sustainability

Opinion

Challenges and Solutions for Sustainable ICT: The Role of File Storage

Luigi Mersico [1], Hossein Abroshan [1,*], Erika Sanchez-Velazquez [1], Lakshmi Babu Saheer [1], Sarinova Simandjuntak [2], Sunrita Dhar-Bhattacharjee [3], Ronak Al-Haddad [1], Nagham Saeed [4] and Anisha Saxena [1]

1 School of Computing and Information Science, Anglia Ruskin University, Cambridge CB1 1PT, UK
2 School of Engineering and the Built Environment, Anglia Ruskin University, Chelmsford CM1 1SQ, UK
3 School of Management, Anglia Ruskin University, Cambridge CB1 1PT, UK
4 School of Computing and Engineering, University of West London, London W5 5RF, UK
* Correspondence: hossein.abroshan@aru.ac.uk

Abstract: Digitalization has been increasingly recognized for its role in addressing numerous societal and environmental challenges. However, the rapid surge in data production and the widespread adoption of cloud computing has resulted in an explosion of redundant, obsolete, and trivial (ROT) data within organizations' data estates. This issue adversely affects energy consumption and carbon footprint, leading to inefficiencies and a higher environmental impact. Thus, this opinion paper aims to discuss the challenges and potential solutions related to the environmental impact of file storage on the cloud, aiming to address the research gap in "digital sustainability" and the Green IT literature. The key findings reveal that technological issues dominate cloud computing and sustainability research. Key challenges in achieving sustainable practices include the widespread lack of awareness about the environmental impacts of digital activities, the complexity of implementing accurate carbon accounting systems compliant with existing regulatory frameworks, and the role of public–private partnerships in developing novel solutions in emerging areas such as 6G technology.

Keywords: digital sustainability; cloud storage; carbon footprint; data management

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1. Introduction

Policymakers and business actors have increasingly recognized the role of digitalization in addressing numerous challenges related to net-zero policies to meet net-zero emission targets [1–7] while maintaining competitiveness (Holzmann & Gregori, 2023) [8]. This convergence between digitalization and sustainability goals is often defined as digital sustainability [9,10].

Digital sustainability leveraging Key Enabling Technologies, such as big data and analytics, the Internet of Things (IoT), and cloud computing [11,12], is reshaping business strategies, creating significant global economic value, and impacting broader socio-economic dynamics while aligning with the United Nations' Sustainable Development Goals (SDGs) [11–13].

The literature on digital sustainability, revolving around the convergence of digital and net-zero imperatives, is increasingly focusing on the negative environmental impact of the rapid adoption of digital technologies [10,14,15]. It highlights the role of data centers' carbon emissions as a potential barrier to meeting net-zero objectives by 2050 [16,17].

According to [18], data centers are among the fastest-growing electricity consumers, accounting for 1.1% to 1.5% of the total annual global electricity demand [19–23] and contributing from 2.5% to 3.7% of all greenhouse gas (GHG) emissions [18–24].

Therefore, the environmental footprint of data centers has raised significant attention in Green IT research. This has led to the emergence of a new stream of research, also known as the "Green cloud paradigm".

This stream of research advocates for the integration of environmentally sustainable practices into cloud computing operations. It focuses on reducing carbon footprints through optimizing energy consumption and using renewable energy sources for data centers [25,26] without sacrificing the quality of service [27]. However, it lacks an investigation of the role of data storage and processing in organizations' carbon footprints.

The surge in electricity consumption and carbon emissions from data centers is related to the exponential growth in the volume of global data and the widespread adoption of cloud computing [23,28]. Indeed, the volume of global data is forecast to reach 181 zettabytes by 2025, driven by the proliferation of cloud computing services and the exponential growth in data production [29] (Figure 1). This vast amount of data necessitates extensive storage and processing capabilities, further exacerbating the energy consumption and carbon emissions of data centers [18].

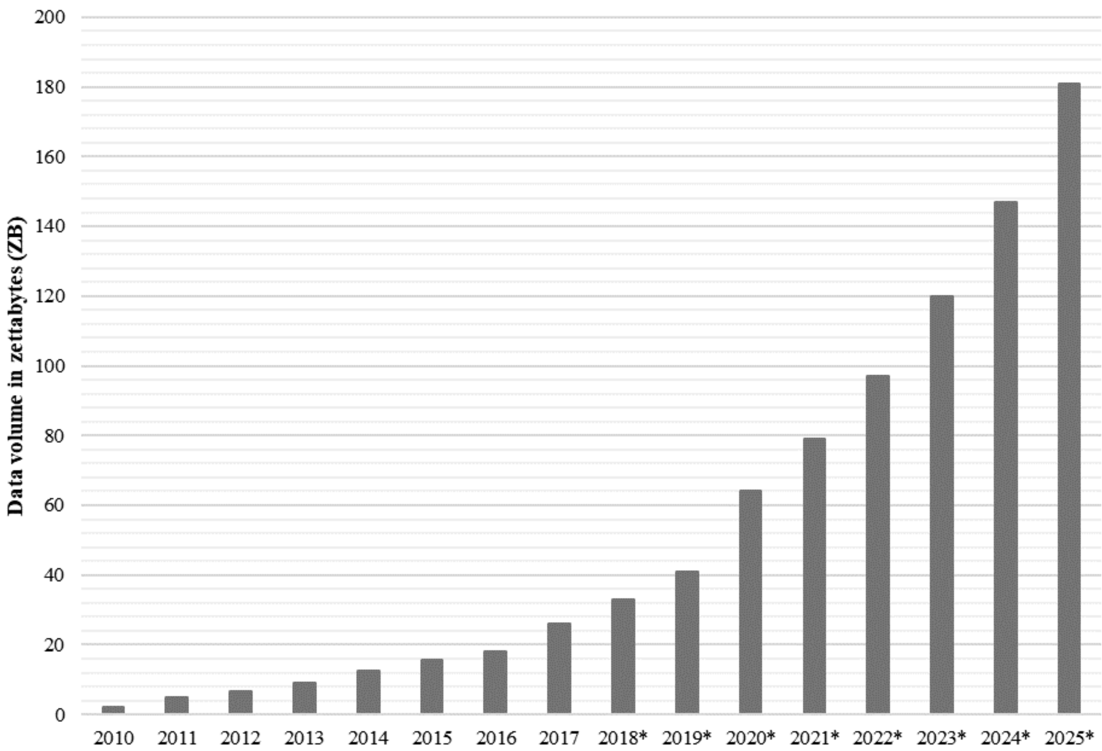

Figure 1. Amount of data created, consumed, and stored 2010–2020, with forecasts to 2025. Source: [29]. Note: * Estimated.

However, on the one hand, existing and limited evidence in practitioners' surveys shows that organizations frequently collect, process, and store data without fully understanding the impact of untracked and unnecessary data on their carbon emissions and operational costs [30,31]. This issue seems to be exacerbated by a widespread lack of awareness among employees, who often retain data out of habit or fear of future necessity, thereby perpetuating mismanagement practices [30,31].

On the other hand, the existing academic literature has mainly focused on energy-efficient strategies for data centers [32–36], revealing a significant gap in understanding the role of data mismanagement in achieving "digital decarbonization" [31,37]. This gap is particularly relevant in light of the widespread diffusion of data-hoarding practices [38], which complicates organizations' efforts to reduce carbon emissions within digital operations.

To address this issue, the present opinion paper explores the challenges and existing solutions related to reducing carbon footprints by minimizing file storage on the cloud. The primary aim is to fill the research gap in "digital sustainability" and Green IT literature. To achieve this aim, this paper provides a concise review of existing studies using the classification framework developed by [39,40]. It further discusses insights from two workshops on "Sustainability and ICT", held at the School of Computing and Information Science, Anglia Ruskin University in Cambridge, United Kingdom, involving leading experts from academia and industry in order to specifically address the impact of data storage practices as advocated by [37].

Key findings show that (1) a significant lack of awareness about the sustainability of digital activities among organizations is a major factor contributing to the increasing carbon footprint of digital activities; (2) existing metering solutions lack compliance, highlighting the need for regulatory-compliant standards for carbon emissions reporting and disclosure to address challenges related to end-user knowledge of cloud infrastructure and inaccuracies; and (3) cross-organizational projects led by public research institutions and private businesses, committed to achieving net-zero emissions, play a critical role in implementing domain-specific innovation, with one of the most recurring applications being emerging 6G technologies.

Besides this Introduction, this paper is organized as follows: Section 2 provides an overview of the existing literature. Section 3 presents experts' perspectives on core themes related to reducing the carbon footprint of cloud storage. Section 4 discusses the key themes concerning the challenges, solutions, and research agendas proposed by the expert contributors. Finally, Section 5 concludes the study.

2. Background Literature Review

This section synthesizes the existing literature focusing on Green IT and data storage and discusses each theme using an adaptation of the classification framework of [39,40] as a lens to investigate the topics.

The framework (Table 1) provides a comprehensive way to categorize the literature into business, technology, conceptualization, and domain/application themes. The framework classified cloud computing into 4 top and 10 sub-themes. The four top themes are Business Issues, Conceptualization, Domains and Applications, and Technology Issues.

Table 1. Cloud computing literature classification framework. Source: authors' elaboration on [40].

Theme	Sub-Theme
Conceptualization	Foundational themes
Technology Issues	Service and resource management
Business issues	Cloud computing adoption, acceptance and implementation, compliance and regulatory issues
Domains and Applications	e-science, e-health, mobile computing, IoT, knowledge management

The "Business Issues" theme encompasses studies focused on the business-related aspects of cloud computing. The "Technology Issues" theme addresses articles centered on the structure, components, and functioning of cloud computing technology, with a particular emphasis on the technical infrastructure. This theme is highly pertinent to this paper's focus, especially in sub-themes like data management, analytics, and data center management, which are directly related to cloud data management practices. "Conceptualization" involves articles that analyze the fundamental understanding of cloud computing, with the prediction sub-theme offering a forward-looking perspective, guiding discussions about future directions in cloud computing and their potential environmental consequences. Finally, the "Domains and Applications" theme incorporates articles examining the effects of cloud computing on specific societal/economic sectors.

Studies included in this section were identified using a stepwise iterative search approach [8,9] through the Scopus and Google Scholar databases by using the combination of keywords listed in Table 2.

Table 2. Literature selection process. Source: authors' elaboration.

Search Query	Results	Date Range
("cloud comp*" OR "cloud serv*" OR "cloud platf*") AND ("sustainab*" OR "environm*") (Topic)	28,133	1993–2024
A. ("cloud comp*" OR "cloud serv*" OR "cloud platf*") AND "sustainab*" (title)	130	2009–2024
B. ("cloud comp*" OR "cloud serv*" OR "cloud platf*") AND "carbon footprint" (title)	6	2014–2022
C. ("cloud comp*" OR "cloud serv*" OR "cloud platf*") AND "carbon emission*" (title)	3	2019–2023
D. ("cloud comp*" OR "cloud serv*" OR "cloud platf*") AND "Co2*" (title)	5	2013–2023
E. ("cloud comp*" OR "cloud serv*" OR "cloud platf*") AND "environmental impact" (title)	3	2020–2024
F. ("green cloud comp*" OR "green cloud serv*" OR "green cloud platf*") (title)	108	2011–2023
G. ("LCA" OR "life cycle assessment" OR "lifecycle assessment") AND "Data" (title)	6	2014–2024
H. "Data transfer" (title)	69	2011–2024
I. "Data management" (title)	251	2009–2024
J. "data" AND "networking" (title)	60	2014–2024
K. "Data storage" AND "environment*" (title)	43	2012–2024
L. "Data" AND "carbon footprint" (title)	4	2017–2024

This search initially cast a net of 28,133 academic papers. Therefore, as a first screening to obtain the most focused literature on the topic, the search was limited to ("cloud comp*" OR "cloud serv*" OR "cloud platf*") and "sustainab*" words in the title. For completeness, the search was integrated with "green cloud comp*" OR "green cloud serv*" OR "green cloud platf*". This approach resulted in 278 unique records (20 duplicated).

To refine the sample and determine the eligibility of documents, exclusion criteria were created in line with the PRISMA Guidelines [41,42]. The exclusion criteria included (a) documents not indexed in Computer Science, Engineering, Environmental Science, or Business Management and Accounting, (b) literature reviews, (c) articles not published in peer-reviewed journals or by relevant industrial practitioners, and (d) documents not published in the English language. No time restrictions were imposed with the purpose of collecting all relevant literature available in the examined databases. One hundred articles were identified as eligible.

2.1. Conceptualization

When addressing reductions in carbon footprints, three main themes emerge. The first theme revolves around technological issues. The primary focus is on optimizing the core infrastructure that supports cloud computing to enhance resource utilization and minimize the carbon footprint. This includes addressing challenges related to data processing, data transmission, and data storage. The second theme focuses on business issues related to sustainable management and reporting. Stakeholders, from customers to governments, are increasingly urging organizations to fulfill their sustainability responsibilities. This includes developing ESG-compliant reporting and accounting frameworks and leveraging tools like Life Cycle Analysis [43] and the GHG Protocol [44] to effectively manage the ecological footprint of data and networks. While the third theme focuses on domain-specific applications.

2.2. Technological Issues

Technological Issues address three key areas: (a) data processing, (b) data transmission, and (c) data storage.

2.2.1. Data Processing

Data processing is among the most energy-intensive activities in cloud computing. Servers consume substantial electrical power and produce heat while processing and generating data, necessitating effective cooling solutions to maintain operational efficiency [16]. The issue of "needless work"—where resources are expended on non-productive tasks—further exacerbates energy wastage [45]. According to [19], a significant portion of energy in data centers is consumed by servers performing idle tasks. Indeed, in [46], the authors highlight that the processor on an idle server accounts for 53% of the consumption of energy. Implementing advanced solutions such as server virtualization is crucial for minimizing this waste by enabling the more efficient use of server capacity and reducing the number of active physical servers required [47,48].

With respect to this point, the literature shows that innovative approaches focusing on data processing [49,50] in cloud network design and data center management are needed. Since resource overloads (e.g., CPU, memory, network, and storage) can degrade service performance and lead to Service Level Agreement (SLA) violations [51], the adoption and selection policy of virtual machines (VMs) plays a crucial role in streamlining the use of computing resources [52]. Thus, data processing becomes relevant. It revolves around developing algorithms to optimize requests to the most suitable VMs [53–55], schedule task execution [56,57], and allocate workloads efficiently [58,59], all while ensuring compliance with security requirements [60,61].

2.2.2. Data Transmission

Regarding data transmission, the Carbon Cost of Connectivity emerges as a key issue. In [62], the authors estimate that the energy used by the Internet today is consumed in the access network.

Data transmission not only requires substantial power but also contributes to carbon emissions throughout the lifecycle of the data—from creation to deletion [23].

Thus, optimization techniques, such as more efficient routing algorithms [53] and data compression [63], can reduce the volume of data transmitted and consequently lower the energy required. Strategies to reduce transmission loads consider that implementing stricter data management protocols can help in minimizing unnecessary transmissions. For example, reducing the frequency and size of data backups and employing data deduplication techniques can significantly decrease the carbon emissions associated with extensive data movement across networks [64].

2.2.3. Data Storage

According to [65], the storage of digital data consumes an increasing amount of energy, driven by the ever-growing size of data centers [62]. Data lifecycle management can play a crucial role in reducing this impact. Techniques like hierarchical storage management (HSM) and the strategic archiving of data have emerged to reduce the need for frequent access to infrequently used data, thus saving energy [66]. Emerging innovations in storage technology and integrating renewable energy sources into data center operations, as explored by [51], can offset the consumption of non-renewable energy sources.

Thus, the transition to green cloud computing requires robust policy frameworks that encourage the adoption of renewable energies and energy-efficient technologies. Reports by organizations such as the Green Grid and research by the authors of [67] emphasize the importance of policy measures that incentivize energy efficiency improvements and the integration of sustainable energy sources into the IT sector. For instance, the works of [20] discuss the feasibility of, and strategies for, integrating renewable energy sources like solar and wind energy into data center operations, significantly reducing their carbon footprint and operational costs.

2.3. Business Issues

Despite a considerable amount of literature focusing on the technological challenges associated with the sustainability of data processing, transmission, and storage, the socio-technical aspects of data are relevant. This highlights the critical role of organizational behavior in promoting sustainable practices related to cloud storage, which are also aimed at compliance with regulatory frameworks.

2.3.1. Adoption and Acceptance of Cloud Storage

Cloud storage is becoming increasingly attractive to various organizations, including large enterprises, small and medium-sized enterprises (SMEs), and public administrations aiming to align with country-specific digital agendas [33,68,69]. In 2023, the adoption rates for cloud computing in Europe showed large enterprises at 77.6%, medium-sized enterprises at 59%, and small enterprises at 41.7% [70]. Public services underpinning e-government are particularly prevalent in Denmark, Great Britain, and Sweden, with about 60% of citizens using electronic public services [71]. The widespread adoption is driven by the need to leverage big data and reduce infrastructure costs, enhancing cost-effectiveness—the ratio of utility provided by cloud computing to the monetary expenses involved [72].

However, the survey conducted by [31] revealed that 60% of data stored by organizations in the cloud are unused, and a significant majority (67%) are unaware of the impact these untracked data have on carbon emissions and storage costs. In [38], the authors identified that 83% of IT decision-makers see their companies as data hoarders, with up to 55% of stored data being redundant, obsolete, or trivial (ROT) [73]. Despite this, 68% of respondents claimed sustainability as a priority. This discrepancy highlights the existence of a widespread issue related to data hoarding within corporate culture.

2.3.2. The Problem with Data Hoarding

The utilization of cloud computing services in enterprises, whether large or SMEs, is often dictated not by employee attitudes but by fulfilling job requirements [74], including data availability and security [75]. Corporate data policies often perpetuate the misconception of limitless storage, leading to extensive data hoarding driven by employees' fears of future data needs or uncertainties over data retention [30,38]. Despite recognizing the need to balance business objectives with sustainability goals, many organizations neglect the imperative to eliminate unnecessary data, posing significant risks to their digital carbon footprint and compliance with new regulations [44,73].

Effective data lifecycle management, advocating for responsible data usage, and implementing practices such as regular audits and deletions are crucial. Organizations must foster a culture where the impact of data on sustainability is understood and acted upon. This involves ongoing education and redefining organizational norms around data storage, ensuring compliance, reducing costs, and ultimately supporting corporate sustainability goals [76,77].

Unfortunately, the challenges that emerge from an analysis of this stream of research show that decision-makers realized too late the environmental costs of adopting new technologies and practices, at a time when altering established behaviors became challenging [78]. This issue raises a concrete risk linked to both the detrimental impact that data can have on an organization's digital carbon footprint [37] and compliance with new regulatory frameworks [44].

2.3.3. Measurement of the Environmental Impact of Data

Disclosing carbon emissions poses significant challenges for organizations. Cloud service providers have started offering tools to track sustainability metrics, but these tools provide aggregated data at a service level, making it difficult to directly compare carbon efficiency across services [79]. Both practitioners and the academic-related literature stress the need to define proxy metrics and establish comprehensive carbon accounting systems [37,73,80].

Despite advancements in resource monitoring tools, managing corporate carbon accounts remains challenging due to their need for substantial IT investment and frequent reliance on manual data gathering and calculations, making scalability difficult [81]. Research highlights the existence of several tools designed to measure and manage the carbon impact of data operations.

Among the notable examples, the Data Carbon Ladder, introduced by [73], guides data managers and sustainability officers through the carbon implications of data across their entire lifecycle. This tool assesses data from their creation to their deletion, identifying energy-intensive and high-emission activities and classifying data practices according to their carbon intensity. However, its implementation demands substantial organizational transformation and may be challenging for firms without a specialized sustainability team. The framework also lacks automated tracking mechanisms, necessitating manual evaluation.

On the other hand, the Green Algorithms tool, developed by [82], is tailored for high-performance computing environments, which restricts its utility to a specific sector and excludes wider computing or business applications. It requires precise details about hardware, energy sources, and operational conditions, posing a challenge for those without comprehensive knowledge of their infrastructure. The precision of its carbon footprint calculations heavily relies on the detail and accuracy of the data provided by users.

Furthermore, the CO2.js tool, created by the Green Web Foundation (The Hague, Netherlands) [83], enables developers to calculate the carbon emissions of web pages and digital products in real time, considering elements like data transfer, server energy sources, and user interactions. However, it employs broad assumptions in its emissions calculations, potentially leading to inaccuracies if the actual conditions deviate substantially from these assumptions.

A shared aspect of these tools is their requirement for regular updates to remain current and precise, mirroring advancements in technology and shifts in regulatory frameworks on carbon emissions disclosure.

2.3.4. Regulatory Compliance

One of the emerging issues between measuring the environmental impact of data and the available tools is directly tied to the broader challenges of regulatory compliance. These tools should be aligned with standardized frameworks like the GHG Protocol [44], which provides a structured and compliant method to categorize and manage emissions across three scopes and is crucial for comprehensive reporting and compliance.

Nevertheless, as highlighted by [43], several challenges persist in achieving accurate and compliant carbon accounting for digital data. These include metering indirect emissions within the value chain. Thus, addressing this complexity necessitates an end-to-end approach encompassing the entire data value chain, from data collection and transfer to storage and use.

2.4. Application Domains

The Domains and Applications theme consists of articles that address the impact of cloud computing on specific areas of society. The literature shows the rise of application domains such as knowledge management [37,73], e-science [84–86], e-health [87–89], IoT [90], and mobile computing [91].

2.4.1. Knowledge Management

The significant challenges in the surge of data volume from IoT technologies have been recognized in the application domain of knowledge management (KM) by [37,73], who introduced the concept of "digital decarbonization". KM views data as a knowledge asset that should be reused to minimize database searches and infrastructure usage, thereby reducing power and energy consumption. Their framework, focused on the knowledge base owned by organizations, advocates for considering the entire data, information, knowledge, and wisdom (DIKW) pyramid to effectively manage and mitigate the increase in carbon emissions associated with single-use data processing.

2.4.2. e-Science

In the domain of e-science, data redundancy poses a notable challenge. In [84,85], the authors introduced two open-source frameworks aimed at aiding scientific collaborations in managing and accessing large-scale data efficiently, while [86] identified redundancy issues in Earth Observation (EO) data, noting the environmental impact due to vast storage and data transfer, which results in considerable CO_2 emissions. They highlight the urgency for more efficient data management approaches within the EO community to mitigate redundancy while maintaining data openness.

2.4.3. e-Health

In e-health, security emerges as a key issue [87,89]. Cloud computing in e-health offers scalability, cost savings, and fast deployment, which is crucial for managing electronic health records (EHRs), laboratory information systems, pharmacy information systems, and medical images. However, centralizing sensitive data in the cloud raises serious security and privacy concerns, as it could become vulnerable to attacks and data ownership issues. Future research should explore decentralized storage solutions in e-health, such as blockchain, which can ensure reliability and data accessibility while mitigating the carbon footprint associated with increased cloud reliance [88].

2.4.4. IoT and Mobile Computing

The IoT and mobile computing domains face challenges from the increased cloud network requests due to the proliferation of devices. Mobile cloud computing provides limitless storage on a pay-as-you-go basis, though historically focused on enhancing battery longevity. In [91], the authors highlighted the environmental dilemma posed by mobile device storage capacity. Mobile cloud computing offloads resource-heavy applications to the cloud, freeing mobile devices from local storage constraints but increasing large-scale environmental impacts, as seen in Google's report of 2.8 billion active Android users in 2018 [92].

2.5. Emerging Challenges

This literature review shows the existence of three main challenges. First, the valuation and sustainability of data. In an era of immense data proliferation, understanding the true value and environmental cost of data is essential. As data volumes grow exponentially, the challenge lies in discerning which data are valuable and which are redundant, thereby optimizing storage and processing to reduce environmental impact [93]. Sustainable data management practices need to be developed to ensure that only necessary data are retained, thus minimizing the carbon footprint associated with data storage.

Second, educating employees about the carbon costs associated with their daily digital activities is challenging and requires establishing cross-functional teams and a top-down approach. The support of top management is crucial for this transformation [94]. Top management needs to analyze the impact on organizational dynamics and ensure that the integration of cloud services aligns with existing systems and practices [69,75,76]. Additionally, introducing a Chief Sustainability Officer and fostering a collaborative approach through cross-functional teams is essential for deploying effective sustainability strategies [31].

Third, another significant challenge is implementing accurate carbon accounting systems. The complexity of measuring carbon emissions from various digital activities in compliance with existing reporting directives poses difficulties. Accurately attributing these emissions to specific actions is necessary for effective tool implementation and management [95]. This complexity is compounded by the need for comprehensive and precise data collection methods to handle the heterogeneity of device types, power sources, and geographical variations in carbon intensity.

3. Addressing Challenges: Multiple Perspectives from Leading Experts

This section consolidates the contributions of various experts following the framework set out by [14], focusing on key issues emerging from the two workshops. The insights and practical examples presented by the experts aim to address critical issues in achieving digital sustainability and significantly reduce the carbon footprint associated with data management. The expert contributions are largely presented in an edited form. Below is a table summarizing these contributions (Table 3).

Table 3. Invited contributors and subject list.

Expert ID	Topic	Expert Affiliation	Country
Expert A	Definition of Standards and Guidelines for Sustainability in ICT	Industry	United Kingdom
Expert B	Towards Sustainable Energy Consumption in Wireless Communication	Academia	United Kingdom
Expert C	Energy-aware ICT Metering solutions	Academia	United Kingdom
Expert D	Case study	Public–private partnership organization	United Kingdom

3.1. Contribution 1—The Importance of Educational Campaigns and Awareness of Sustainability

A significant factor contributing to the increasing environmental impact of cloud storage is the lack of awareness among companies and IT users [31]. Many individuals are unaware of the carbon emissions related to everyday digital activities, such as storing files on the cloud and streaming videos. To address this issue, two key actions have been identified: (a) providing concrete examples and labeling, and (b) implementing educational and awareness initiatives.

Firstly, providing specific examples and labeling the carbon footprint associated with activities like streaming a movie or storing a video file can help raise awareness and potentially alter user behavior. Illustrating these impacts can make users more conscious of their digital activities and encourage more sustainable practices.

Secondly, comprehensive educational initiatives and awareness campaigns focused on the environmental impact of digital activities allow us to educate end-users about the consequences of their actions. In this way, they can become more conscious and adopt more sustainable practices. Drawing parallels to successful environmental campaigns, such as reducing plastic bag usage, can help design effective programs.

This approach can lead to establishing internal policies and best practices, such as the existing minimal computing principles [96], to guide the use of cloud storage. Experts emphasize the necessity of clear guidelines to help users make informed decisions, considering both the necessity of storage and its environmental impact. These internal policies can significantly contribute to reducing unnecessary cloud storage usage.

3.2. Contribution 2—Energy-Aware Data Management Strategies

The literature identifies energy-aware data management strategies as a critical issue in cloud computing, with a significant focus on minimizing data waste, such as redundant or obsolete data. This data waste can severely hinder system performance and tie up resources that could be better allocated, leading to slower processing and higher costs [31]. Implementing hierarchical storage management (HSM) and strategic data archiving emerges as vital techniques to mitigate these inefficiencies by reducing the need for frequent access to infrequently used data, thus conserving energy [66].

However, a major challenge in this area is implementing effective data retention policies. These policies must include a robust classification framework for different types of applications (e.g., video, audio, data), alongside a storage timeline and expiry dates for data deletion or retention. This approach aims to free up storage space sustainably and minimize energy consumption by systematically removing unnecessary data.

3.3. Contribution 3—The Role of Simplification and Standardization of the Processes Related to Reporting Carbon Emissions from ICT Services

Simplifying and standardizing the processes related to reporting carbon emissions from ICT services is crucial. Developing tools that accurately measure and report carbon emissions from cloud activities empowers users to make informed decisions, promoting the use of local data centers and personal devices where feasible to minimize carbon footprints. Addressing both direct and indirect carbon emissions from these measurement processes is essential to avoid unintended consequences.

However, the literature highlights the inherent complexity of reporting digital carbon emissions [44]. Thus, future research should focus on simplifying and standardizing these processes. Simplification and standardization can lead to broader adoption and reduced complexity. Making carbon emissions reporting straightforward and uniform enables organizations of various sizes to easily track and manage their carbon footprints. This, in turn, reduces the burden of complying with environmental regulations and facilitates the wider adoption of sustainable practices.

The introduction of standards is a key issue to be addressed. Standards capture best practices, ensure consistency, and optimize the reporting of performance measures in ICT. Experts emphasize that standards, such as those developed by The Open Group, encapsulate methodologies and procedures crafted by industry experts.

These standards provide clear guidelines to help organizations minimize inefficiencies and improve operational performance, which is essential for reducing the carbon footprint of ICT activities. Among the most prominent standards are TOGAF and the Open Standard for Environmentally Sustainable Information Systems [97,98].

TOGAF outlines strategies for developing and rolling out sustainable information systems within organizations. It includes a Digital Sustainability Reference Model that identifies necessary business functions and emphasizes a holistic approach to sustainability. This model highlights the importance of considering both top-down (business needs) and bottom-up (existing technology infrastructure) approaches to comprehensively assess sustainability impacts.

The Open Footprint Standard offers a comprehensive data model for tracking and reporting GHG emissions. It supports accurate and consistent emissions accounting, ensures regulatory compliance, and facilitates industry-wide reporting. The data model's complexity, which includes approximately 90 entities, highlights the necessity of standardized metrics for effective carbon footprint measurement and reporting. However, one of the main challenges is incentivizing compliance with sustainability standards through regulatory measures. Effective incentives and regulations are crucial to ensuring organizations adhere to these standards and make meaningful progress in reducing their carbon footprints.

3.4. Contribution 4—The Role of Regulatory Interventions in Promoting Sustainable ICT Practices

The regulatory landscape for ICT sustainability is rapidly evolving, with a growing emphasis on reducing digital carbon emissions. Although there is a notable gap in the literature regarding public regulatory frameworks, experts stress that effective regulatory measures are crucial for promoting sustainable ICT practices. These frameworks should incentivize companies to adopt sustainable practices and impose penalties for non-compliance. This dual approach motivates organizations to reduce their carbon footprints and invest in greener technologies. Effective regulatory measures and incentives can drive significant reductions in the carbon footprint of ICT services, encouraging broader adoption of sustainable innovations.

Experts highlight the importance of shared responsibility among companies, governments, and users in addressing accountability for carbon emissions in the ICT sector. This accountability can be enforced through trusted frameworks involving certification bodies and public oversight. The verification and certification of carbon reduction are critical regulatory mechanisms, ensuring companies accurately report their carbon emissions and adhere to established standards, similar to financial audits but focused on carbon accounting.

Drawing lessons from other sectors, economic incentives like those used to reduce plastic bag usage can effectively encourage sustainable practices in the ICT sector. Consistent regulations across countries, achieved through international cooperation and standardization, are crucial for globally coordinated sustainability efforts. Emerging regulations around AI ethics must consider sustainability aspects, given the high energy consumption of training large AI models. Regulatory frameworks should incorporate these considerations to ensure comprehensive sustainability. Studies indicate that responsibly implemented AI and digital technologies can significantly reduce emissions, highlighting the necessity of ethical deployment.

Addressing these regulatory challenges requires collaboration between public and private sectors, continuous innovation, and a commitment to integrating sustainability into all ICT operations. Providing companies with guidance and support to meet sustainability standards, along with extending existing audit practices to include carbon accounting audits, fosters a collective effort towards sustainability. This shared responsibility model ensures that all stakeholders are accountable for reducing carbon emissions, promoting a holistic approach to sustainability.

3.5. Contribution 5—The Role of Inter-Organizational Collaborative Projects Focused on Specific Application Domains

The literature recognizes the existence of domain-specific factors that affect the carbon footprint of digital activities. Among these domains, the Internet, telecommunication, and IoT sectors are particularly impactful regarding carbon emissions [93]. The average website produces 1.76 g of CO_2 for every page view, so a site with 100,000 page views per month emits 2112 kg of CO_2 yearly, while the telecommunications landscape alone accounts for 1.6–2% of global carbon emissions.

This necessitates innovation and collaboration across the entire ecosystem's actors, along with standardization efforts to drive sustainability forward. The experts discussed the role of collaborative projects whose aims are to verifiably improve net energy consumption and, with it, the carbon footprints of ICT services in the web-based context of next-generation mobile systems (6G) with a focus on metering tools, green network architecture, and Green KPIs. Thus, among the most prominent domains, three case studies are discussed.

3.5.1. Public–Private Partnership: The Case of the Digital Innovation Zone

The first initiative involves the Digital Innovation Zone (DIZ), a collaborative partnership that brings together organizations from various sectors, including business, healthcare, education, local authorities, and the community sector in West Essex and East Hertfordshire. This partnership leverages digital innovation to enhance services and promote sustainable development, focusing on 5G infrastructure, digital sustainability, digital inclusion, and digital skills. Several projects have been undertaken that directly or indirectly impact sustainability.

One notable project aimed to optimize the DIZ's website to reduce its carbon footprint. This effort demonstrated that even small-scale changes could collectively lead to significant environmental benefits. Although the website is small and has low traffic, the objective is to scale these practices to larger partner organizations' websites. These initiatives illustrate how targeted digital innovations can yield tangible sustainability benefits, even on a small scale. By sharing these practices, the DIZ aims to inspire larger organizations to adopt similar measures, thereby amplifying the overall impact.

3.5.2. Academic/Industry Research on Sustainable Energy Consumption in Wireless Communication in the Telecommunication Sector

The second initiative undertaken by the Internet of Things (IoT) Research Group at the University of West London aims to tackle the telecommunications sector's significant energy demands and carbon footprint through innovative strategies and technologies.

The project's primary objectives are to reduce the telecom sector's carbon emissions and to promote sustainable energy practices. This includes integrating renewable energy sources such as solar, wind, and hydro into telecom operations, and enhancing energy efficiency through the development and implementation of energy-efficient network designs and operational practices. Additionally, the project seeks to innovate with artificial intelligence (AI) and machine learning (ML) techniques to optimize power consumption in next-generation radio access networks (NG-RAN).

One of the key challenges addressed by the project is the rising energy consumption driven by the expanding global population and the increasing demand for connectivity and high-speed data, particularly with the proliferation of IoT and mobile devices. Another major concern is the energy usage of data centers, which are projected to consume up to 8% of global electricity by 2030.

Furthermore, designing energy-efficient technologies that can be feasibly deployed in production networks poses a significant challenge. Balancing the energy savings from AI/ML techniques against the operational energy costs of performing the necessary computations is another critical issue.

Moving forward, the project emphasizes innovation and collaboration across the industry, involving all stakeholders in the telecom ecosystem and reassessing network architecture for greener designs. It is crucial to introduce key performance indicators to measure and improve energy efficiency and promote a shift towards achieving more with less.

3.5.3. Academia/Industry Research within European-Funded Projects

The third initiative discussed is the EXIGENCE Project. The EXIGENCE Project, part of a European-funded initiative, aims to integrate measurement, optimization, and incentives to reduce energy consumption and the carbon footprint of ICT services, particularly focusing on future 6G systems. The project targets significant reductions in energy consumption and carbon emissions, intending to influence both industry practices and policy.

The project involves designing and implementing systems to reliably assess the energy consumption and carbon footprint of ICT services. This requires using accurate metrics to track the environmental impact of various ICT activities. Additionally, the project focuses on developing and implementing optimization techniques to reduce energy usage, including innovative approaches to managing data and network resources efficiently.

Another key aspect of the project is creating incentive mechanisms to encourage both service providers and end-users to adopt energy-saving practices. This involves exploring novel incentive models that are compatible with reducing energy consumption and carbon footprints.

To define the key metrics for assessing the success of the EXIGENCE project, the primary Key Performance Indicator (KPI) is to reduce the energy consumption and carbon emissions of various ICT services, with a particular focus on video streaming as a primary use case. For more demanding services, such as private networks built over non-public networks, the project aims to achieve significant reductions in energy use. Additionally, the project seeks to identify use cases where it is feasible to bring the carbon footprint down to zero, particularly in realistic deployment scenarios.

These KPIs provide clear targets for the project, ensuring that efforts are aligned with tangible environmental benefits and that progress can be systematically tracked and evaluated.

4. Discussion and Recommendations for Future Research

Our findings consolidate knowledge gathered from two workshops titled "Sustainable ICT" held at the School of Computing and Information Science, Anglia Ruskin University. These workshops, combined with a systematic literature review using the Cloud Computing Classification Framework [40], highlighted primary challenges, emerging solutions, and potential future research directions related to digital sustainability and efficient file storage management on the cloud.

4.1. Interpretation of the Results

This study interpreted the results by identifying three main challenges and four different solutions for reducing the carbon footprint related to file storage on the cloud.

With respect to challenges, firstly, while public and private organizations are aware of the challenges in adhering to sustainability principles, a significant lack of awareness about the sustainability of digital activities persists. The literature and expert opinions reveal that IT decision-makers seldom prioritize these issues [31]. Therefore, awareness campaigns and educational initiatives about the environmental impact of digital activities are essential to increase the willingness of end-users to adopt more sustainable practices.

Secondly, challenges persist regarding energy-aware data retention policies. While the literature highlights techniques like hierarchical storage management (HSM) to reduce the need for frequent access to infrequently used data, issues related to automatic data retention policies remain. Experts advocate for developing a classification framework for different types of applications (e.g., video, audio, data), alongside a storage timeline and expiry dates for data deletion or retention, to address these challenges effectively.

Thirdly, the introduction of regulatory-compliant standards for reporting and disclosure of carbon emissions is also critical. The literature identifies the main limitations of existing tools, such as challenges for those lacking comprehensive knowledge of their infrastructure and inaccuracies when actual conditions deviate from assumptions (e.g., data transfer, server energy sources, user interactions).

Regarding solutions, the Data Classification and Retention Policy seems to be the first step in implementing a categorization framework based on data type (e.g., video, audio, documents) and usage frequency. By assigning different retention timelines for each category, the system can automatically delete or archive infrequently accessed data, reducing unnecessary storage and energy consumption.

Secondly, energy-aware storage management, such as hierarchical storage management (HSM), seems to be a suitable technique for minimizing the energy needed to store and retrieve data by prioritizing low-power storage options for less frequently accessed data. This reduces the need for high-performance servers to manage cold data, reducing overall energy usage.

Thirdly, carbon accounting frameworks such as TOGAF [97] and the Open Footprint Standard [98] can enable organizations to track, report, and reduce the carbon emissions generated by their data storage operations. On the one hand, TOGAF provides a structured approach to embedding carbon accounting and sustainability metrics into the core IT architecture of an organization, ensuring sustainability is considered in strategic planning and operational processes [97]. On the other hand, the Open Footprint Standard, developed by The Open Group, aims to create a common data model for recording and managing environmental footprint data, including all types of GHG emissions [98].

This standard facilitates the consistent measurement and reporting of Scope 1, 2, and 3 emissions, providing a comprehensive framework for organizations to manage their carbon footprints effectively.

Finally, inter-organizational collaborative projects focused on specific application domains are also vital. The public sector and universities, committed to achieving net-zero emissions, play a critical role in conducting lifecycle assessments to identify the primary contributors to carbon emissions. These assessments can guide more focused and effective sustainability strategies across different network types and technological implementations, including emerging 6G technologies [99].

4.2. Implications

This study's implications include advocating for incentivization schemes to promote sustainable practices and fostering organizational environmental responsibility. It also stresses the importance of standardizing and regulating sustainable practices across industries and governmental organizations to enhance accountability in environmental reporting. Moreover, this paper emphasizes the role of funding and regulatory frameworks in supporting collaborative efforts for sustainability research and development, particularly in emerging technological areas.

4.3. Limitations

This paper's limitations include the lack of a detailed evaluation of specific technological solutions and their practical implementation, potential biases in the selection of literature due to exclusion criteria, and the absence of real-world case studies to demonstrate the effectiveness of proposed solutions. Moreover, this paper acknowledges that the identified limitations may constrain the generalizability of the findings and the practical application of the research.

4.4. Future Work

Future studies can conduct and propose in-depth research focused on developing community-wide awareness campaigns and educational initiatives to address the need for more awareness about the sustainability of digital activities among organizations. This can be achieved through campaigns like those used to reduce single-use plastic bags, advocating for both a reduction in single-use products and the reuse of plastic items. This aligns with the reuse principle advocated by knowledge management, which views data as a valuable asset and advocates for digital decarbonization through the elimination of single-use knowledge and the reuse of data assets [37].

We also suggest introducing public/private incentivization schemes to support organizations adopting best practices and regulatory-compliant standards for carbon emissions reporting and disclosure to address challenges related to end-user knowledge about the environmental impacts of storing unnecessary files/data on the cloud. To achieve net-zero emissions, it is also important to perform cross-organizational projects led by public research institutions and private businesses in implementing domain-specific innovation, particularly in emerging areas such as 6G technologies.

5. Conclusions

The negative environmental impact of digitalization has been increasingly discussed in the literature [10,14], particularly focusing on data centers' electricity consumption and GHG emissions. However, there has been a lack of focus on the role of data mismanagement in achieving digital decarbonization. This research position paper aims to explore the significant challenges and existing solutions related to reducing the carbon footprint by minimizing file storage on the cloud. Utilizing the approach outlined by [14], it provides a comprehensive perspective on various aspects of "digital sustainability" and "green cloud" related to cloud file storage.

This responds to a call to action in [10] for "Digital sustainability and climate change: research opportunities", focusing on Green IT to reduce the direct environmental impact of IS use at an organizational level.

The novelty of this paper lies in its focus on addressing the role of data mismanagement in the quest for digital decarbonization. While much of the existing literature has concentrated on the environmental impact of data centers' energy consumption and greenhouse gas (GHG) emissions, this research shifts attention to how the management, storage, and retention of digital data contribute to the carbon footprint of cloud computing.

By exploring strategies to minimize file storage on the cloud, this paper provides a new perspective on "digital sustainability" and "green cloud" initiatives, filling a critical gap in Green IT research.

Three main challenges have been identified: (a) the evaluation and sustainability of data to develop energy-aware data management strategies and minimize data waste, (b) educating employees about the carbon costs associated with their daily digital activities, and (c) implementing accurate carbon accounting systems in compliance with regulatory frameworks.

Potential solutions, leveraging expert opinions, include collaborative projects between public research institutions and private businesses to achieve net-zero emissions, particularly in emerging fields like 6G technology, and the introduction of widely recognized standards such as TOGAF and the Open Footprint Standard to enhance corporate sustainability practices.

This paper has several policy implications. Firstly, introducing incentivization schemes that reward sustainable practices and penalize non-compliance can foster a culture of environmental responsibility within organizations. Secondly, organizations should focus on establishing and adopting these standards across industries to promote transparency and accountability in environmental reporting. Thirdly, supporting collaborations through funding and regulatory frameworks will encourage joint efforts in sustainability research and development.

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