Green Cloud Computing: Sustainability and Its Impact on the Environment and Natural Resources

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Abstract— Cloud computing has become an important part of modern technology because it provides flexible computing, storage and networking services. However, the increasing use of cloud services also creates environmental concerns due to electricity consumption, carbon emissions, water usage and electronic waste generated by data centres. This paper presents a review of Green Cloud Computing and its role in reducing the environmental impact of cloud infrastructure. The study reviews existing research on energy-efficient resource allocation, virtualization, workload consolidation, carbon-aware scheduling, renewable energy, cooling systems and hardware lifecycle management. The literature indicates that efficient resource utilization and workload scheduling can help reduce unnecessary energy consumption. It also shows that reducing electricity consumption alone is not enough to achieve complete environmental sustainability. Water consumption, electricity sources and hardware replacement must also be considered. Based on the reviewed studies, this paper proposes an Integrated Green Cloud Sustainability Strategy that combines energy management, carbon monitoring, water awareness and responsible hardware management. The proposed framework is conceptual and requires future simulation or practical implementation for validation. The study highlights the importance of considering environmental impact while maintaining cloud performance, reliability and service quality.

Keywords— Carbon emissions; Cloud computing; Data centres; Energy efficiency; Green cloud computing; Sustainability; Water consumption.

I. INTRODUCTION

Cloud computing provides computing resources, storage and applications through the internet. It allows users and organizations to access services without maintaining large physical infrastructure. Virtualization and shared resources help cloud providers serve many users through common data centres.

Although cloud computing offers several advantages, it also depends on physical infrastructure such as servers, storage devices, networking equipment, electricity and cooling systems. These facilities consume electricity and may contribute to greenhouse gas emissions. The environmental impact also includes water used for cooling, resources required to manufacture hardware and electronic waste generated when equipment is replaced.

Research by Baliga et al. [1] explains that the energy consumption of cloud computing includes processing, storage and network communication. Masanet et al. [2] highlight the importance of using reliable data when estimating global data-centre energy consumption. Dayarathna et al. [3] also discuss different methods for measuring and estimating data-centre energy use.

Green Cloud Computing focuses on reducing the environmental impact of cloud infrastructure while maintaining its performance and reliability. It includes energy-efficient resource allocation, virtualization, workload scheduling, cooling management, renewable energy usage and responsible hardware management [4], [5].

However, many existing approaches focus mainly on electricity consumption. Carbon emissions, water usage and hardware lifecycle impacts are often considered separately. This creates a need for a more integrated approach to cloud sustainability.

The main contribution of this study is a review of existing Green Cloud Computing techniques and a conceptual framework that considers energy, carbon, water and hardware lifecycle impacts together.

The study aims to:

- Review environmental impacts of cloud computing.
- Study existing energy-efficient cloud techniques.
- Understand carbon emissions and water consumption.
- Examine hardware lifecycle and electronic waste.
- Propose an integrated Green Cloud Sustainability Strategy.

II. RELATED WORK

Several researchers have studied methods to improve the environmental performance of cloud computing. The existing research can be grouped into the following main areas.

A. Energy Efficiency and Resource Management

Buyya et al. [4] discussed energy-efficient management of data-centre resources and identified important challenges in cloud computing. Beloglazov et al. [6] presented energy-aware resource allocation techniques to improve data-centre efficiency.

Virtualization allows multiple virtual machines to run on physical servers. It helps improve hardware utilization and reduce the need for unnecessary physical machines. Hamdi and Chainbi [7] studied virtual machine consolidation techniques and their effect on energy consumption.

Dayarathna et al. [3] reviewed different data-centre energy models and explained the importance of measuring energy consumption at different infrastructure levels.

B. Carbon-Aware Scheduling and Sustainable Architecture

Energy consumption and carbon emissions are related, but they are not the same. The amount of carbon emitted depends on the source of electricity used by a data centre.

Bahreini et al. [8] studied carbon-aware workload dispatching, where workloads can be scheduled according to electricity carbon intensity. This approach can help reduce operational

emissions when workloads have sufficient scheduling flexibility.

Procaccianti et al. [9] reviewed energy efficiency in cloud software architecture. Gill and Buyya [5] presented a broad classification of sustainable cloud computing techniques, covering application design, resource management and data-centre operations.

C. Water Consumption and Hardware Lifecycle

Data centres require cooling systems to maintain suitable operating temperatures. Some cooling technologies consume significant amounts of water. Mytton [10] discussed the challenges of measuring and reporting data-centre water consumption.

Lei et al. [11] reviewed the factors affecting water consumption in data-centre workloads. Their work highlights the importance of cooling technology, electricity supply, location and equipment efficiency.

Hardware manufacturing also contributes to environmental impact. Servers and networking equipment require materials and energy during manufacturing. Their replacement can increase electronic waste. Life-cycle assessment provides a method for studying environmental impacts throughout the life of a product [12].

The reviewed studies provide useful techniques for improving cloud sustainability. However, there is still a need to consider energy, carbon, water and hardware lifecycle impacts together when making cloud-management decisions.

III. METHODOLOGY

A. Research Design

This study follows a structured narrative literature review approach. It examines published research papers, surveys and standards related to Green Cloud Computing and environmental sustainability.

The study is based on secondary information. No original measurements were collected from a live data centre, and no practical cloud implementation was performed.

The reviewed literature was organized into the following topics:

- Energy consumption in cloud data centres.
- Energy-efficient resource allocation.
- Virtualization and workload consolidation.
- Carbon-aware workload scheduling.
- Data-centre cooling and water consumption.
- Hardware lifecycle and electronic waste.

B. Literature Search

Research related to the topic was considered from scholarly sources such as IEEE Xplore, ACM Digital Library, ScienceDirect, SpringerLink and Google Scholar.

The main search terms included:

- Green Cloud Computing.
- Energy-efficient data centres.
- Cloud resource management.
- Carbon-aware scheduling.
- Data-centre water consumption.
- Hardware lifecycle and e-waste.

The selected publications were studied to understand their objectives, techniques, contributions and limitations.

This is a narrative review and not a completed systematic review. Therefore, no database screening counts or experimental results are claimed.

C. Proposed Conceptual Model

Based on the reviewed literature, this study proposes an Integrated Green Cloud Sustainability Strategy (IGCSS).

The purpose of this strategy is to help cloud data centres consider environmental factors while managing workloads and infrastructure.

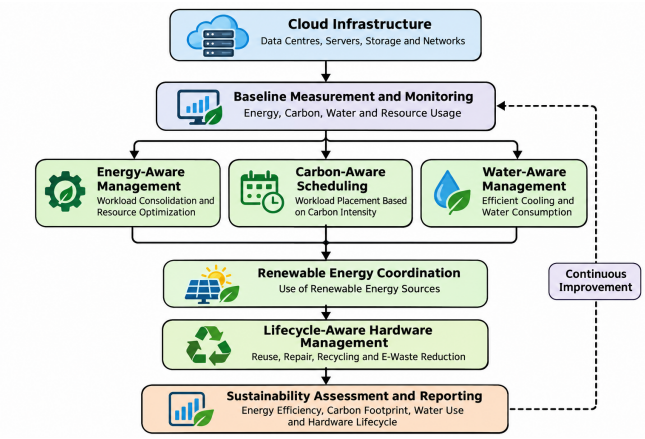


Figure 1: Integrated Green Cloud Sustainability Strategy (IGCSS) Framework

The proposed model includes the following stages:

1. Collect information about workloads, electricity, water and hardware.
2. Identify energy consumption, carbon emissions and water requirements.
3. Check workload requirements such as deadlines, performance and security.
4. Select suitable energy-efficient scheduling and resource-management actions.
5. Monitor the results and compare them with the original condition.

D. Proposed System Architecture

The proposed architecture contains five main layers. Each layer performs a specific task to support sustainable cloud operations.

As shown in Fig. 1, the architecture begins with collecting information from cloud workloads and data-centre infrastructure. The collected information is checked against workload and service requirements.

The sustainability decision layer compares different environmental factors before suggesting an action. The execution layer applies suitable resource-management techniques. Finally, the monitoring layer checks whether the changes provide the expected benefits without affecting service quality.

E. Main Components of the Proposed Strategy

1. Monitoring and Data Collection:

This component collects information about server utilization, electricity consumption, cooling systems, water usage and hardware. Accurate information is necessary before making sustainability decisions. Data-centre energy measurement and water-consumption monitoring are important for understanding the environmental impact of cloud infrastructure [2], [3], [10],

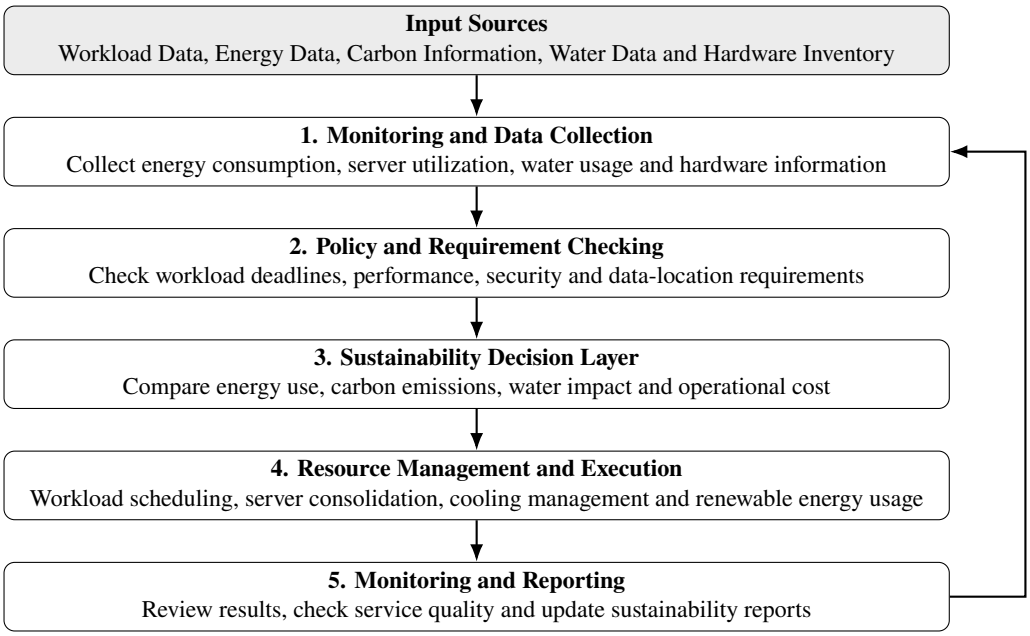


Figure 2: Proposed architecture of the Integrated Green Cloud Sustainability Strategy

[11].

2. Policy and Requirement Checking:

Every workload has different requirements. Some applications need immediate responses, while other jobs can be delayed. This component checks deadlines, performance, security and data-location restrictions before selecting a suitable action. Workload requirements and sustainability constraints must be considered when designing cloud architectures [15], [17], [19].

3. Sustainability Decision Layer:

This component considers energy consumption, carbon emissions, water usage and operating cost. It helps identify suitable alternatives without focusing on only one environmental factor. Carbon-aware workload scheduling and integrated resource management can support these decisions [8], [17], [18], [21].

4. Resource Management and Execution:

This component supports techniques such as virtual machine consolidation, energy-aware scheduling, cooling management and renewable energy coordination. These techniques help improve resource utilization and support energy-efficient cloud operations [4], [6], [7], [13], [20].

5. Monitoring and Reporting:

After an action is performed, the results are monitored. The system checks whether energy consumption, carbon emissions and water usage have changed while maintaining service quality. Appropriate energy and water metrics help evaluate environmental performance and support transparent reporting [2], [3], [10], [11].

F. How the Proposed Solution Works

Consider a cloud data centre that needs to run a report-generation job. The job must finish by the end of the day, but it does not need to start immediately.

The proposed strategy would work as follows:

1. Check the computing resources required by the job and its completion deadline.
2. Check electricity consumption and carbon intensity for available time slots.
3. Verify that delaying or moving the job will not affect security or performance.
4. Compare suitable options based on energy, carbon, water and cost.
5. Run the job and compare the actual result with the original baseline.

For example, if electricity is expected to have lower carbon intensity later in the day, the job may be scheduled for that time, provided its deadline is not affected.

This example explains the proposed concept. It is not a result from a real data-centre experiment.

IV. RESULTS AND DISCUSSION

A. Findings from the Literature Review

The reviewed studies show that Green Cloud Computing involves several techniques for reducing the environmental impact of cloud infrastructure.

The major findings are discussed below.

Energy Efficiency:

Virtualization and resource consolidation can improve the utilization of physical servers. When workloads are managed properly, unnecessary servers can be placed in low-power states, reducing avoidable electricity use .

Carbon Emission Reduction:

Carbon-aware scheduling can help reduce operational emissions by considering the carbon intensity of electricity at different times and locations. This approach is most suitable for workloads that can be delayed or moved without affecting their deadlines .

Water Management:

Cooling systems are an important part of data-centre operations. The reviewed studies show that water consumption depends on cooling technology, climate, electricity supply and facility design .

Hardware Lifecycle:

Repairing, reusing and extending the useful life of hardware can help reduce unnecessary equipment replacement. Proper recycling and disposal are also important for reducing electronic waste.

B. Comparison of Sustainability Techniques

Table I presents a qualitative comparison of the techniques discussed in the reviewed literature.

C. Discussion

The literature indicates that no single technique is sufficient to achieve complete cloud sustainability.

Virtualization and consolidation mainly address resource utilization and energy consumption. Carbon-aware scheduling considers the environmental impact of electricity sources. Cooling management addresses energy and water requirements, while hardware lifecycle management focuses on equipment use and electronic waste.

The proposed Integrated Green Cloud Sustainability Strategy combines these approaches into one conceptual framework.

An important consideration is that an improvement in one area may create a problem in another. For example, a cooling method may reduce electricity consumption but increase direct water usage. Similarly, moving a workload to another location may reduce carbon emissions but increase network energy and latency.

Therefore, environmental improvements must be evaluated along with performance, reliability, cost and security requirements.

D. Limitations of the Proposed Approach

The proposed framework is conceptual and has not been tested in a live cloud environment.

Its practical implementation would require reliable energy, carbon, water and hardware data. The availability and accuracy of these details may vary between cloud providers and geographical locations.

The framework also requires further testing to understand the effect of workload changes, electricity forecasts, cooling conditions and hardware replacement decisions.

No numerical reduction in energy, emissions or water consumption is claimed by this study.

V. CONCLUSION AND FUTURE WORK

Green Cloud Computing is an important approach for reducing the environmental impact of cloud infrastructure. This review examined energy consumption, carbon emissions, water usage and hardware lifecycle impacts associated with data centres.

The reviewed literature shows that virtualization, workload consolidation, carbon-aware scheduling, renewable energy, cooling management and responsible hardware use can contribute to more sustainable cloud operations.

Based on these findings, this paper proposes an Integrated Green Cloud Sustainability Strategy. The framework brings environmental monitoring, workload management and performance requirements together in a common conceptual approach.

However, the proposed framework has not yet been experimentally validated. Future work can include implementing the model in a cloud simulation environment, testing it with real workload data, incorporating regional water information and evaluating its effect on energy consumption, carbon emissions and service quality.

VI. DECLARATIONS

A. Funding

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

B. Conflict of Interest

The authors declare no conflict of interest.

C. Data Availability

This study is based on published research and secondary sources. No original experimental dataset was generated. The references used in the study are listed in this paper.

D. Ethics Statement

This study did not involve human or animal subjects.

E. Author Contributions

Tanmay Mahajan: Conceptualization, literature review, methodology and original draft preparation.

Ajinkya R: Literature review, analysis and documentation.

Pratik D: Literature review, discussion and review of the manuscript.

All authors have reviewed and approved the manuscript.

VII. REFERENCES

REFERENCES

[1] J. Baliga, R. W. A. Ayre, K. Hinton, and R. S. Tucker, "Green cloud computing: Balancing energy in processing, storage, and transport," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 149–167, 2011.

[2] E. Masanet, A. Shehabi, N. Lei, S. Smith, and J. Koomey, "Recalibrating global data center energy-use estimates," *Science*, vol. 367, no. 6481, pp. 984–986, 2020.

[3] M. Dayarathna, Y. Wen, and R. Fan, "Data center energy consumption modeling: A survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 732–794, 2016.

[4] R. Buyya, A. Beloglazov, and J. Abawajy, "Energy-efficient management of data center resources for cloud computing: A vision, architectural elements, and open challenges," in *Proc. International Conference on Parallel and Distributed Processing Techniques and Applications*, 2010.

[5] S. S. Gill and R. Buyya, "A taxonomy and future directions for sustainable cloud computing: 360 degree view," *ACM Computing Surveys*, vol. 51, no. 5, 2018.

[6] A. Beloglazov, J. H. Abawajy, and R. Buyya, "Energy-aware resource allocation heuristics for efficient management of data centers for cloud computing," *Future Generation Computer Systems*, vol. 28, no. 5, pp. 755–768, 2012.

Table 1: Comparison of Green Cloud Computing Techniques

Technique	Main Purpose	Environmental Benefit	Limitation
Virtualization	Run multiple virtual machines on shared physical servers	Improves hardware utilization and reduces unnecessary infrastructure	Requires proper resource allocation
Workload Consolidation	Combine workloads on fewer active servers	Can reduce electricity consumption	May affect performance if servers become overloaded
Carbon-Aware Scheduling	Schedule flexible workloads according to electricity carbon intensity	Can reduce operational carbon emissions	Depends on workload flexibility and reliable carbon information
Renewable Energy	Use renewable electricity sources	Can reduce dependence on fossil-fuel electricity	Depends on availability and reliability
Cooling Management	Improve cooling-system efficiency	Can reduce cooling energy and improve facility operation	Water and energy trade-offs depend on local conditions
Hardware Lifecycle Management	Repair, reuse and recycle equipment	Can reduce hardware waste and replacement impacts	Requires proper maintenance and lifecycle information

[7] S. Hamdi and W. Chainbi, "A survey on energy aware VM consolidation strategies," *Sustainable Computing: Informatics and Systems*, vol. 23, pp. 80–87, 2019.

[8] T. Bahreini, A. N. Tantawi, and A. Youssef, "A carbon-aware workload dispatcher in cloud computing systems," in *Proc. IEEE International Conference on Cloud Computing*, 2023.

[9] G. Procaccianti, P. Lago, and S. Bevini, "A systematic literature review on energy efficiency in cloud software architectures," *Sustainable Computing: Informatics and Systems*, vol. 7, pp. 2–10, 2015.

[10] D. Mytton, "Data centre water consumption," *npj Clean Water*, vol. 4, Article 11, 2021.

[11] N. Lei, J. Lu, A. Shehabi, and E. Masanet, "The water use of data center workloads: A review and assessment of key determinants," *Resources, Conservation and Recycling*, vol. 219, Article 108310, 2025.

[12] International Organization for Standardization, *ISO 14040:2006 Environmental Management—Life Cycle Assessment— Principles and Framework*, ISO, 2006.

[13] S. Bharany et al., "A systematic survey on energy-efficient techniques in sustainable cloud computing," *Sustainability*, vol. 14, no. 10, 2022.

[14] D. Biswas, S. Jahan, S. Saha, and M. Samsuddoha, "A succinct state-of-the-art survey on green cloud computing: Challenges, strategies, and future directions," *Sustainable Computing: Informatics and Systems*, vol. 44, 2024.

[15] S. Ahmadisakha and V. Andrikopoulos, "Architecting for sustainability of and in the cloud: A systematic literature review," *Information and Software Technology*, vol. 171, Article 107459, 2024.

[16] N. Katal, S. Dahiya, and T. Choudhury, "Energy efficiency in cloud computing data centers: A survey on software technologies," *Cluster Computing*, vol. 26, no. 3, pp. 1845–1875, 2023.

[17] R. Buyya, S. Ilager, and P. Arroba, "Energy-efficiency and sustainability in new generation cloud computing: A vision and directions for integrated management of data centre resources and workloads," *Software: Practice and Experience*, vol. 54, no. 1, pp. 24–38, 2024.

[18] N. Bashir et al., "The sunk carbon fallacy: Rethinking carbon footprint metrics for effective carbon-aware scheduling," in *Proc. ACM Symposium on Cloud Computing*, 2024.

[19] P. Verma, A. K. Maurya, and R. S. Yadav, "A survey on energy-efficient workflow scheduling algorithms in cloud computing," *Software: Practice and Experience*, vol. 54, no. 5, pp. 637–682, 2024.

[20] L. Helali and M. N. Omri, "A survey of data center consolidation in cloud computing systems," *Computer Science Review*, vol. 39, Article 100366, 2021.

[21] A. N. Khan and M. Zakarya, "Energy, performance and cost efficient cloud datacentres: A survey," *Computer Science Review*, vol. 40, Article 100390, 2021.