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## Green Cloud Computing: AI-Driven Energy Optimization Techniques

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### ABSTRACT:

As the digital landscape continues to evolve, cloud computing has become integral to the advancement of modern information and communication technologies (ICT). It provides scalable, flexible, and cost-effective solutions that support diverse industrial applications. Nevertheless, this rapid expansion has raised concerns regarding its environmental consequences—particularly in relation to energy consumption and electronic waste generation. In response, the concept of green cloud computing has emerged, emphasizing environmentally sustainable practices while preserving the performance and economic advantages of conventional cloud systems.

This paper investigates the foundational aspects of cloud computing and examines recent innovations designed to improve energy efficiency and reduce carbon emissions. It also identifies unresolved challenges in the field and suggests directions for future research to encourage the adoption of more ecologically responsible cloud infrastructures. As demand for large-scale data storage and real-time access to virtual resources grows, cloud computing continues to underpin the expansion of digital services. By facilitating secure data transfer and seamless scalability, it empowers organizations to operate more efficiently. Given its pivotal role in the tech industry, cloud computing is poised to support ongoing digital transformation while integrating sustainability into its core framework.

**Keywords :** green cloud computing; green information; communication technologies; environment fortification. environmental protection; sustainability

### Introduction:

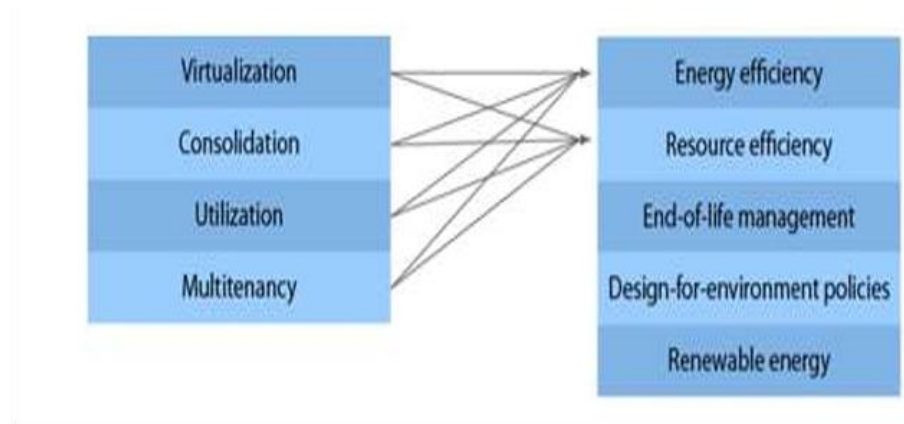
The concept of *green cloud computing* has gained increasing attention in the information technology (IT) sector due to its potential to support environmental sustainability. It represents the intersection of ecological responsibility and cloud-based service delivery, where IT resources are accessed over the internet in a manner that minimizes environmental harm. At its core, green cloud computing focuses on optimizing computational efficiency while reducing carbon emissions and ecological waste [1]. This approach aligns with broader global efforts to address climate change, especially as traditional IT infrastructure has been a significant contributor to energy consumption and greenhouse gas emissions [15].

Cloud computing provides on-demand access to computing resources across the globe, offering considerable advantages in terms of performance and cost-effectiveness when compared to traditional dedicated hardware. However, these benefits come with significant energy requirements, as large-scale data centers power these services and contribute substantially to CO<sub>2</sub> emissions. Green cloud computing aims to mitigate this environmental impact through the use of renewable energy, energy-efficient infrastructure, and sustainable IT practices such as recycling obsolete equipment and minimizing hazardous materials [24,25].

The transition to green cloud computing is driven by the imperative to develop resource-efficient, low-carbon, and recyclable digital solutions. Key areas of research include power management, virtualization, high-performance computing, load balancing, and systems for data reuse and recycling. As user demand for both quality service and sustainability grows, vendors are increasingly focused on delivering energy-efficient cloud provisioning that does not compromise performance standards.

The development of green cloud computing is inherently linked to advancements in green data centers, which form the operational backbone of cloud infrastructure. Data centers accounted for approximately 1.3% of global energy use in 2010, according to Koomey. A GeSI report further projected that the share of carbon dioxide emissions from ICT technologies would rise from 1.3% in 2002 to 2.3% by 2020. In response to these trends, researchers at Lawrence Berkeley National Laboratory and Northwestern University developed the Cloud Energy and Emissions Research Model (CLEER), designed to estimate energy savings from migrating localized software and computation to cloud-based server farms. Their findings suggest that moving applications like email and customer relationship management tools to the cloud could reduce their primary energy footprint by up to 87% for U.S. businesses [4].

While the model may not capture every variable, it offers valuable insights into potential energy savings and supports the case for transparency and accountability in energy consumption by internet-based companies. The environmental advantages of cloud computing are significantly amplified when data centers operate according to green computing principles [28,30].



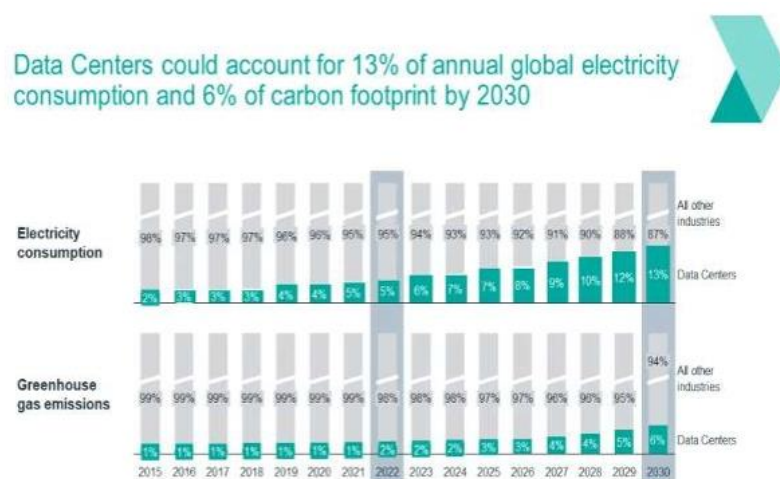
**Figure-1: This diagram explains the relationship between cloud computing and green computing.**

The cloud computing service model operates on the principle of delivering high-capacity computing and storage infrastructure to end users via a shared pool of resources managed by service providers. These services typically offer users access to software applications, data storage, and processing capabilities on demand, facilitated by a high-speed network that connects clients to centralized data centers. Although cloud service models may vary, they fundamentally revolve around subscription-based access to scalable computing resources maintained by the provider.

Green cloud computing (GCC) extends this model by incorporating environmentally conscious computing practices. It emphasizes the deployment and management of ICT infrastructure—such as energy-efficient processors, storage systems, and networking hardware—in a way that minimizes ecological impact. This approach not only seeks to optimize energy use but also addresses issues such as electronic waste management and the reduction of toxic materials. The broader field of green computing, from which GCC draws its foundation, focuses on minimizing environmental harm throughout the entire lifecycle of computing technologies. It promotes sustainable design, efficient use, and responsible disposal or recycling of equipment.

The shift toward cloud-based services brings notable advantages, including operational simplicity, cost-efficiency, and reduced maintenance burdens [10]. When combined with green practices, cloud computing also contributes to sustainability goals, making it a compelling option for modern IT management. As the environmental crisis intensifies, these benefits become increasingly relevant. According to the International Energy Agency (IEA), global carbon dioxide emissions from fossil fuels and industrial activities reached 36.8 gigatons in 2022—marking a 0.9% increase from the previous year and setting a new record. Projections indicate this figure could rise to 42 gigatons by 2030 if no additional climate action is undertaken, potentially leading to a global temperature increase of 2.7°C by the century's end—posing severe risks to ecosystems and human society [3].

In light of mounting environmental regulations and investor scrutiny, businesses are under increasing pressure to adopt low-emission practices. Green cloud computing emerges as a viable solution, offering opportunities to reduce carbon output and energy use through optimized data center operations, renewable energy integration, and sustainable resource management. Without decisive shifts in energy consumption, current practices—especially those involving fossil fuels to power data centers—will continue to escalate greenhouse gas emissions. These facilities rely heavily on energy-intensive systems for cooling, redundancy, and round-the-clock processing, all of which contribute significantly to environmental degradation. By 2030, data centers are expected to account for a substantial share of global electricity usage and carbon emissions if these challenges remain unaddressed.



**Figure-2: Data Centers' Share of Global Energy Use and Emissions (2015–2030)**

## Services of Cloud Computing

Cloud computing is supported by a network of interconnected data centers that deliver a variety of services over the internet. These services are commonly classified into three primary models: **Software as a Service (SaaS)**, **Platform as a Service (PaaS)**, and **Infrastructure as a Service (IaaS)**. Each model provides a distinct level of abstraction and functionality tailored to different user needs [6, 9, 10].

### *Software as a Service (SaaS):*

SaaS allows users to access software applications remotely through the cloud, typically via a web browser. This model reduces the need for internal IT management, software installation, and data storage, as the provider hosts and maintains the software infrastructure. Popular SaaS solutions include tools for customer relationship management (CRM), enterprise resource planning (ERP), and collaboration platforms such as Slack. By offloading operational overhead, SaaS enables organizations to streamline access and deployment of applications.

### *Platform as a Service (PaaS):*

PaaS provides a complete development and deployment environment in the cloud. It enables developers to build, test, and deploy applications without the need to manage the underlying hardware or system software. While it shares similarities with SaaS, PaaS is specifically oriented toward software creation and delivery. The platform includes runtime environments, development frameworks, and integration tools that facilitate the entire software lifecycle.

### *Infrastructure as a Service (IaaS):*

IaaS offers fundamental computing resources such as virtual servers, storage, and networking components over the internet. Clients can scale their infrastructure needs dynamically without investing in physical hardware. A notable example is Amazon EC2, which allows users to provision virtual machines and manage computing resources based on demand. IaaS is particularly beneficial for organizations seeking flexibility and control over their IT infrastructure while minimizing capital expenditure.

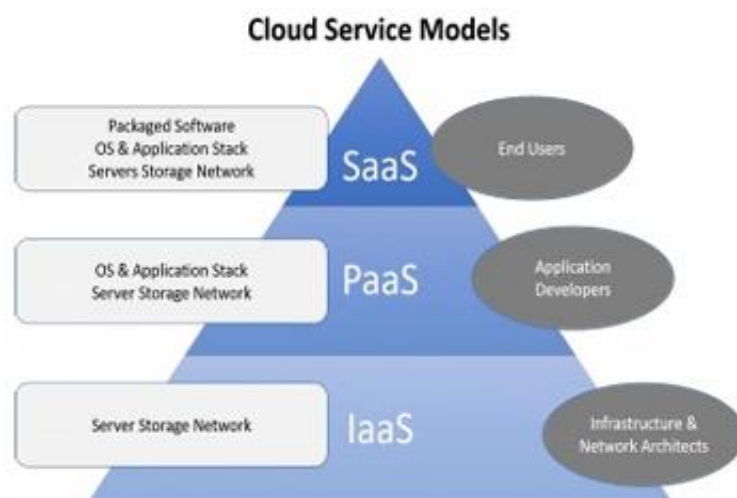


Figure-3: Classification and User Roles in Cloud Service Delivery Models

## Overview of Cloud Computing

Cloud computing has emerged as a transformative paradigm in modern computing due to its ability to deliver scalable, high-performance computing and storage capabilities without the need for extensive on-premise infrastructure. By leveraging virtualization technologies within centralized data centers, it enables organizations to access complex applications and data storage solutions in a flexible and cost-effective manner. Its appeal largely stems from the financial efficiency it offers, minimizing the need for substantial investments in hardware and software.

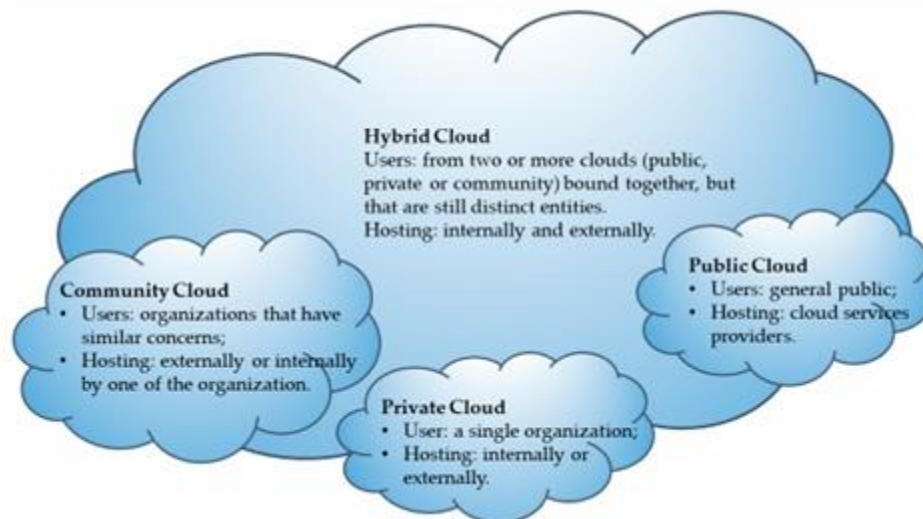
The foundational principles of cloud computing incorporate a range of computing models and technologies, including both well-established and contemporary approaches. Traditional paradigms such as parallel computing, distributed computing, and virtualization are integrated with newer architectural concepts like Service-Oriented Architecture (SOA), Microservices, grid computing, and containerization. This evolving ecosystem supports highly dynamic, service-driven solutions that are continuously optimized from both hardware and software perspectives [16].

Heininger identifies several defining characteristics of cloud computing, including ubiquity, scalability, service-centricity, consumption-based billing, and user self-service capabilities. These traits underscore the adaptability and user-oriented nature of cloud services. According to the National Institute of Standards and Technology (NIST), cloud computing is best described as a model that allows for "ubiquitous, convenient, on-demand network access

to a shared pool of configurable computing resources"—such as networks, servers, storage, applications, and services—which can be quickly provisioned and released with minimal managerial oversight.

Buyya et al. further conceptualize cloud computing as a parallel and distributed system composed of interconnected and virtualized nodes, collectively delivering unified computing services based on service-level agreements negotiated between providers and consumers. This framework not only facilitates efficient resource utilization but also enhances responsiveness to user demands.

The cloud service landscape is generally categorized into three primary models: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). IaaS and PaaS cater primarily to developers and software vendors, providing backend infrastructure and development platforms, respectively, while SaaS targets end users by offering complete application solutions delivered via the cloud [7].



**Figure-4: Classification of Cloud Deployment Models and Their Characteristics**

Kliazovich et al. describe a cloud data center, from an energy efficiency standpoint, as a system composed of computing and communication resources structured to convert consumed electrical power into computational or data transmission tasks that meet user requirements [11]. This perspective particularly aligns with the Infrastructure as a Service (IaaS) model, where energy usage and efficiency are critical considerations in service delivery.

In addition to IaaS, Software as a Service (SaaS) also contributes to environmental sustainability by centralizing processing tasks and enabling resource sharing. This consolidation reduces the amount of physical equipment required, leading to decreased energy consumption and electronic waste. SaaS providers can further enhance sustainability by hosting their applications on eco-friendly data centers, minimizing redundancy, and employing energy-efficient software algorithms—all while maintaining compliance with Service Level Agreements (SLAs) [26].

Compared to individual users, cloud service providers have greater incentives and capabilities to invest in sustainable technologies and practices. In the case of Platform as a Service (PaaS), providers may introduce features such as energy-aware compilers and intelligent scheduling systems that optimize application execution with minimal environmental impact [29].

Green cloud computing encourages SaaS and PaaS providers alike to integrate tools and methods that enable energy optimization at the software level [20]. These strategies contribute to the broader effort of reducing the ecological footprint of IT infrastructure.

The rising adoption of cloud technologies by both individuals and enterprises can be largely attributed to the operational advantages they offer. These include enhanced flexibility, improved disaster recovery mechanisms, lower capital investment in ICT infrastructure, streamlined collaboration across organizational units, and the convenience of automatic software updates. Together, these factors have accelerated the shift toward cloud-based solutions while aligning them with sustainable development goals.

## Research Method:

As emphasized by Webster and Watson, a comprehensive literature review serves as a crucial step in building a credible foundation for scholarly advancement [36]. To assess the current landscape of research on green cloud computing, both academic and non-academic sources were examined. The academic review included materials such as journal articles, conference proceedings, technical reports, and scholarly books. These were sourced from prominent scientific databases, including the ISI Web of Science, the Association for Computing Machinery (ACM) Digital Library, IEEE Xplore, Scopus, and ScienceDirect—platforms known for providing access to leading journals and peer-reviewed publications in the field of computer science [36].

To guide the search process, a set of targeted keywords was used, including "green cloud computing," "sustainable cloud computing," and the term "sustainable" in combination with "cloud computing."

This structured approach yielded a total of 1,922 relevant results (Table1):

**Table 1.** Numbers of papers in international databases.

Year	Database				
	Web of Science	ACM Digital Library	IEEE Computer Society	Scopus	Science Direct
2009	7	4	4	8	10
2010	3	4	12	17	19
2011	12	15	21	42	41
2012	22	12	37	70	73
2013	31	12	43	82	83
2014	61	12	51	84	142
2015	65	3	63	84	201
2016	48	16	48	94	266
Total	249	78	279	481	835

### Architecture of GCC:

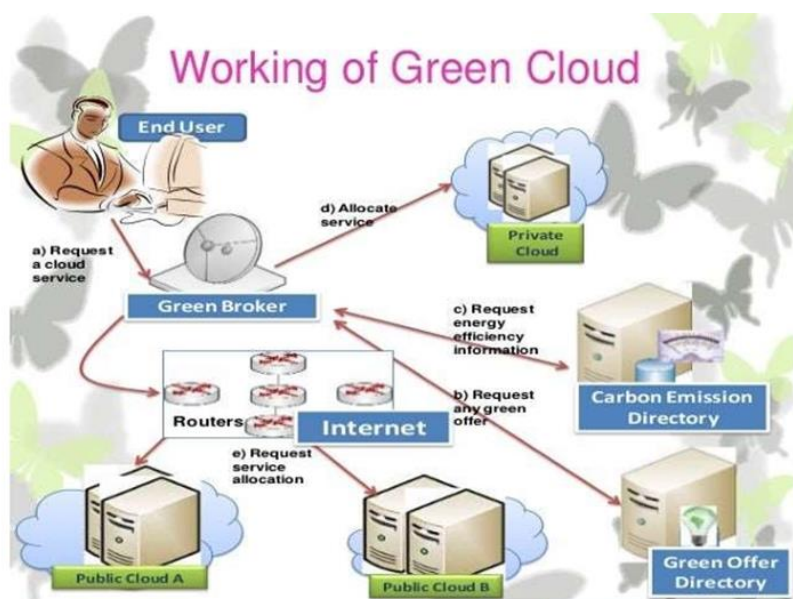
The conceptual framework of green cloud computing encompasses several key components that collaboratively promote environmentally sustainable practices in cloud service delivery. The operational model begins with the end user, who initiates a service request. This request is then mediated by a specialized entity known as the Green Broker, responsible for allocating resources in an energy-efficient manner while considering associated carbon emissions [17,23].

Green cloud computing integrates various actors, including public and private cloud providers, as well as directories that store data on carbon footprints and environmentally friendly service options. These directories play a critical role by offering reference points for carbon-aware decision-making, enabling brokers to prioritize sustainable service alternatives [27].

At its core, green cloud computing aims to reduce the ecological impact of cloud infrastructure through strategies such as server virtualization, adoption of renewable energy sources, and optimized energy distribution. By implementing these methods, the model effectively minimizes power consumption and lowers greenhouse gas emissions, thereby supporting a more sustainable digital ecosystem [12].

### Roles in the Green Cloud Model:

- End Users: Initiate requests for cloud-based services.
- Green Broker: Oversees service allocation, focusing on energy efficiency and emission reduction.
- Cloud Providers: Both public and private entities fulfill user demands with cloud-based solutions.
- Directory Services: Maintain and reference carbon footprint data and sustainable service options to inform resource allocation.



**Figure-5:** Architecture and Workflow of a Green Cloud Computing Environment



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## **Impact of GCC on environment:**

Green cloud computing involves the creation, deployment, and operation of cloud computing systems with an emphasis on environmental sustainability. Its main aim is to lower energy usage, decrease carbon dioxide emissions, and reduce other harmful environmental consequences linked to IT infrastructure. This approach supports a more sustainable cloud ecosystem that lessens the environmental footprint of cloud computing services [13].

Key environmental benefits of green cloud computing include:

### ***Reducing Carbon Emissions***

Adopting green computing practices plays an essential role in lowering the carbon footprint of technology use. Transitioning to public cloud services can dramatically reduce CO<sub>2</sub> emissions. Estimates suggest that migrating to the cloud may cut global CO<sub>2</sub> emissions by around 59 million tons annually, equivalent to removing about 22 million vehicles from the roads. In Europe, data centers accounted for 2.7% of total electricity consumption in 2018, with projections indicating a rise to 3.21% by 2030 if current consumption trends continue, according to the European Commission. This demonstrates the considerable energy demand of data centers, which is expected to grow as more organizations adopt cloud computing.

### ***Decreasing Energy Consumption***

Green cloud computing focuses on energy efficiency by optimizing power usage within data centers. These centers employ advanced energy management techniques that adjust consumption dynamically to match workload demands. According to the International Energy Agency (IEA), data centers consume between 1% and 1.5% of global electricity. In 2021, their energy use ranged from 220 to 320 terawatt-hours, making up roughly 0.9% to 1.3% of worldwide electricity demand—a significant increase of 10% to 60% compared to 2015 levels [18].

### ***Lowering Greenhouse Gas Emissions***

Cloud computing helps reduce greenhouse gas emissions generated by conventional data centers. A survey by Accenture found that businesses could decrease carbon emissions per user by 30% to 90% through cloud adoption. While accurately measuring carbon emissions remains a challenge, moving to cloud-based IT environments is a valuable strategy for businesses seeking to reduce their environmental impact.

### ***Promoting Dematerialization***

The cloud enables instant sharing of digital content across devices and locations, supporting dematerialization—the replacement of physical products with virtual alternatives that have a lower carbon footprint. Switching to cloud infrastructure reduces reliance on physical hardware, which in turn lowers energy use and environmental impact. These sustainable practices can also boost business efficiency, reduce costs, and improve overall profitability.

### ***E) Optimizing Data Center Location***

Selecting data center sites strategically is critical for sustainability. Factors such as availability of renewable energy, favorable climate conditions for natural cooling, and proximity to end-users (to reduce latency) all influence the environmental efficiency of cloud services. Green cloud computing aims to meet the rising demand for cloud resources while minimizing carbon emissions, power consumption, and other negative environmental effects traditionally associated with data centers.

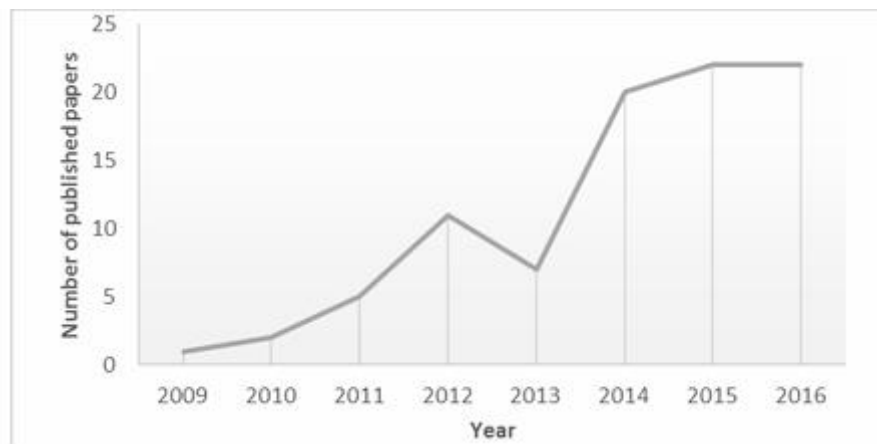
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## **Green Cloud Computing Status and Trends:**

Interest in exploring the environmental impact of cloud computing has grown significantly, largely driven by the rising focus on green computing within the tech community. This attention partly arose following a Gartner report that estimated the global ICT sector was responsible for roughly 2% of worldwide CO<sub>2</sub> emissions. In 2009, Liu et al. introduced the concept of Green Cloud—a novel architecture aimed at reducing power consumption in data centers. However, efforts to develop strategies for lowering data center energy use predate this work and have gained momentum since then. These foundational studies have played a critical role in the advancement of green cloud computing [33].

At the core of green cloud computing are green data centers, designed to optimize energy efficiency and minimize both CO<sub>2</sub> emissions and electronic waste. This comprehensive approach extends beyond ICT hardware to include all relevant environmental factors such as building design, lighting, and cooling systems. The scope of green computing encompasses not only the energy consumption of computing devices but also networks, cooling infrastructure, and broader environmental concerns like carbon emissions, waste management, and the use of natural resources [34].

Within this framework, research interests have diversified across various subfields of green computing. Initially, investigations focused on the interplay between sustainability and cloud computing. The trajectory of this research has been influenced by the growing environmental awareness and the widespread adoption of cloud technologies. Academic publications reflect this trend, showing a steady increase in research on green cloud computing from 2009 through 2016, with the exception of a slight dip in 2013 (see Figure 6).



**Figure-6: Trend in Number of Published Research Papers (2009–2016)**

We categorized green cloud computing research into five main groups: models and methods, architectures, frameworks, algorithms, and general issues. These studies focus on addressing environmental challenges such as enhancing energy efficiency, managing data center resources (both hardware and software) effectively, lowering operational expenses, and decreasing carbon emissions. Some works tackle multiple environmental challenges simultaneously, and certain studies span more than one category—for example, combining frameworks with algorithms or models and methods with architectures [13].

Table 2 summarizes the reviewed papers by their respective categories and the environmental issues they address. For each publication, we identified the primary category and one or more environmental concerns for which the authors proposed solutions.

Efficient resource management plays a critical role in boosting cloud computing performance by reducing energy use, electronic waste, and operational costs. In the context of green cloud computing, resource management involves leveraging heterogeneous, geographically distributed resources to fulfill client demands while minimizing environmental harm [33]. Notably, several factors that benefit cloud service providers also align with environmental goals—for instance, lowering energy consumption reduces operational costs and simultaneously cuts CO<sub>2</sub> emissions.

Many green cloud computing studies introduce new methods and models aimed at optimizing resource management or minimizing energy consumption, with numerous papers presenting novel algorithms. Other topics, such as environmental impact metrics, broader analyses of negative environmental effects, and the role of providers in promoting sustainability, are grouped under general issues.

Beyond academic research, we also reviewed reports from ICT organizations, consulting firms, NGOs, and other relevant sources. These non-academic materials significantly shape perceptions of green cloud computing among various stakeholders—including businesses, government agencies, and individual users. In some cases, they may provide a more accurate reflection of the real-world impact of technological changes, given their influence on market trends and adoption. Together, academic and non-academic studies offer a comprehensive understanding of green cloud computing, which is essential from both technical and societal perspectives [15].

Moreover, fostering strong collaboration between academic institutions and industry stakeholders is essential for the advancement of green cloud computing. Academic researchers provide valuable theoretical frameworks, models, and experimental results that can inform and guide practical implementations. Meanwhile, industry players offer real-world challenges, data, and deployment environments that help validate and refine these innovations.

This partnership enables the development of energy-efficient cloud technologies that are not only technically sound but also scalable and economically viable. By working together, both sectors can promote the integration of sustainable practices into the lifecycle of cloud services—from design and resource allocation to operation and maintenance.

Additionally, collaboration encourages the establishment of industry standards and best practices focused on reducing environmental impact. Such joint efforts accelerate the adoption of green cloud solutions, supporting broader environmental objectives while helping organizations achieve cost savings and operational efficiencies in an increasingly cloud-dependent world.

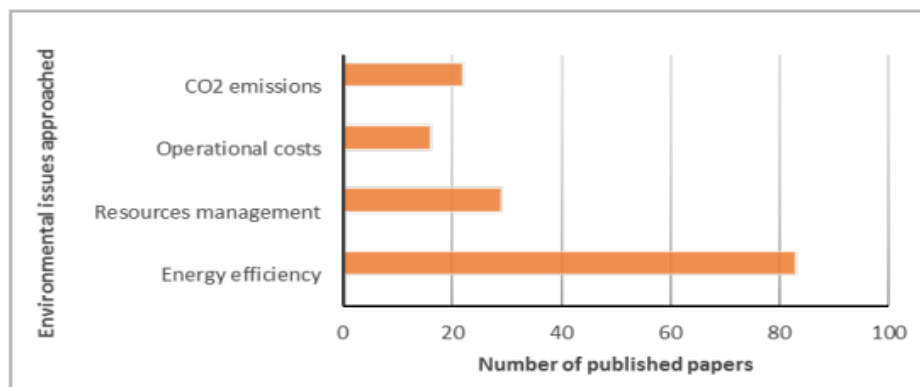
The most studied topic is optimization of energy consumption, followed by resource management.

**Table 2.** Classification of the papers reviewed.

Category	Surveys	Survey Focus			
		Energy Efficiency	Resource Management	Operational Costs	CO <sub>2</sub> Emissions
Algorithms	[17–25]	✓	✓		
	[26,27]	✓			✓
	[28–38]	✓			
	[39,40]	✓		✓	
	[41]	✓	✓	✓	
	[42]	✓	✓	✓	
Architectures	[11,43–45]	✓	✓		
	[12,46–50]	✓			
	[51]	✓		✓	
Frameworks	[52]				✓
	[53,54]	✓	✓		
	[55,56]	✓		✓	✓
	[57]	✓		✓	
	[58,59]	✓			
General Issues	[60–65]	✓			
	[66–68]	✓			✓
	[69]	✓	✓		
	[70]	✓	✓		✓
	[71]	✓		✓	
	[72]				✓
	[73]	✓		✓	✓
Models & Methods	[74,75]	✓	✓		✓
	[76–80]	✓			✓
	[81–87]	✓	✓	✓	
	[88]		✓		
	[89–98]	✓			
	[99–101]				✓
	[102]	✓		✓	✓
	[103]	✓		✓	
	[104]	✓			✓

**Figure-7: Distribution of Research Papers by Environmental Issue Addressed**

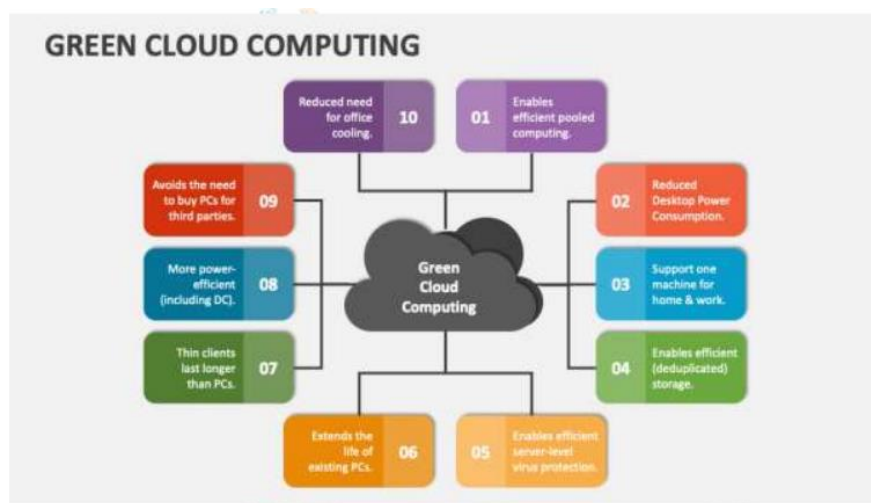
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## Benefits Of GCC:

Adopting green cloud computing practices benefits both organizations and the environment by promoting resource efficiency, reducing waste, and minimizing energy consumption.



**Figure-8: Benefits of Green Cloud Computing**

- **Efficient Multi-Tenant Computing:** Green cloud computing optimizes the use of shared resources, improving computing power utilization, which lowers costs and reduces energy consumption.
- **Lower Desktop Power Usage:** Prioritizing thin clients and virtual desktops significantly cuts power consumption compared to traditional desktop setups, supporting environmental sustainability.
- **Single Device Access for Home and Work:** Users can access their work environment from anywhere using one device, reducing the need for multiple machines and decreasing energy use.
- **Storage Efficiency through Deduplication:** Cloud storage employs deduplication to remove redundant data, saving storage space and minimizing energy required to maintain infrastructure.
- **Centralized Antivirus Protection:** Server-level security in cloud data centers enhances antivirus effectiveness while reducing the energy needed to protect individual devices.
- **Extending PC Lifespan:** By enabling remote access to applications and data, organizations can extend the useful life of existing PCs, lowering electronic waste.
- **Longevity of Thin Clients:** Thin clients typically last longer than traditional PCs, contributing to reduced e-waste and increased sustainability.
- **Energy-Efficient Data Centers:** Green data centers use advanced cooling, efficient hardware, and renewable energy sources to minimize their environmental footprint.
- **Minimized Hardware Purchases:** Cloud access reduces the need to provide physical PCs to contractors or temporary staff, cutting down on hardware-related energy use.
- **Reduced Office Cooling Needs:** Centralizing computing in data centers decreases heat output in offices, lowering the demand for air conditioning and cooling.

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## Challenges in implementation of green cloud computing :

### *Lack of Awareness:*

- There is a widespread lack of understanding about environmentally friendly cloud computing among the general public. Many individuals are unaware of its environmental implications and need to be informed about the importance of adopting green computing infrastructures.

### *Implementation Costs:*

- Some argue that traditional methods are more cost-effective in the short term. However, neglecting the long-term environmental consequences of such choices may have severe repercussions for humanity. It is crucial to consider both direct and indirect environmental impacts when selecting technologies.

### *Managing Heat Removal Needs:*

- The growing use of computing devices increases the demand for cooling systems, which in turn raises overall energy consumption [5].

### *Electronic Waste Disposal:*

- Proper management of e-waste remains a significant environmental challenge linked to cloud computing infrastructure.

### *Mixed Environmental Impact:*

- Cloud computing integrates various innovations to enhance resource efficiency. However, experts and service providers acknowledge both positive and negative environmental effects associated with these advancements.

### *A Paradigm Shift:*

- Green cloud computing represents a transformative approach, merging technological innovation with ecological stewardship. This synergy addresses the dual challenges of technological advancement and climate change, fostering more resilient and sustainable systems.

### *Global Environmental Benefits:*

- Adopting green cloud computing has wide-reaching effects on global sustainability efforts. By optimizing energy consumption, lowering emissions, and encouraging renewable energy use, it supports climate action and promotes a more competitive and sustainable future [33].

### *Balancing Growth and Sustainability:*

- Green cloud computing plays a vital role in managing environmental impacts while supporting the rapid expansion of digital technologies.

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## Discussion of the Topics in the Review Articles :

Green cloud computing aims to reduce energy consumption and carbon footprints by improving cloud energy efficiency and integrating renewable energy sources. Cloud users contribute by replacing high-power devices with low-power alternatives, while cloud providers implement strategies ranging from simple server power management (such as turning servers on/off or sleep modes) to advanced approaches like auto-scaling and virtualization for optimized resource use.

The development of green cloud computing is closely linked to green data centers, which are designed to minimize environmental impact through efficient lighting, cooling, building materials, and computing infrastructure. These data centers often employ low-emission materials and alternative energy sources, promoting sustainability [22].

Energy-saving efforts occur at two levels: the server level, focusing on minimizing the power of individual servers through techniques like reducing CPU clock speeds and powering down idle components; and the data center level, emphasizing virtualization and energy-aware scheduling to optimize server pools. Effective scheduling allows resources to be used efficiently while maximizing the number of servers in low-power states.

Researchers identify three main energy consumers in data centers: computing hardware, communication devices, and physical infrastructure. Hardware optimization often involves dynamic voltage and frequency scaling (DVFS) and power management technologies, while software improvements include efficient programming and workload management.

Thermal management is another crucial factor. Enhancing airflow, intelligent cooling systems, and situating data centers in cooler climates significantly reduce energy needs. Additionally, integrated energy management systems can optimize workloads, cooling, and waste heat recovery.

Importantly, the use of renewable energy complements energy efficiency, significantly lowering carbon emissions. Researchers have proposed unified architectures to monitor and reduce the carbon footprint based on emission rates, data center power efficiency, and virtual machine utilization [35].

The advantages of green cloud computing primarily revolve around saving energy and lowering carbon emissions. From the perspective of energy efficiency, cloud providers can promote greener computing by enhancing the cloud's energy performance and utilizing renewable energy sources. Users can contribute by switching from power-intensive devices to more energy-efficient alternatives. Energy reduction techniques range from straightforward methods, like managing server power states (turning them off or into sleep mode), to more advanced strategies, such as auto-scaling infrastructure and applying virtualization to optimize resource use. The advancement of green cloud computing is strongly tied to the progress of green data centers, where infrastructure components—including lighting, electrical, mechanical, building materials, and IT systems—are designed to maximize energy savings and minimize environmental impact. Such data centers often employ low-emission construction materials, alternative energy sources, and efficient power usage for equipment operation and maintenance. Achieving reduced energy consumption in servers involves two main approaches: minimizing power use at the individual server level and optimizing energy consumption across server pools in data centers. At the server level, techniques include powering down chip components, lowering CPU frequencies, increasing energy efficiency per unit of work, enabling operation at higher temperatures, improving workload handling, and shutting off idle parts. At the data center level, virtualization is emphasized to boost resource utilization while maintaining flexibility and reliability.

Additionally, improving data center architecture and scheduling with energy awareness can lead to significant power savings. Kliazovich and colleagues identified three major energy consumers: computing devices, communication equipment, and the physical data center infrastructure. Reducing energy use can be approached through hardware or software optimizations. Hardware strategies often employ dynamic voltage and frequency scaling and power management technologies, while software approaches focus on efficient program design, reduced storage demands, and advanced computing models like distributed and grid computing. Early work in this field included a heuristic algorithm based on virtual machine migration to optimize VM placement, yielding energy reductions of about 27% compared to traditional methods. Subsequent research has developed numerous algorithms aimed at balancing time, cost, and energy consumption to optimize cloud resource use. Thermal regulation is crucial for data center efficiency; improvements such as optimized hardware layouts to manage hot and cold airflow, smart cooling system controllers, and choosing data center locations with cooler climates (under 13°C for several months) contribute to energy savings. Integrated energy management systems have been proposed to coordinate workload, cooling, local power generation, and heat recovery. Sustainable energy strategies must balance energy efficiency with the use of renewables. As noted by Bateman and Wood, cloud computing qualifies as “green” when powered by renewable energy. Another key benefit is reducing carbon emissions, a focus for both cloud users and providers. Emissions are directly linked to energy use and are often addressed through energy-saving measures rather than as a separate concern. Architectures have been proposed to reduce the carbon footprint of cloud infrastructures, considering factors like CO<sub>2</sub> emission rates, data center power efficiency (the proportion of energy used directly by IT equipment), and virtual machine efficiency at maximum utilization.

The advantages of green cloud computing highlighted in the literature are closely interconnected. Lowering energy consumption not only reduces operational costs but also decreases CO<sub>2</sub> emissions. Additionally, minimizing the amount of equipment used contributes to further reductions in energy use and the generation of electronic waste. Enhancing energy efficiency alongside reducing infrastructure demands can significantly cut carbon emissions associated with cloud computing. Beyond these direct environmental impacts, green cloud computing also fosters indirect benefits, such as promoting education, spreading environmental awareness, supporting sustainable governance, and improving communication channels for ecological initiatives and networks. Other broad strategies identified for advancing green cloud computing emphasize the importance of both providers and users adopting environmentally friendly ICT hardware and software. Cloud providers should actively monitor and analyze the power usage of their servers, cooling systems, and client applications, along with their environmental impacts. Software across all layers must be designed to promote ecological efficiency, with comprehensive design approaches that integrate all relevant factors—such as cooling, memory, networking, and CPU usage—into software scheduling and resource allocation processes.

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## Conclusions:

Cloud computing represents a novel model that combines existing technologies to enhance resource utilization efficiency. The outcomes of applying these technologies are diverse. Both service providers and researchers from organizations focused on environmental protection have pointed out both positive and negative environmental impacts of cloud computing. Generally, cloud computing can support a sustainable relationship with the environment if hardware manufacturers and service providers align their practices with environmental regulations and heed the recommendations of NGOs aimed at mitigating the adverse effects of hardware and software. This paper reviews the contributions of cloud computing to environmental sustainability based on current research in this area [2,31].

### *Key points include:*

- (1) The primary touted advantage is improved energy efficiency. To comply with environmental regulations, cloud service providers must minimize reliance on non-renewable energy and increase the use of renewable energy sources. Current studies indicate that the share of clean energy use remains relatively high, surpassing that from non-renewable sources [14].
- (2) While greater use of renewable energy can reduce CO<sub>2</sub> emissions, the expected levels of reduction remain uncertain because the shift to renewables has not yet reached anticipated targets.
- (3) Reducing electronic waste is another significant but debated benefit. Cloud computing may decrease the volume of physical equipment needed by organizations and slow the pace of hardware replacement; however, these are long-term effects, and it is challenging to predict whether cloud computing will adequately address this complex global issue.

The cloud computing market is expanding rapidly, and if this trend continues, its environmental impacts will become clearer over time. Positive ecological outcomes depend on the commitment of both providers and users to environmental goals, as is the case with any policy prioritizing sustainability. The information presented in this paper aims to inform readers about the current landscape of green cloud computing.

As a result of the research undertaken, we mention the following aspects, which should be considered by cloud suppliers as well as users if cloud computing is to have a favorable relationship with the environment.

- (1) Providers of cloud computing services should justify the benefits to organizations in terms of a proper cost–benefit ratio.
- (2) Cloud technologies should be implemented according to green ICT principles, with the minimum possible negative influences on the environment.
- (3) Reducing energy consumption, CO<sub>2</sub> emissions, and e-waste should be a priority for the suppliers of cloud services, as well as for consumers when they choose their suppliers.
- (4) Environmental organizations should make sure that information is clearly available on the influence of cloud technologies on the environment. Specific objective analyses should be performed, aimed at providing data to organizations interested in adopting these technologies.
- (5) Cloud service suppliers should be aware of all the environmental recommendations in every country and adapt their activities accordingly.

Green cloud computing represents a transformative approach that integrates advanced technologies to promote energy efficiency and environmental sustainability in the rapidly growing digital landscape. Its primary benefits are closely intertwined, including significant reductions in energy consumption, carbon emissions, and operational costs. These outcomes are achievable through a combination of hardware and software innovations, along with the strategic use of renewable energy sources. Cloud providers are increasingly focusing on improving the energy efficiency of their infrastructure by adopting techniques such as dynamic voltage and frequency scaling (DVFS), power management technologies, and virtualization. Virtualization, in particular, plays a vital role in optimizing resource utilization, enabling flexible workload management, and allowing idle servers to enter low-power states, which collectively contribute to lower energy usage across server pools. At the same time, users also participate by shifting from energy-intensive personal computing devices to more energy-efficient endpoints that rely on cloud resources, thereby indirectly reducing the overall energy footprint.

Despite these promising developments, challenges remain, particularly in terms of minimizing e-waste and increasing the share of renewable energy usage within cloud operations. While cloud computing can reduce the amount of physical equipment organizations require, and potentially slow down equipment turnover, this long-term benefit is difficult to quantify and depends on broader industry adoption of sustainable practices. The transition to renewable energy is another critical factor in the green credentials of cloud computing. Although progress has been made, current data indicates that renewable energy usage is still not sufficiently widespread to meet the high expectations set by environmental advocates. Thus, carbon emissions reductions, while correlated with energy efficiency gains, may not yet fully align with sustainability goals [32].

The positive impacts of green cloud computing extend beyond the direct environmental benefits. By fostering a culture of sustainability, cloud computing encourages broader awareness and education on environmental issues, supports sustainable governance, and facilitates improved communication networks for environmental projects. Providers and consumers alike are encouraged to adopt environmentally friendly ICT hardware and software, measure power consumption and cooling requirements accurately, and design solutions that integrate all components—CPU, memory, network, and cooling—into energy-aware scheduling and resource management frameworks [8,19].

In conclusion, green cloud computing offers a compelling pathway to more sustainable IT operations by reducing energy consumption, carbon emissions, and operational expenses, while enhancing resource utilization. The synergy between technological innovation, renewable energy integration, and sustainable infrastructure design is essential for realizing these benefits. However, success depends on the commitment of all stakeholders—cloud providers, users, policymakers, and equipment manufacturers—to adopt and promote eco-friendly practices.

## REFERENCES:

1. Hilty, M.L.; Arnfalk, P.; Erdmann, L.; Goodman, J.; Lehmann, M.; Wager, A.P. The relevance of information and communication technologies for environmental sustainability—A prospective simulation study. *Environ. Model. Softw.* 2006, 21, 1618–1629. [CrossRef]
2. Koomey, J. Growth in Data Center Electricity Use 2005 to 2010. 2011. Available online: <http://www.analyticspress.com/datacenters.html> (accessed on 12 June 2016).
3. GeSI. GeSI SMARTer 2020: The Role of ICT in Driving a Sustainable Future. 2013. Available online: <http://gesi.org/SMARTer2020> (accessed on 2 November 2016).
4. Masanet, E.; Shehabi, A.; Ramakrishnan, L.; Liang, J.; Ma, X.; Walker, B.; Hendrix, V.; Mantha, P. The Energy Efficiency Potential of Cloud-Based Software: A U.S. Case Study. 2013. Available online: <https://www.osti.gov/scitech/servlets/purl/1171159> (accessed on 12 January 2017).
5. Rasheed, H. Data and infrastructure security auditing in cloud computing environments. *Int. J. Inf. Manag.* 2014, 34, 364–368. [CrossRef]
6. Armbrust, M.; Fox, A.; Griffith, R.; Joseph, A.D.; Katz, R.H.; Konwinski, R.; Lee, G.; Patterson, D.; Rabkin, A.; Stoica, I.; et al. Above the Clouds a Berkeley View of Cloud Computing. 2009. Available online: <http://cacs.usc.edu/education/cs653/Armbrust-CloudComp-Berkeley09.pdf> (accessed on 14 June 2016).
7. Youseff, L.; Butrico, M.; Da Silva, D. Toward a Unified Ontology of Cloud Computing. In *Proceedings of the Grid Computing Environments Workshop*, Austin, TX, USA, 12–16 November 2008; IEEE: New York, NY, USA, 2008; pp. 1–10. [CrossRef]
8. Heininger, R. IT Service Management in a Cloud Environment: A Literature Review. In *Proceedings of the 9th Workshop on Information Systems and Services Sciences*, München, Germany, 8–10 May 2012; pp. 1–12.
9. Mell, P.; Grance, T. The NIST Definition of Cloud Computing. 2009. Available online: <http://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-145.pdf> (accessed on 14 June 2016).
10. Buyya, R.; Yeo, C.S.; Venugopal, S.; Broberg, J.; Brandic, Y. Cloud computing and emerging IT platforms: Vision, hype, and reality for delivering computing as the 5th utility. *Future Gener. Comput. Syst.* 2009, 25, 599–616. [CrossRef]

11. Kliazovich, D.; Bouvry, P.; Khan, S.U. GreenCloud: A packet-level simulator of energy-aware cloud computing data centers. *J. Supercomput.* 2012, 62, 1263–1283. [CrossRef]
12. Liu, L.; Wang, H.; Liu, X.; Jin, X.; He, W.B.; Wang, Q.; Chen, Y. GreenCloud: A new architecture for green data center. In *Proceedings of the 6th International Conference Industry Session on Autonomic Computing and Communications Industry Session*, Barcelona, Spain, 15–19 June 2009; ACM: New York, NY, USA, 2009; pp. 29–38. [CrossRef]
13. *Journal of Emerging Technologies and Innovative Research (JETIR)* A survey on Green Cloud Computing Current Trends and Upcoming Research Challenges (ISSN-2349-5162).
14. [https://www.researchgate.net/figure/Architectural-Diagram-for-Green-Cloud-Computing20\\_fig2\\_261990887](https://www.researchgate.net/figure/Architectural-Diagram-for-Green-Cloud-Computing20_fig2_261990887)
15. Emerging Issues of Green Computing in IT, *International Journal of Scientific & Engineering Research* Volume 8, Issue 5, May-2017, ISSN 2229-5518.
16. <https://www.mygreatlearning.com/blog/virtualization-in-cloud-computing/>
17. Green Cloud Computing Architecture with Efficient Resource Allocation System, *International Journal of Trend in Research and Development*, Volume 3(6), ISSN: 2394-9333
18. <https://www.techtarget.com/searchdatacenter/tip/Four-ways-to-reduce-data-center-powerconsumption>
19. <https://www.sciencedirect.com/topics/computerscience/dematerialization>
20. <https://www.parallels.com/blogs/ras/what-is-green-cloud-computing/>
21. How Cloud Computing Paves the Way for Green IT Solutions (scand.com)
22. Green Cloud Computing: The Future of Sustainable Cloud Computing <https://cloud.report/articles/green-cloud-computing-the-future-of-sustainable-cloud-computing>
23. Cloud Computing Sustainability & The Green Cloud | Accenture <https://www.accenture.com/us/en/insights/strategy/green-behind-cloud>
24. Building a Sustainable Future with Green Cloud Computing(eleviant.com) <https://www.eleviant.com/insights/blog/building-a-sustainable-future-with-green-cloud-computing/>
25. Top 5 Environmental Benefits of Cloud Computing Today — Lateral (getlateral.com)
26. <https://www.techtarget.com/searchstorage/definition/green-cloud>
27. Google Cloud aims for carbon-free energy for its data centers | Google Cloud Blog <https://cloud.google.com/blog/topics/inside-google-cloud/announcing-round-the-clock-clean-energy-forcloud>
28. Green Cloud Computing: 5 Impactful Strategies Leading to Net Zero (datadynamicsinc.com)
29. <https://aws.amazon.com/sustainability/>
30. <https://news.microsoft.com/en-CEE/2023/05/18/microsoft-is-committed-to-achieving-zero-carbonemissions-and-waste-by-2030/>
31. <https://newsroom.ibm.com/2021-02-16-IBM-Commits-To-Net-Zero-Greenhouse-Gas-Emissions-By2030>
32. (PDF) A Review on Green Computing for Eco-Friendly and Sustainable IT (researchgate.net)
33. [https://www.researchgate.net/publication/235632619\\_A\\_Review\\_on\\_Green\\_Computing\\_for\\_EcoFriendly\\_and\\_Sustainable\\_IT](https://www.researchgate.net/publication/235632619_A_Review_on_Green_Computing_for_EcoFriendly_and_Sustainable_IT)
34. 29.R. Badre, “A Survey on Energy Efficiency in Cloud Computing *International Journal of Advanced Research in A Survey on Energy Efficiency in Cloud Computing*,” no. April, 2016.
35. I. Labunska, K. Brigden, D. Santillo, and P. Johnston, “Organic chemical and heavy metal contaminants in wastewater discharged from three textile manufacturing and washing facilities in Mexico.”
36. Analyzing the Past to Prepare for the Future: Writing a Literature Review.