. Furthermore, the study recognizes the challenges associated with the practical implementation of sustainability metrics, green building principles, and brownfield development within data centres. Overcoming financial constraints, technological limitations, and regulatory barriers requires further investigation and collaboration with industry partners and stakeholders. Lastly, while the framework presents a comprehensive approach, its long-term impact and effectiveness in achieving sustainable operations remain to be extensively assessed. Future research should focus on evaluating the real-world outcomes resulting from the adoption of the framework, tracking the environmental improvements achieved, and studying the extent to which the framework drives systemic change within the data centre industry. Future research can build upon this study and address the gaps, ultimately contributing to the practical implementation of sustainable practices in data centres and fostering a greener and more sustainable future.

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Abbreviations

List of metrics abbreviations used in the paper and their full definitions:

PUE	Power Usage Effectiveness
DCiE	Data Centre Infrastructure Efficiency
CUE	Carbon Usage Effectiveness
WUE	Water Usage Effectiveness
WRecR	Water Recycling Rate
ERR	E-waste Recycling Rate
WRedR	Waste Reduction Rate
WHRE	Waste Heat Recovery Efficiency
WHP	Waste Heat to Power Ratio

References

1. Zhang, R. Role of power electronics in Grid 3.0. *iEnergy* **2022**, *1*, 387–390. [CrossRef]
2. Bytyqi, A.; Gandhi, S.; Lambert, E.; Petrovic, N. A Review on TSO-DSO Data Exchange, CIM Extensions and Interoperability Aspects. *J. Mod. Power Syst. Clean Energy* **2022**, *10*, 309–315. [CrossRef]
3. Hu, J.; Vasilakos, A.V. Energy Big Data Analytics and Security: Challenges and Opportunities. *IEEE Trans. Smart Grid* **2016**, *7*, 2423–2436. [CrossRef]
4. Sikora, A. European Green Deal—Legal and financial challenges of the climate change. *ERA Forum* **2021**, *21*, 681–697. [CrossRef]
5. International Energy Agency. World Energy Outlook 2012. Available online: https://www.iea.org/reports/world-energy-outlook-2012 (accessed on 17 November 2012).
6. IRENA. Enabling Technologies. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Enabling-Technologies_Collection_2019.pdf (accessed on 12 September 2019).
7. Lyu, W.; Liu, J. Artificial Intelligence and emerging digital technologies in the energy sector. *Appl. Energy* **2021**, *303*, 117615. [CrossRef]
8. Javadpour, A.; Sangaiah, A.K.; Pinto, P.; Ja'fari, F.; Zhang, W.; Abadi, A.M.H.; Ahmadi, H. An energy-optimized embedded load balancing using DVFS computing in cloud data centers. *Comput. Commun.* **2023**, *197*, 255–266. [CrossRef]

9. The Green Grid. Green Grid Data Center Power Efficiency Metrics: PUE and DCiE. Available online: https://www.missioncriticalmagazine.com/ext/resources/MC/Home/Files/PDFs/TGG_Data_Center_Power_Efficiency_Metrics_PUE_and_DCiE.pdf (accessed on 15 February 2007).
10. The Green Grid. Carbon Usage Effectiveness (CUE): A Green Grid Data Center Sustainability Metric. Available online: https://www.thegreengrid.org/en/resources/library-and-tools/241-Carbon-Usage-Effectiveness-%28CUE%29%3A-A-Green-Grid-Data-Center-Sustainability-Metric (accessed on 2 December 2010).
11. The Green Grid. Water Usage Effectiveness (WUE): A Green Grid Data Center Sustainability Metric. Available online: https://www.thegreengrid.org/en/resources/library-and-tools/238-Water-Usage-Effectiveness-%28WUE%29%3A-A-Green-Grid-Data-Center-Sustainability-Metric- (accessed on 1 March 2011).
12. Capozzoli, A.; Pellerin, R.; Perino, M.; Serale, G. Environmental performance evaluation of large industrial data centers. *Energy Procedia* **2014**, *62*, 220–229.
13. Da Costa, G.; Lange, J.P.; Zilio, C. The design and management of data centers powered by renewable energy. *Comput. Commun.* **2018**, *129*, 87–102.
14. Sivathanu, S.; Leivadeas, A.; Papazoglou, M. A model for sustainable data center energy management. *J. Parallel Distrib. Comput.* **2018**, *120*, 240–252.
15. Daly, H.E. Sustainable development—Definitions, principles, policies. In *The Future of Sustainability*; Springer: Dordrecht, The Netherlands, 2006; pp. 39–53.
16. Wang, J.; Dong, K.; Sha, Y.; Yan, C. Envisaging the carbon emissions efficiency of digitalization: The case of the internet economy for China. *Technol. Forecast. Soc. Chang.* **2022**, *184*, 121965. [CrossRef]
17. International Energy Agency. Together Secure Sustainable Digitalization & Energy. Available online: https://www.iea.org/reports/digitalisation-and-energy (accessed on 14 November 2017).
18. International Energy Agency. Data Centres and Data Transmission Networks. Available online: https://www.iea.org/reports/data-centres-and-data-transmission-networks (accessed on 11 September 2022).
19. Masanet, E.R.; Brown, R.E.; Shehabi, A.; Koomey, J.G.; Nordman, B. Estimating the energy use and efficiency potential of U.S. data centers. *Proc. IEEE* **2011**, *99*, 1440–1453. [CrossRef]
20. Energy Star, E. Report to Congress on Server and Data Center Energy Efficiency Public Law 109-431. Available online: https://www.energystar.gov/ia/partners/prod_development/downloads/EPA_Report_Exec_Summary_Final.pdf (accessed on 2 August 2007).
21. Oluwole-ojo, O.; Zhang, H.; Howarth, M.; Xu, X. Energy Consumption Analysis of a Continuous Flow Ohmic Heater with Advanced Process Controls. *Energies* **2023**, *16*, 868. [CrossRef]
22. Xu, S.; Zhang, H.; Wang, Z. Thermal Management and Energy Consumption in Air, Liquid, and Free Cooling Systems for Data Centers: A Review. *Energies* **2023**, *16*, 1279. [CrossRef]
23. Shi, W.; Cao, J.; Zhang, Q.; Li, Y.; Xu, L. Edge Computing: Vision and Challenges. *IEEE Internet Things J.* **2016**, *3*, 637–646. [CrossRef]
24. Dogan, A.; Yilmaz, S.; Kuzay, M.; Yilmaz, C.; Demirel, E. CFD Modeling of Pressure Drop through an OCP Server for Data Center Applications. *Energies* **2022**, *15*, 6438. [CrossRef]
25. Greenberg, S.; Mills, E.; Tschudi, B.; Rumsey, P.; Myatt, B. Best practices for data centers: Lessons learned from benchmarking 22 data centers. In Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA, USA, 3 August 2006; pp. 76–87.
26. National Renewable Energy Laboratory (NREL). Estimating Data Center Water Use. Available online: https://www.nrel.gov/docs/fy15osti/62742.pdf (accessed on 16 January 2015).
27. Global E-Waste Monitor 2020. Global E-Waste Monitor 2020: Quantities, Flows, and the Circular Economy Potential. Available online: https://ewastemonitor.info/gem-2020/ (accessed on 12 July 2020).
28. Chu, W.X.; Wang, C.C. A review on airflow management in data centers. *Appl. Energy* **2019**, *240*, 84–119. [CrossRef]
29. Mastroianni, M.; Palmieri, F. Energy-aware Optimization of Data Centers and Cybersecurity Issues. In Proceedings of the 2022 IEEE Intl Conf on Dependable, Autonomic and Secure Computing, Intl Conf on Pervasive Intelligence and Computing, Intl Conf on Cloud and Big Data Computing, Intl Conf on Cyber Science and Technology Congress (DASC/PiCom/CBDCom/CyberSciTech), Falerna, Italy, 12–15 September 2022; pp. 1–7.
30. Lei, N. A Hybrid Physics-Based and Data-Driven Modeling Framework for Energy and Water Use Analysis of Data Centers with Spatio-Temporal Resolution. Ph.D. Thesis, Northwestern University, Evanston, IL, USA, 2022.
31. Zhu, X.; Jiang, W.; Liu, F.; Zhang, Q.; Pan, L.; Chen, Q.; Jia, Z. Heat to Power: Thermal Energy Harvesting and Recycling for Warm Water-Cooled Datacenters. In Proceedings of the 2020 ACM/IEEE 47th Annual International Symposium on Computer Architecture (ISCA), Virtual, 30 May–3 June 2020; pp. 405–418.
32. Mohiddin, S.K.; Suresh Babu, Y. Green Computing an Eco Friendly It Environment for Upcoming Technologies. In *Go Green for Environmental Sustainability*; CRC Press: Boca Raton, FL, USA, 2021; Volume 6, pp. 87–100.
33. Koronen, C.; Åhman, M.; Nilsson, L.J. Data centres in future European energy systems—Energy efficiency, integration and policy. *Energy Effic.* **2020**, *13*, 129–144.
34. Patel, C.D.; Sharma, R.K.; Bash, C.E.; Beitelmal, M.H. Energy Aware Computing through Probabilistic Switching: A Study of Tradeoffs. In Proceedings of the 17th IEEE Symposium on Mass Storage Systems, College Park, MA, USA, 27–30 March 2000.

35. Evans, R.; James, J.A.; Reda, S. Assessing the potential for data center waste heat recovery. *Energy Convers. Manag.* **2012**, *53*, 1–10.
36. Sodiq, A.; Baloch, A.A.B.; Khan, S.A.; Sezer, N.; Mahmoud, S.; Jama, M.; Abdelaal, A. Towards modern sustainable cities: Review of sustainability principles and trends. *J. Clean. Prod.* **2019**, *227*, 972–1001. [CrossRef]
37. Ezeokoli, N.I.; Nwankwo, E.E. Green building design principles: A quantitative study of architects' perception in Nigeria. *Archit. Eng. Des. Manag.* **2019**, *15*, 451–465.
38. Ali, M.; Rahnamayiezekavat, P. Environmental sustainability and energy-efficient building design: An integrated optimisation approach. *Energy Build.* **2020**, *211*, 109762.
39. Azari, R.; Abbasabadi, S.; Malkawi, A.M. Green building certification systems: Evaluating the gap between the energy performance of certified buildings and actual energy consumption. *Energy Policy* **2020**, *137*, 111144.
40. Liu, H.; Jin, H.; Liao, X.; Hu, L.; Yu, C. Performance and energy modeling for live migration of virtual machines. *Clust. Comput.* **2013**, *16*, 249–264. [CrossRef]
41. Usman, M.J.; Ismail, A.S.; Abdul-Salaam, G.; Chizari, H.; Kaiwartya, O.; Gital, A.Y.; Abdullahi, M.; Aliyu, A.; Dishing, S.I. Energy-efficient Nature-Inspired techniques in Cloud computing datacenters. In *Telecommunication Systems*; Springer LLC.: New York, NY, USA, 2019; Volume 71, pp. 275–302.
42. Fathi, H.; Khosravi, A.; GhasemAghaei, R. Energy efficiency optimization in data centers using machine learning techniques. *J. Ambient Intell. Humaniz. Comput.* **2020**, *11*, 1123–1134.
43. Duan, L.; Deng, Q. A survey on data center networking for cloud computing. *Comput. Netw.* **2020**, *172*, 107144.
44. Farahnakian, F.; Liljeberg, P.; Plosila, J. Energy-efficient virtual machines consolidation in cloud data centers using reinforcement learning. In Proceedings of the 2015 22nd Euromicro International Conference on Parallel, Distributed, and Network-Based Processing (PDP), Turku, Finland, 4–6 March 2015; pp. 186–193.
45. Gong, Z.; Gu, X.; Wilkes, J. PRESS: Predictive elastic resource scaling for cloud systems. In Proceedings of the 2010 International Conference on Network and Service Management (CNSM), Niagara Falls, ON, Canada, 25–29 October 2010; pp. 9–16.
46. Kumar, S.M.; Kumar, S.V.; K, S.L.; Karthik, G.S. Challenges and Approaches in Green Data Center. *Proc. J. Adv. Appl. Sci. Res.* **2022**, *4*, 1.
47. Marzban, A.; Rajaei, A.; Khanmohammadi, S. A review on data center cooling systems: Design, energy performance assessment, and research trends. *Sustain. Cities Soc.* **2017**, *34*, 362–379.
48. Xu, Z.; Wang, Y.; Wu, Y. Performance evaluation and optimization of liquid cooling in data centers. *Energy Build.* **2018**, *158*, 1102–1112.
49. Kocyigit, O.; Abu Al-Rub, R.K. Optimization of data center cooling using computational fluid dynamics and genetic algorithms. *Appl. Energy* **2019**, *233–234*, 42–54.
50. Zhou, J.; Zhang, Y.; Wang, Z.; Zhou, J. Control strategy for improving energy efficiency of data center cooling systems based on model predictive control. *Appl. Energy* **2020**, *260*, 114285.
51. Özdemir, H.; Çomaklı, O. Design and optimization of an energy-efficient data center cooling system using the Taguchi method. *Appl. Therm. Eng.* **2019**, *151*, 846–856.
52. Zhang, Z.; Shen, L.; Zhou, J. A novel energy-aware resource management scheme for edge computing-enabled data centers. *Future Gener. Comput. Syst.* **2020**, *110*, 390–400.
53. Aazam, M.; Zeadally, S.; Harras, K.A. Comprehensive energy management, service migration, and replication using machine learning in data centers. *J. Netw. Comput. Appl.* **2019**, *127*, 61–72.
54. Zheng, Z.; Zhu, X.; Wang, C. Adaptive data center energy management considering uncertain electricity prices. *J. Clean. Prod.* **2017**, *142*, 2195–2207.
55. Certifications and Compliance. Available online: https://datacenter.com/about_us/certifications/ (accessed on 4 February 2017).