International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

Green Computing for Sustainable ICT: Integrating Energy Efficiency, AI-Optimization, Cloud-Edge Computing, and Circular E-Waste Management

Authors: Mrs Radhika Kidambi
Department of Computer Applications
radhikasbcms@gmail.com
SBCMS, Bengaluru

Mrs K V L Sowjanya
Department of Computer Applications
sowjiramesh8184@gmail.com
SBCMS, Bengaluru

ABSTRACT:

The rapid growth of Information and Communication Technology (ICT) infrastructure has significantly transformed modern society while contributing to increasing energy consumption, carbon emissions, and electronic waste (e-waste). Green Computing and Sustainable Technology provide a systematic approach to addressing these environmental challenges by integrating sustainability principles throughout the lifecycle of digital systems, including design, manufacturing, deployment, operation, and disposal. This paper presents a comprehensive framework for sustainable computing by examining key technologies such as hardware virtualization, energy-efficient cloud and edge computing, power-aware software optimization, and intelligent resource management. The study further investigates circular-economy practices, including sustainable procurement, device life extension, component reuse, recycling, and responsible e-waste management. In addition, the role of Artificial Intelligence (AI)-based energy management and renewable energy integration in optimizing computing resources and reducing carbon emissions is examined. The proposed approach highlights the importance of combining technological innovation with organizational policies and environmental practices to improve energy efficiency and resource utilization. The findings indicate that coordinated adoption of green IT strategies can reduce the environmental impact of digital infrastructure while supporting scalable and sustainable ICT development. This study provides a foundation for developing environmentally responsible computing systems aligned with the objectives of a sustainable digital future.

KEY WORDS: Green Computing, Sustainable Technology, Energy Efficiency, Cloud Computing, Edge Computing, Artificial Intelligence, Renewable Energy, E-Waste Management, Circular Economy.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

INTRODUCTION

Information and communication technology has become a fundamental component of modern society, supporting applications in education, healthcare, transportation, finance, manufacturing, governance, and scientific research. The increasing adoption of cloud computing, high-performance computing, artificial intelligence (AI), and connected devices has transformed the delivery of digital services. However, this expansion has also increased the environmental footprint associated with computing infrastructure, electricity consumption, natural resource extraction, and electronic waste generation. Green computing, green IT (information technology), or Information and Communication Technology Sustainability, is the study and practice of environmentally sustainable computing or IT. Green and sustainable computing research has expanded across technical, organizational, and strategic dimensions in recent years. Contemporary work emphasizes that the environmental impact of digital technologies must be assessed across their entire life cycle rather than focusing only on operational electricity consumption. One recent study highlights the importance of verifiable carbon accounting, life cycle-oriented design practices, and infrastructure-level energy efficiency, presenting a comprehensive framework for sustainable computing. This perspective shows that the environmental cost of computing includes manufacturing processes, hardware replacement cycles, and cooling infrastructures in addition to energy use.

The ICT sector has transformed economies and societies but contributes significantly to global energy consumption and carbon emissions. Rapid expansion of cloud services, artificial intelligence workloads, and billions of connected devices has driven demand for energy and materials. Green IT is an interdisciplinary approach that combines engineering, operations, procurement, and policy to minimize the environmental impact of ICT while maintaining performance and user needs. This paper synthesizes technical and managerial strategies for sustainable computing environments, emphasizing practical deployment and measurable outcomes.

The goals of green computing include optimising energy efficiency during the product's lifecycle; leveraging greener energy sources to power the product and its network; improving the reusability, maintainability, and repairability of the product to extend its lifecycle; improving the recyclability or biodegradability of e-waste to support circular economy ambitions; and aligning the manufacture and use of IT systems with environmental and social goals. Green computing is important for all classes of systems, ranging from handheld systems

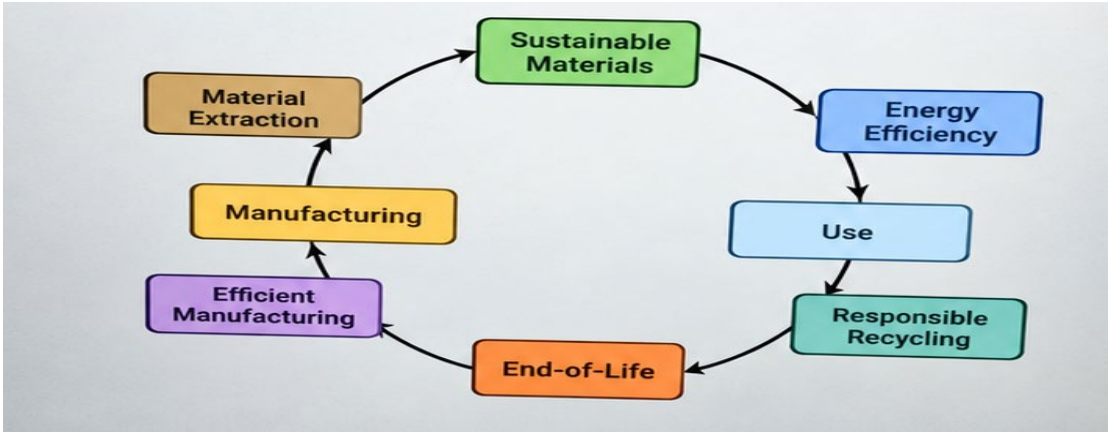
(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

to large-scale data centers. According to the International Energy Agency, data centres accounted for about 1.5% of global electricity consumption in 2024 (~415 TWh), and under its central scenario, demand could roughly double to ~945 TWh by 2030, with AI workloads a major driver of growth. Sustainable development is a concept that redefines the notion of the general interest by integrating environmental, social, and economic considerations. Many corporate IT departments have green computing initiatives to reduce the environmental effect of their IT operations. Yet it is also clear that the environmental footprint of the sector is significant, estimated at 5-9% of the world's total electricity use and more than 2% of all emissions. Data centers and telecommunications networks will need to become more energy efficient, reuse waste energy, use more renewable energy sources, and use less water for cooling to stay competitive. In the European Union, policy efforts and industry initiatives aim for climate-neutral data centers by 2030.

LITERATURE REVIEW

Research on Green IT spans energy-efficient hardware design, low-power software algorithms, data-center cooling innovations, virtualization and consolidation, lifecycle assessment (LCA), and policy frameworks. Seminal studies quantify energy footprints of data centers and propose efficiency metrics (PUE, CUE). Literature emphasizes that coordinated improvements across hardware, software, and operational processes yield the highest returns. Emerging work examines sustainability of AI workloads, circular economy models for ICT, and region-specific constraints in developing countries.



Lifecycle stages and intervention points for sustainable ICT systems.

A. GREEN IT PRINCIPLES

Green Information Technology is founded on a structured set of principles that guide the design, deployment, and management of computing systems with minimal

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

environmental impact. These principles aim to balance technological advancement with ecological responsibility.

- **Energy Efficiency as a Core Objective**: Energy efficiency is the central pillar of Green IT. It focuses on reducing the energy required per unit of computation without compromising system performance or reliability. This includes optimizing hardware power consumption, eliminating idle resource usage, and implementing intelligent power management techniques. Efficient systems reduce operational costs while directly lowering carbon emissions associated with electricity generation.
- **Resource Optimization and Utilization:** Traditional computing environments often suffer from underutilized resources, where servers operate at less than 20–30% capacity. Green IT emphasizes maximizing resource utilization through consolidation, dynamic allocation, and shared infrastructure. Higher utilization results in fewer physical devices, reducing energy use, cooling requirements, and material consumption.
- **Lifecycle-Based Design Approach:** Green IT extends beyond operational efficiency to encompass the entire lifecycle of computing environment. This includes sustainable material selection, energy-efficient manufacturing, long service life, repairability, and responsible end-of-life disposal. Lifecycle-based design reduces embedded carbon emissions and mitigates the growing problem of electronic waste.
- **Use of Renewable and Low-Carbon Energy Sources:** Integrating renewable energy into IT operations is a fundamental Green IT principle. Systems are designed to operate efficiently under variable energy availability, allowing workloads to align with renewable generation patterns such as solar and wind cycles.
- **Measurement, Transparency, And Accountability:** Quantifiable metrics such as Power Usage Effectiveness (PUE), Carbon Usage Effectiveness (CUE), and energy-per-operation metrics enable organizations to track progress and ensure accountability. Continuous monitoring supports data-driven decision-making and policy enforcement.

B. ENERGY-EFFICIENT HARDWARE

C. Hardware components form the foundation of sustainable computing environments. Energy efficient hardware design significantly reduces baseline power consumption and thermal output**.**

- **Low-Power Processor Architectures:** Modern processors are engineered for energy proportionality, ensuring that power consumption scales with workload intensity.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

Techniques such as Dynamic Voltage and Frequency Scaling (DVFS) adjust processor speed based on demand, reducing unnecessary energy usage during low-load periods. Architectures optimized for performance-per-watt, including ARM-based systems, are increasingly adopted for edge computing and cloud workloads.

- **Memory and Storage Efficiency:** Memory subsystems contribute substantially to power consumption in data centers. Energy efficient memory technologies, including low-power DDR and intelligent memory controllers, reduce energy usage during idle states. Solid-state drives (SSDs) consume less power than traditional hard disk drives while delivering higher throughput, further improving energy efficiency.
- **Specialized Accelerators:** Hardware accelerators such as GPUs, TPUs, and AI inference chips enable computationally intensive tasks to be executed faster and with lower total energy compared to general-purpose processors. By offloading specific workloads, accelerators reduce execution time and overall power draw.
- **Thermal-Aware Hardware Design:** Efficient thermal design minimizes heat generation at the component level, reducing the burden on cooling systems. Advanced heat sinks, low-power circuit layouts, and efficient power supplies collectively contribute to lower operational temperatures and energy consumption.
- **Virtualization, Containerization, And Workload Consolidation:** These technologies are critical enablers of Green IT by transforming how computing resources are deployed and utilized.
- **Server Virtualization:** Virtualization allows multiple virtual machines to run on a single physical server, dramatically increasing resource utilization. This consolidation reduces the number of physical servers required, lowering energy consumption, cooling demand, and hardware procurement costs.
- **Containerization for Lightweight Deployment:** Containers offer a lightweight alternative to virtual machines by sharing the host operating system kernel. This reduces overhead and allows higher density deployment of applications. Container orchestration platforms enable dynamic scaling, ensuring resources are allocated only when required.
- **Intelligent Workload Consolidation:** Workload consolidation involves migrating and scheduling applications to minimize active hardware during low-demand periods. Idle servers can be powered down or placed in low energy states, significantly reducing

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

energy waste. Advanced schedulers incorporate energy awareness by considering power consumption and thermal impact during placement decisions.

- **CIRCULAR ECONOMY AND ELECTRONIC WASTE MANAGEMENT**

  Extending Hardware Life Cycles: Extending the useful life of IT equipment can reduce demand for newly manufactured devices and limit the generation of e-waste. Organizations can achieve this through preventive maintenance, modular hardware design, component upgrades, battery replacement, software support, and refurbishment. Equipment replacement decisions should consider performance requirements, reliability, security, energy efficiency, repair costs, and embodied environmental impacts. A balanced assessment is preferable to replacement decisions based exclusively on equipment age or electricity consumption.

- **Reuse, Refurbishment, and Recycling:** The circular economy promotes the retention of products and materials at their highest practical value for as long as possible. In ICT, this involves prioritizing maintenance and reuse before considering recycling or disposal. Functional devices may be reassigned to less demanding workloads, refurbished for secondary users, or returned through manufacturer take-back programmes. Equipment that cannot be reused should be processed through authorized recycling channels that recover valuable materials and manage hazardous components appropriately. Data security is also essential. Storage devices must undergo secure data sanitization before reuse, resale, or recycling. A successful e-waste management programme therefore integrates environmental responsibility, information security, and documented chain-of-custody procedures.

- **Sustainable Procurement:** Procurement decisions influence the environmental impact of ICT throughout the supply chain. Organizations should consider product energy efficiency, expected service life, repairability, spare-part availability, recycled materials, supplier environmental practices, and end-of-life recovery options. Life cycle costing can complement purchase-price comparisons by accounting for electricity consumption, maintenance, replacement, and disposal costs over the expected operating period. Environmental criteria can also be incorporated into supplier evaluation and contractual performance requirements.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

D. Carbon Accounting: Carbon accounting estimates greenhouse gas emissions associated with computing operations and their supply chains. Depending on the assessment boundary, relevant sources include electricity consumption, fuel use, cooling-related emissions, equipment manufacturing, transportation, and end-of-life treatment. A simplified operational emissions estimate is given by

$$C_{op} = \sum_{i=1}^{n} E_i \times EF_i$$

Expanded form:

$$C_{op} = E_1EF_1 + E_2EF_2 + \cdots + E_nEF_n$$

Where:

C_{op} = Total operational carbon emissions

E_i = Activity data or energy consumption for activity i

EF_i = Emission factor for activity i

n = Total number of activities

i = Index representing each activity

Appropriate unit conversions are required to express the result in a consistent unit, such as kilograms of carbon dioxide equivalent. A comprehensive assessment should document whether emission factors are location-based or market-based, how renewable electricity claims are treated, and whether embodied emissions are included. Carbon estimates should also disclose uncertainty and data limitations.

These objectives establish green computing as an interdisciplinary activity requiring contributions from engineers, software developers, infrastructure administrators, procurement teams, organizational leaders, and policymakers.

TOPIC HIERARCHY ANALYSIS AND THEMATIC TAXONOMY

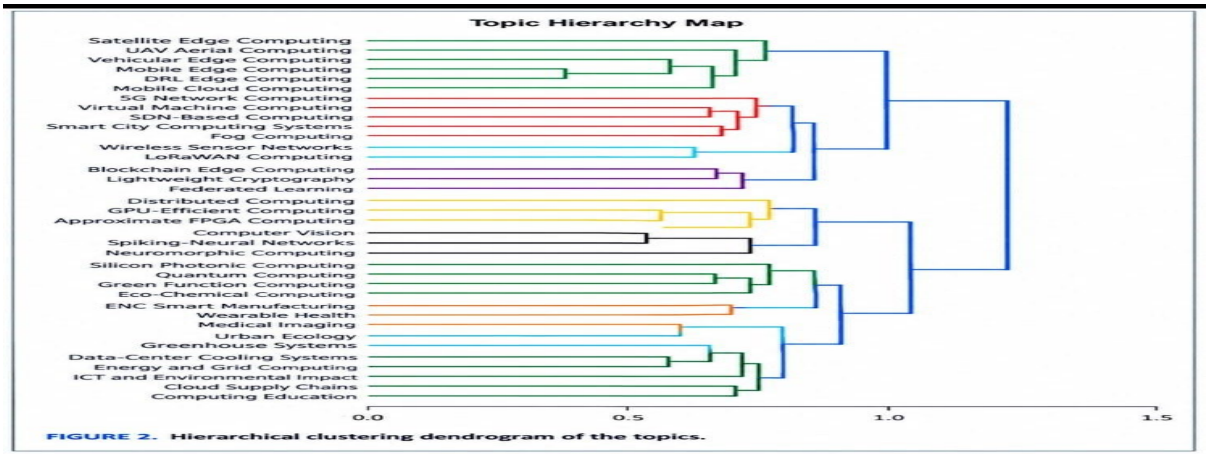


FIGURE 2. Hierarchical clustering dendrogram of the topics.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

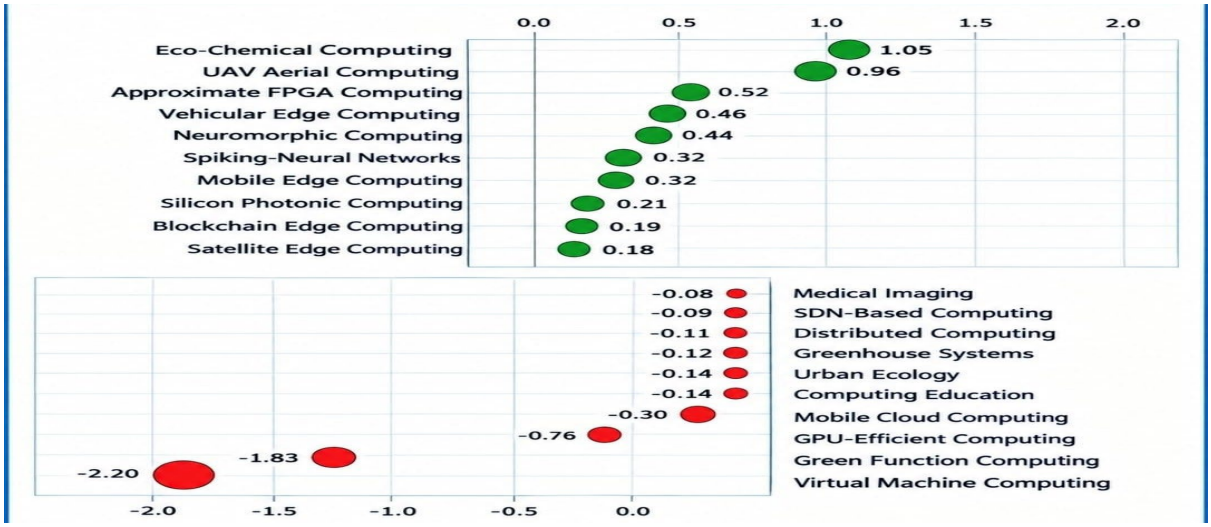
International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

Provide a complementary representation of the hierarchical and thematic organization of the green computing field. While the dendrogram in Figure 2 captures the semantic proximity and hierarchical relationships among topics, Table 3 offers a structured taxonomy that highlights how diverse subdomains converge into broader research themes. The results indicate that green computing research evolves as an integrated and multi-dimensional field that combines hardware efficiency, system optimization, environmental sustainability, and human-centred innovation, contributing to a comprehensive understanding of the field's conceptual structure, thematic evolution, and interdisciplinary integration.

The resulting heatmap visualizes the degree of semantic proximity between these topics. Darker shades indicate stronger similarity values. This analysis reveals how related research areas cluster within the broader domain of green and sustainable computing. The similarity values ranged from a maximum of 0.92 to a minimum of 0.43, indicating substantial variation in the degree of thematic proximity among topics. As illustrated in the heatmap, strong semantic correlations were found between "Virtual Machine Computing" and "Green Function Computing" (0.92). High similarity values were also observed between "Virtual Machine Computing" and "GPU-Efficient Computing" (0.89), as well as between "Virtual Machine Computing" and "Approximate FPGA Computing" (0.89). In addition, "Approximate FPGA Computing" and "Energy and Grid Computing" showed a close relationship (0.88). These associations reflect a strong methodological overlap between energy-efficient virtualization, hardware optimization, and computational resource management. Moderate-to-high links were observed between "Green Function Computing" and "Approximate FPGA Computing" (0.85), as well as between "Green Function Computing" and "GPU-Efficient Computing" (0.84). In addition, "GPU-Efficient Computing" and "Approximate FPGA Computing" showed a strong association (0.80), while "Virtual Machine Computing" and "Mobile Edge Computing" were also closely related (0.79). In contrast, the lowest similarity values were recorded between "GPU-Efficient Computing" and "Silicon Photonic Computing" (0.43), and between "ICT and Environmental Impact" and "Green Function Computing" (0.43). These minimal correlations indicate that GPU-based and photonic computing follow distinct technological paths toward hardware efficiency, while environmental impact assessment remains conceptually distant from physics-based computational modelling.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

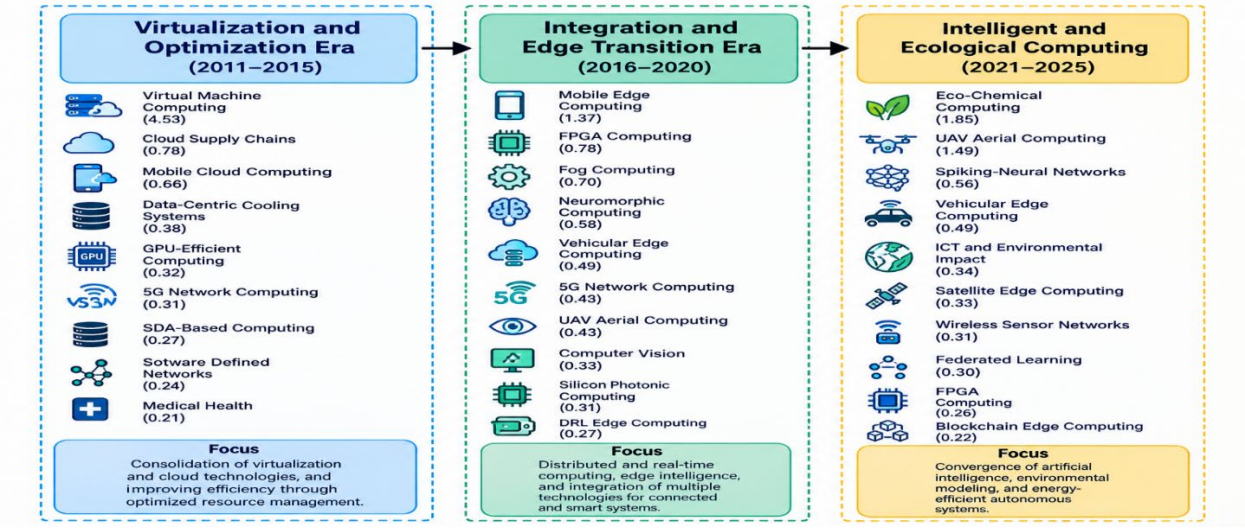
International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026



Overall trend values of the top 10 increasing and decreasing topics.

The figure clearly demonstrates the distinct difference between rapidly emerging themes such as ‘‘Eco-Chemical Computing’’ and ‘‘UAV Aerial Computing’’ and declining areas such as ‘‘Virtual Machine Computing’’ and ‘‘Green Function Computing’’. This transformation reflects a fundamental change not only in technological architectures but also in research priorities. While energy saving, hardware acceleration, and virtualization-oriented studies dominated in the earlier period, in recent years these themes have been replaced by data-centered, AI-supported, and autonomously adaptive systems. Thus, the field has evolved toward autonomous and distributed computing paradigms with high environmental awareness and efficient energy management.

Developmental stages of green computing



(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

The three major developmental stages of green computing identified between 2011 and 2025. As the number of publications in green and sustainable computing increased sharply after 2010, the analysis focused on the last fifteen years. The aim was to examine how research priorities evolved over time. Topic trend data were divided into three consecutives five-year periods (2011-2015, 2016-2020, and 2021-2025). For each period, the ten most prominent topics were identified and analyzed according to their thematic content. Based on these dominant topics, three main eras and their research foci were defined. The ‘‘Virtualization and Optimization Era’’ (2011-2015) focused on cloud-based infrastructures and hardware-level energy management. Representative topics included ‘‘Virtual Machine Computing’’, ‘‘Cloud Supply Chains’’, ‘‘Mobile Cloud Computing’’, and ‘‘GPU-Efficient Computing’’. Studies in this stage emphasized workload efficiency and energy aware computation within centralized environments such as data centers. This period established the technical foundations of sustainable computing.

CONCLUSION

Green computing has evolved from a narrow focus on energy-efficient devices into a comprehensive approach to environmentally sustainable information and communication technology. The environmental impact of ICT extends across raw material extraction, manufacturing, transportation, operation, cooling, maintenance, and end-of-life management. Therefore, effective sustainability strategies must address the complete life cycle of computing systems.

This paper examined technical, operational, organizational, and policy-based approaches to sustainable computing. Energy-efficient hardware, optimized software, virtualization, data centre management, renewable electricity, sustainable AI, and circular economy practices can collectively reduce the environmental footprint of digital infrastructure. Carbon accounting and measurable performance indicators provide the basis for evaluating these interventions and identifying opportunities for continuous improvement.

The increasing electricity demand associated with data centres and AI reinforces the need to consider absolute resource consumption alongside efficiency improvements. Organizations should adopt transparent measurement practices, extend hardware service life where appropriate, prioritize responsible procurement, and establish accountable sustainability governance.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

Ultimately, sustainable computing requires coordinated action by researchers, technology providers, enterprises, policymakers, and users. Integrating environmental considerations into the design, deployment, operation, and disposal of ICT systems can support digital innovation while contributing to broader environmental and sustainable development objectives.

The topic extraction and hierarchical taxonomy showed that research activity is concentrated around a set of core areas that combine hardware efficiency, cloud and edge architectures, and environmental assessment. Dominant topics such as ‘‘Virtual Machine Computing’’, ‘‘Green Function Computing’’, ‘‘ICT and Environmental Impact’’, ‘‘Energy and Grid Computing’’, and ‘‘GPU Efficient Computing’’ form the foundational layer of the field, while emerging topics including ‘‘Eco-Chemical Computing’’, ‘‘UAV Aerial Computing’’, ‘‘Approximate FPGA Computing’’, and ‘‘Neuromorphic Computing’’ indicate a clear shift toward AI-enabled, low power, and environmentally grounded solutions. The similarity and clustering analyses demonstrated that these topics are not isolated silos but constitute an interconnected landscape in which technical, infrastructural, and ecological concerns are tightly coupled.

LIMITATIONS AND RECOMMENDATIONS

Although this study provides a comprehensive and systematically structured overview of green computing research, several limitations should be considered. The analysis is based solely on Scopus-indexed publications, which may omit regional journals, conference papers, and non-indexed sources, limiting the global completeness of the dataset. The accuracy of semantic modelling is also affected by variability in titles, abstracts, and author keywords, as incomplete or overly broad metadata can introduce ambiguity even after preprocessing. In addition, topic interpretation and label assignment involve a degree of subjectivity, particularly in interdisciplinary areas where conceptual boundaries overlap. Temporal trends based on relative topic proportions reflect thematic shifts but do not account for citation influence or real-world impact. Future research can address these limitations through broader datasets and more advanced analytical techniques. Transformer-based large language models with domain specific fine-tuning, contrastive text encoders, and time aware neural embeddings can improve semantic precision and capture conceptual evolution more effectively. Full-text processing supported by LLM-driven summarization, semantic chunking, and retrieval-augmented indexing may reduce dependency on incomplete abstracts. Multimodal approach that incorporate text, figures, tables, and citation graphs can reveal deeper thematic structures. Integrating collaboration networks, funding data, and impact-based indicators would further

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 11, CONFLUENCE - 2026

enhance the interpretive depth of trend analyses and enable more robust, forward-looking assessments of sustainability-oriented research.

REFERENCES

1) International Energy Agency, "Energy and AI," IEA, Paris, France, 2025. [Online]. Available: https://www.iea.org/reports/energy-and-ai
2) The Green Grid, *PUE: A Comprehensive Examination of the Metric*. The Green Grid. [Online]. Available: https://www.thegreengrid.org/
3) European Commission, "Energy performance of data centres," Directorate-General for Energy. [Online]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive/energy-performance-data-centres_en
4) European Commission, "Green cloud and green data centres," Shaping Europe's Digital Future. [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/green-cloud
5) European Commission, "Study on greening cloud computing and electronic communications services and networks: Towards climate neutrality by 2050," Mar. 2022. [Online]. Available: https://digital-strategy.ec.europa.eu/en/library/study-greening-cloud-computing-and-electronic-communications-services-and-networks-towards-climate
6) IEEE, "Green Computing for Energy Transition: A Survey," *IEEE Xplore*. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10251799

(This work is licensed under a Creative Commons Attribution 4.0 International License.)