

Chapter 12

Green Cloud Computing: Opportunities and Challenges

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ABSTRACT

Green cloud computing has emerged as a critical area of research and development in response to the escalating environmental impact of traditional data centers. This chapter investigates the opportunities and challenges associated with the adoption of environmentally sustainable practices in cloud computing. The ever-growing demand for computational resources necessitates a paradigm shift towards more energy-efficient and eco-friendly solutions. The opportunities presented by green cloud computing lie in the potential to significantly reduce carbon footprints and energy consumption. The integration of renewable energy sources, energy-efficient hardware, and optimized resource allocation techniques contribute to minimizing the environmental impact of cloud infrastructure. Additionally, the implementation of virtualization and consolidation strategies enhances server utilization, further improving energy efficiency. However, the realization of these opportunities is accompanied by a set of challenges.

1. INTRODUCTION TO GREEN CLOUD COMPUTING

1.1 Overview of Green Cloud Computing

The idea behind “green cloud computing” is to reduce the negative impact on the environment and increase the efficiency of cloud computing systems. This programme aims to decrease the resource use and carbon footprint associated with cloud computing. Reducing the environmental impact of cloud services is the primary objective of green cloud computing (Li, G., Zhang, Z., Lin, K. J., & Zhong, L. 2011) (Beloglazov, A., & Buyya, R. (2010) (Mao, M., Zhang, S., & Chen, S., 2012). This is achieved via optimising resource management, using renewable energy sources, and using energy-efficient procedures. There are several important aspects and challenges in the field of green cloud computing:

- **Energy Efficiency:** The idea of creating and running data centres in an energy-efficient way is fundamental to green cloud computing. Utilising energy-efficient hardware components, implementing better cooling systems, and optimising power distribution and utilisation are all part of the package. Improving resource utilisation and drastically reducing energy usage and consumption are both made feasible by virtualization technologies, which allow task consolidation onto a smaller number of physical servers.
- **Renewable Energy Integration:** The use of renewable energy sources is key to green cloud computing’s approach to powering data centres. Cloud providers may reduce their carbon footprint and reliance on fossil fuels by powering their operations with renewable energy. This includes solar, wind, hydroelectric, and similar technologies. Incorporating renewable energy sources into data centres requires careful planning, infrastructure design, and collaboration with energy providers.
- **Resource Optimization:** Green cloud computing relies heavily on efficient management of resources. Energy-aware algorithms and policies can optimise power usage without sacrificing performance by dynamically allocating computer resources based on demand. Task scheduling, load balancing, and power management are some of the methods that may be used to achieve better resource utilisation and energy efficiency.
- **Lifecycle Management:** Throughout the whole lifecycle of a cloud service—from production to operation to disposal—the idea of green cloud computing considers environmental impacts. It is essential to reduce electronic waste, use effective recycling and disposal methods, and use hardware components that are kind to the environment. Reducing the environmental effect of cloud services is possible through the adoption of circular economy principles, which promote the sustainable use of resources.
- **Environmental Metrics and Reporting:** Precise monitoring and reporting of ecological impact metrics is important for environmentally conscious cloud computing. Using agreed metrics, we can assess and contrast the environmental performance of different cloud providers. Efficient use of power (PUE), carbon (CUE), and water (WUE) are a few examples of such measurement systems. With open and honest information, customers can make informed choices about the impact of cloud services on the environment.
- **Green Policies and Incentives:** The involvement of governments and regulatory agencies in supporting eco-friendly cloud computing is important. Renewable energy sources and energy-efficient practices in the cloud can be promoted through financial incentives, new rules, and regula-

tion. Possible strategies to promote the creation and maintenance of ecologically conscious cloud infrastructure include tax incentives, subsidies, and certification schemes.

Remember that green cloud computing has several benefits, such as reducing energy consumption, operational expenditures, carbon emissions, and having a positive impact on the environment (Srirama, S. N., & Buyya, R. 2012) (Zhan, J., Deng, X., et al., 2013). Businesses' attempts to meet their CSR requirements and achieve their broader sustainability objectives are both aided by this. With the continued growth of cloud computing, the adoption of ecologically conscious cloud computing practices is gaining prominence. Integrating energy-efficient technologies, renewable energy sources, resource optimisation, and responsible lifecycle management responsibilities pave the way for an IT sector that is more ecologically aware and sustainable through green cloud computing.

1.2 Importance of Energy Efficiency in Cloud Computing

There are several important reasons why energy efficiency is important in cloud computing, such as:

- The environmental impact: data centres that house cloud computing services consume large amounts of energy for cooling and powering their operations. Data centres contribute to environmental harm and carbon dioxide emissions due to the quantity of energy they require. Developing and implementing energy efficiency solutions can help cloud service providers significantly reduce their carbon footprint and decrease their impact on the environment.
- Saving Money: Data centres frequently incur substantial operational expenditures, with energy costs making up a sizable portion of that total. Providers of cloud services can cut costs by reducing their overall energy consumption through the adoption of more energy-efficient practices (Gupta, S., Grover, S., Kumar, P., & Chana, I. 2017) (Ahmadian, A., Ameri, M., & Taheri, J. 2017). Reduced electricity consumption means more money in the pockets of service providers and customers alike thanks to virtualization technologies, improved cooling systems, and energy-efficient hardware.
- Energy efficiency helps cloud service companies scale their operations, which in turn increases their capacity. By optimising resource utilisation and implementing energy-efficient designs, data centres can handle increasing workloads and client needs without increasing their energy usage. Efficient resource management allows for the most effective use of computer resources, which in turn leads to increased scalability and less waste.
- Consumer Interest in Eco-Friendly Products: More and more people and businesses are concerned about their influence on the environment, and they are seeking out greener options. One competitive advantage that cloud service providers might have is the ability to attract environmentally sensitive clientele. Energy efficiency and environmental sustainability should be prioritised in order to acquire this advantage. Environmentally friendly methods may boost customer loyalty and demand while also improving a supplier's reputation.
- Resource Conservation: By lowering energy use, cloud computing helps save valuable resources. Designing with energy efficiency in mind reduces the strain on power systems and the need for fossil fuels. Both the ecology and the reliability of electricity networks benefit from this resource-saving technique.

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- There has been a lot of innovation in hardware, software, and infrastructure technologies driven by the need to make things more energy efficient. Improvements in cooling systems, power management tactics, virtualization technologies, and energy-efficient CPUs will benefit the whole IT industry. The rise of cloud computing has accelerated the pace of innovation in energy-efficient technologies, which could impact other sectors.

Ultimately, cloud computing's energy efficiency is important for many reasons, such as lowering costs, facilitating scalability, reducing environmental impact, satisfying consumer needs, preserving resources, and promoting technological advancements (Rong, C., Nguyen, S. T., & Jaatun, M. G. 2013) (Huang, D., Guo, S., et al., 2017). Implementing this important component of ethical and environmentally sustainable cloud computing operations will benefit both businesses and the environment.

1.3 Objectives of This Work

This work is summarized in 10 sections.

2. ENERGY CONSUMPTION IN CLOUD COMPUTING

2.1 Energy Consumption Trends in Data Centers

Concerns about data centres' excessive energy use have been on the rise in tandem with the popularity of cloud services and other forms of digital technology. Important developments in data centre energy use include the following:

- The use of virtualization and server consolidation has proved important in improving energy efficiency. The advancement of energy efficiency may be attributed in large part to these technologies. By utilising virtualization approaches and consolidating several physical servers onto fewer hardware resources, data centres may increase resource utilisation while minimising energy consumption. As a result of this trend, we have improved our energy usage and reduced the number of underutilised servers.
- Processors, memory modules, storage devices, and networking gear that consumes less energy is becoming more popular among data centre operators. For the time being, this pattern is predicted to hold. The server industry is now focused on developing more power-efficient designs in an effort to decrease power consumption without sacrificing performance. Specialised accelerators and low-power central processing units are examples of these designs.
- Improved Cooling Efficiency: Data centres' cooling systems are a major source of their energy bills. In order to improve the effectiveness of their cooling systems, data centres are integrating sophisticated cooling technologies such as liquid cooling, economizers, and hot aisle/cold aisle configurations. These methods have the potential to lower cooling energy requirements while keeping operational temperatures where they should be.
- Using energy from sustainable sources: Renewable energy sources are quickly replacing traditional power sources for data centres. In an effort to lessen their impact on the environment, some massive data centres are acquiring renewable energy certificates, putting solar panels on site, or

developing wind farms. A data center's overall environmental effect can be lessened by the use of renewable energy sources, which lessens reliance on fossil fuels.

- Updates to the measurement of power use effectiveness (PUE): Data centres' environmental effect may be measured using Power Usage Effectiveness (PUE) or any similar metric. Data centres have long prioritised improving their power utilisation efficiency (PUE) through infrastructural optimisation, cooling system efficacy, and the deployment of more energy-efficient technology. An improved energy efficiency and less energy waste are shown by a lower PUE value.
- Energy Management and Monitoring: Data centres are increasingly using advanced energy management and monitoring technologies to keep tabs on and improve their energy use. With the help of sophisticated energy management systems and real-time monitoring, data centre operators may identify high-energy-use areas, optimise the placement of workloads, and implement energy-saving regulations. The data provided by these systems allows for both continuous improvement and greater energy efficiency.
- Governments and industry groups are working on regulations and standards to improve data centre energy efficiency. The goal of implementing these rules and regulations is to improve energy efficiency. Implementing schemes like the ENERGY STAR programme for data centres and the European Code of Conduct for data centres can help achieve this goal by providing guidelines and standards for data centre energy efficiency. Data centres that follow these rules and regulations are more likely to implement energy-saving practices.

These shifts have prompted businesses to look for solutions to the problems caused by data centres' excessive energy use (Jing, L., & He, H., 2014) (Li, Q., & Buyya, R., 2010) (Yang, C., Chen, L., et al., 2012) (Al-Fares, M., Loukissas, A., & Vahdat, A. 2008) (Tyagi, A.K., 2022). Data centres strive for greater energy efficiency and less environmental effect through the use of virtualization, advanced cooling techniques, renewable energy sources, virtualization, virtualization, and enhanced energy management systems. Consistent innovation, collaboration, and adherence to standards aimed at optimising energy efficiency will propel future gains even further.

2.2 Environmental Impact of Cloud Computing

The environmental impacts of cloud computing might be positive or negative. Despite its many advantages in resource efficiency and scalability, it causes problems with energy consumption and carbon emissions. Additionally, it provides other benefits. Here are a few key aspects about the impact of cloud computing on the environment:

- A lot of energy is consumed by cloud data centres since they need a lot of electricity to power and cool their infrastructure. Data centres impose a strain on local power grids and add to global warming pollution through their energy use. Cloud computing facilitates resource consolidation and virtualization, which can lead to better energy efficiency, as compared to traditional IT infrastructure.
- Pollutant Discharges: Both the direct and indirect emissions of carbon are accounted for in the carbon footprint of cloud computing. Data centres produce direct emissions as a result of their operations, which involve power consumption and the operation of cooling systems. Servers and networking devices, together with their production and eventual disposal, are major sources of

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indirect emissions in the IT industry. Through the implementation of energy-efficient practices and the utilisation of renewable energy sources, data centres may help reduce carbon emissions.

- Cloud computing allows for the consolidation and virtualization of servers, allowing for better utilisation of existing resources. By pooling their customers' computer resources, cloud companies may achieve better server utilisation rates. The cloud provider's overall energy usage per job is reduced as a result of this. However, environmental efficiency can still be impacted by insufficient resource allocation and poor utilisation rates.
- Data Centre Cooling Systems: Data centre cooling systems can involve a substantial amount of energy. Minimising energy consumption is feasible through the optimisation of cooling infrastructure and the adoption of more efficient cooling technologies, including economizers and liquid cooling. Data centre operators are looking at new cooling technologies to help their buildings use less energy.
- Cloud computing relies on a broad array of electronic equipment, which means that it produces a substantial amount of electronic waste. The production, upkeep, and eventual disposal of IT equipment have the potential to affect the natural world if not managed properly. Reducing the environmental effect requires both appropriate disposal methods and responsible e-waste recycling.
- Where and How Data Centres Are Located: Data centres' impact on the environment might vary depending on where they are located. A number of elements can influence the overall environmental effect, including the accessibility of sustainable power infrastructures, the existence of cool temperatures, and the geographic closeness to renewable energy sources. By using renewable energy sources and choosing environmentally friendly locations, data centres may lessen their impact on the environment.
- Multi-Tenancy Efficiency: Since several clients share the same infrastructure in the cloud, resource efficiency may be improved through the multi-tenancy paradigm. By combining users' workloads, cloud providers may increase utilisation rates and do away with the need for individual servers on-premises. Conversely, to prevent unforeseen consequences, data isolation and security measures must be put into place.
- Green Initiatives and Environmental Certifications: A growing number of cloud companies are embracing green efforts and striving for environmental certifications. For instance, they support sustainable infrastructure designs, invest in renewable energy sources, and adopt energy-efficient activities. A dedication to environmentally friendly corporate practices is demonstrated, for instance, by certifications such as ISO 14001 and LEED (Leadership in Energy and Environmental Design).

We must prioritise energy efficiency, include renewable energy sources, handle electronic trash responsibly, and build sustainable infrastructure if we want to lessen the environmental impact of cloud computing. Collaboration between cloud providers, governments, and industry groups is necessary to set regulations, standards, and incentives that promote green cloud computing. Constant innovation along with eco-friendly tech is essential for making cloud services even more sustainable.

2.3 Challenges in Reducing Energy Consumption Using Cloud Computing Services

There are a lot of problems that cloud service providers need to fix before they can lower their energy use. A few of the most major obstacles are these:

- Allocation and utilisation of resources: Allocating and using resources properly is important for reducing energy use. However, keeping utilisation rates high while dynamically allocating resources to meet unpredictable demands could be challenging. To ensure that resources are available when needed while energy is used efficiently, it is important to have advanced algorithms for managing resources and techniques for optimising workloads.
- Although virtualization encourages better resource utilisation, it also introduces additional overhead, which might impact energy efficiency. The hypervisor layer and virtualization software necessitate processing power and memory, leading to an increase in energy consumption. Finding a happy medium between virtualization's benefits and the costs it causes is important for optimising energy efficiency.
- Cooling Needs: A large portion of a data center's total energy usage goes into cooling the facility. Information technology equipment requires efficient cooling methods to keep it at a proper temperature. Yet, cooling challenges like hot spots and inefficient cooling systems may be addressed with careful infrastructure design, airflow management, and cooling technologies, all while minimising energy use.
- Optimisation of Hardware: Reduced energy consumption is mostly attributable to hardware components' energy efficiency, including servers, storage devices, and networking gear. Regardless, it's possible that older equipment is less energy efficient, and it might be costly to upgrade infrastructure to newer, more efficient gear. Finding a happy medium between reducing hardware inefficiencies and increasing hardware efficiency is a problem for cloud service providers.
- Challenges Facing More Than One Renter: Problems with achieving energy efficiency arise from the multi-tenancy model of cloud computing, wherein several customers use the same infrastructure. To maximise resource utilisation, safeguard sensitive data, and isolate workloads, sophisticated management and isolation approaches are required.
- Their energy consumption is affected by both their physical location and the limitations placed on them by the power system. Renewable energy sources' scarcity, proximity to power networks, and local regulations are only a few of the variables that could impact energy choices. Data centres may have challenges in reducing their energy use if they are unable to connect to local power grids or obtain access to renewable energy sources.
- When using the cloud, you may have to choose between energy efficiency and performance. Quite simply, cloud computing's energy efficiency and performance are not the same thing. Aggressive energy-saving measures, including reducing resources or combining workloads, may impact application performance and even the user experience. A difficulty for cloud service providers is figuring out how to meet performance requirements while reducing energy consumption to an appropriate level.

This means that a comprehensive strategy is necessary for success in overcoming these challenges. This strategy must to incorporate new technological advancements, algorithms for effective resource management, cooperation within the business, and support from regulators. Research and innovation in areas such as designing energy-efficient hardware, optimising workloads, cooling technologies, and integrating renewable energy sources are important for overcoming these issues and achieving sustainable energy usage in cloud computing services.

3. GREEN COMPUTING TECHNOLOGIES

3.1 Virtualization and Server Consolidation for Green Cloud Computing

Virtualization and server consolidation are essential measures that must be taken to promote green cloud computing and increase energy efficiency. Virtualization and server consolidation help provide eco-friendly cloud services by doing the following:

- **Enhanced Use of Available Resources** Through the use of virtualization, it is feasible to run several virtual machines (VMs) on a single physical server, leading to better utilisation of resources. By reducing the number of physical servers needed to handle workloads, resource utilisation rates can be significantly improved. Consolidation has led to an optimisation of energy use by reducing the number of unused servers and eliminating the need to maintain surplus hardware.
- **Server Power Efficiency:** Servers can run closer to their maximum capacity using virtualization, allowing for more efficient power usage. Conventional servers sometimes run at lower utilisation rates, leading to less efficient use of energy. Thanks to virtualization, server capacity may be easily increased or decreased to meet fluctuating workload demands. This contributes to the efficient distribution of resources. The server's power efficiency is improved and its energy consumption is reduced as a result.
- **A decrease in the duration of server downtime:** Virtualization allows for server consolidation, which reduces the number of physical servers and makes upgrades and maintenance easier. By pooling their resources, these servers reduce the amount of downtime required for physical server maintenance. This results in less energy consumption during server downtime, which includes less power utilised for idle functions and less cooling needed for offline servers.
- **Data centres are able to reduce their cooling costs and boost their cooling efficiency** by consolidating servers and reducing physical equipment. Less heat is produced by fewer servers, leading to a decrease in the requirement for cooling. The quantity of energy needed for cooling can be reduced by designing and optimising cooling systems to fit the lower footprint of the infrastructure.
- **The ability to effectively manage hardware lifecycles** is one of the many benefits of virtualization. It is possible to retire or reuse hardware without impacting services by transferring virtual machines (VMs) to newer hardware. This system's adaptability promotes good practices for managing electronic waste and aids in the reduction of electronic rubbish.
- **Virtualization provides cloud services with scalability and operational flexibility.** Better management of load balancing and resource allocation could be possible with the ability to easily move workloads between various physical servers. Due to its flexibility, it is possible to improve resource utilisation, decrease energy waste, and respond to changes in job requirements.

- Two elements that contribute to the creation of green data centres are the usage of virtualization and the consolidation of servers. When data centres reduce the number of physical servers, they may improve the efficiency of their cooling systems, power distribution, and space utilisation. Data centres' environmental effect is lessened and energy efficiency is increased as a result of this design concept.

Keep in mind that virtualization and server consolidation have great potential for energy savings, but they also require careful planning and execution for optimal performance. To achieve energy savings goals while still meeting performance requirements, optimisation of certain areas including workload placement, virtual machine density, and resource allocation algorithms is required. The two primary approaches to achieving energy efficiency and promoting green cloud computing are server consolidation and virtualization. By enhancing resource utilisation, decreasing energy use, and optimising infrastructure, these techniques lead to a more sustainable and environmentally friendly cloud computing ecosystem.

3.2 Dynamic Resource Management and Load Balancing

To optimise resource utilisation and achieve energy economy in cloud computing, two important components are dynamic resource management and load balancing. Below, we've outlined a few key points of green cloud computing, such as dynamic resource management and load balancing:

- The phrase "dynamic resource management" describes how computer resources are adjusted in real-time to meet the demands of running programmes or other tasks. It ensures efficient use of resources while also making sure performance requirements are satisfied. Dynamic resource management relies on the following key components:
- supplying Materials: As part of dynamic resource management, resources are allocated according to the present workload. Automatically increasing or decreasing the number of containers or virtual machines (VMs), providing storage resources on demand, and adjusting CPU and RAM allocations are all part of this.
- It is important for cloud services to be able to adjust their resources to meet fluctuating demand. We call this flexibility. Thanks to elasticity, this feature may be automated by adding or removing resources based on specified criteria or workload patterns. On top of making sure resources are available when needed, this also helps keep energy usage down when demand is low.
- Resource Migration: With dynamic resource management, you can easily transfer containers or virtual machines (VMs) to a different physical server. This helps to maximise resource utilisation and keep the system's burden evenly distributed. Workloads that are already running can be moved utilising live migration techniques without affecting the service in any way. Better load balancing and distribution of resources are the outcomes of this.
- Predictive Resource Management: State-of-the-art approaches to managing resources utilise algorithms for machine learning and predictive analytics to identify trends in workload and resource needs. By looking at patterns and data from the past, resource managers may proactively assign resources to meet future demands. They can reduce energy loss while maximising resource use in this way.

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The purpose of load balancing is to enhance performance, prevent specific servers from being overcrowded, and optimise the utilisation of computer resources by distributing workloads equally across them. When it comes to load balancing, certain methods work better than others:

- **Traffic Distribution:** Least Connections, Round-Robin, and Weighted Distribution are just a few of the methods that load balancers use to distribute incoming network traffic among several servers. This ensures that workloads are distributed evenly, which helps to prevent servers from becoming overwhelmed and improves resource utilisation overall.
- **Workload Monitoring:** Load balancers should be kept in the loop on the status and utilisation of servers' resources and performance. Monitoring resources like CPU utilisation, memory usage, and network traffic allows load balancers to make informed decisions about task allocation and resource distribution. Factors including server availability, capacity, and performance are considered in these selections.
- Load balancers can adapt to new workload patterns with the help of dynamic load balancing. Their ability to adapt workload distributions in real-time in response to factors like server availability, response times, and network congestion is impressive. Dynamic load balancing ensures optimal resource utilisation and continuous adaptability to fluctuating demand. There are several benefits of using green cloud computing: An assortment of ways in which load balancing and dynamic resource management help to environmentally friendly cloud computing are listed below:
- **Optimal Use of Resources:** By distributing resources dynamically according to workload demands, resource management promotes optimal utilisation. In the long run, this helps cut down on energy waste and boosts efficiency.
- **Improving the Efficiency of the Application:** In order to improve application performance and reduce resource bottlenecks, load balancing techniques ensure that workloads are distributed evenly among servers. Doing so improves resource utilisation and decreases the need for overprovisioning.
- **Elasticity and scalability capabilities:** Allocating more or fewer resources in reaction to fluctuating demand is possible with dynamic resource management. This kind of scalability encourages adaptability and enables optimal use of resources, which in turn decreases energy consumption during periods of low demand. By spreading the burden over many servers, load balancing makes them more resilient to failures. One advantage of load balancing is fault tolerance. It is possible to have workloads moved to other available servers automatically in the event that one of them goes down. This lessens the time the server is down and helps keep service uninterrupted.
- **Predictive Resource Allocation:** Proactive resource allocation is made feasible via the implementation of modern resource management methods that utilise predictive analytics. It is feasible to allocate resources in advance by forecasting workload and demand patterns; this reduces energy waste and makes better use of available resources. Optimal resource utilisation and energy efficiency in cloud computing may be achieved via the implementation of dynamic resource management and load balancing algorithms.

Hence, by improving workload distribution, dynamically modifying resource allocations, and forecasting resource demands, these ideas assist to contribute to green cloud computing.

3.3 Renewable Energy Integration in Data Centers

One of the most important steps in making cloud computing more environmentally friendly and sustainable is powering data centres with renewable energy. The main benefits of using renewable energy sources in data centres are as follows:

- **Renewable Energy production on-Site:** Data centres may include renewable energy production technologies into their facilities. Wind turbines, solar panels, or even geothermal systems might be part of these systems. These systems help lessen reliance on grid power that comes from fossil fuels by producing electricity from renewable sources. When data centres generate their own power from renewable sources, they are able to use clean energy in their operations without a middleman.
- **Power Purchase Agreements (PPAs):** Data centres can team up with renewable energy providers to buy power. Power purchase agreements (PPAs) allow for the direct purchase of renewable energy from renewable energy projects such as wind farms, solar farms, and others. This means that data centres may still help generate and use clean energy, even when it's impractical or insufficient to do so on-site.
- **Certificates representing the production of one megawatt-hour (MWh) of renewable energy are known as renewable energy certificates (RECs).** Energy from renewable sources is known as RECs. Data centres may help the renewable energy industry expand by purchasing renewable energy credits (RECs) from projects that generate renewable energy. This would lessen their impact on the environment and the market. Data centres can use renewable energy certificates (RECs) to claim they are using renewable energy even while they aren't physically connected to renewable power sources.
- **Interaction with the Electrical Grid and Net Metering:** Data centres may talk to the power grid and use net metering software. If data centres have more renewable energy than they need, they can feed it back into the grid using net metering. They can make up for their energy use during periods when generation is low by doing this. In turn, this ensures that renewable energy sources' contributions are balanced with the energy that is pulled from the grid.
- **Combining renewable energy generation with energy storage devices like batteries allows data centres to store excess renewable energy for usage during peak demand or periods of low renewable energy supply.** Reduce reliance on grid power and increase energy efficiency by utilising energy storage devices to provide a consistent and uninterrupted flow of power from renewable sources.
- **Demand Response Programmes:** Data centres can adjust their energy use in response to changes in the grid's capacity or the availability of renewable energy sources by participating in demand response programmes. By reducing their energy use during peak demand or periods when renewable energy is limited, data centres contribute to grid stability and encourage the incorporation of renewable power sources.
- **Strategies for Green Power Procurement:** Data centres might prioritise cloud service providers and colocation facilities who have committed to using renewable energy. Data centres help increase the demand for renewable energy and establish relationships with providers who prioritise green power procurement, which in turn helps expand clean energy output.

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- Before implementing renewable energy sources, data centres should focus on energy efficiency to reduce total energy use. For the simple reason that implementing energy efficiency measures can lead to a general decrease in energy usage. Proper utilisation of renewable energy sources and reduction of energy waste are both achievable goals with the help of energy-efficient infrastructure, server consolidation, cooling optimisation, and power management strategies.

It should be remembered that integrating renewable energy sources into data centres calls for careful preparation, infrastructure design, and cooperation with power suppliers. Site selection, feasibility studies, fiscal investments, and regulatory compliance are just a few of the obstacles that must be overcome. When data centres see the need to incorporate renewable energy sources, they help create a greener future by reducing emissions of greenhouse gases and promoting the usage of this type of energy in the IT industry.

4. ENERGY-AWARE RESOURCE ALLOCATION AND SCHEDULING FOR GREEN CLOUD COMPUTING

4.1 Energy-Aware Task Scheduling Algorithms for Green Cloud Computing

An integral part of promoting green computing and energy efficiency in cloud environments is energy-aware work scheduling algorithms. These algorithms are developed with the aim of efficiently allocating computing workloads to available resources, all the while considering energy use constraints. Some of the most important parts and approaches of energy-aware job scheduling algorithms are:

- **Energy Models and Consumption Estimation:** In order to determine how much power different resources and tasks use, task scheduling algorithms that take energy consumption into account often use energy models and estimation methods. In order to estimate the amount of power needed to execute certain actions, these models consider many characteristics, such as CPU utilisation, memory utilisation, and communication overhead.
- To ensure that resources run in low-power or sleep modes while they are not being used, task scheduling algorithms can utilise power state management methodologies. Job scheduling on resources in states that optimise energy efficiency can lead to a decrease in energy consumption. In order to prevent unnecessary delays, the algorithms should factor in the time required to change power states.
- Reducing the number of active resources required to complete a given work is the primary objective of energy-aware task scheduling algorithms. The process of migrating and consolidating tasks does this. Reduced energy consumption is achieved by intelligent job assignment, which allows for the deactivation of unused or underutilised resources. Utilising task migration techniques allows for the dynamic balancing of workloads across resources. In this way, efficiency in energy consumption may be maximised without sacrificing performance.
- Algorithms for scheduling tasks take into account load balancing and resource utilisation to ensure the lowest feasible energy use. In order to avoid wasting energy and using unnecessary resources, it is important to divide tasks fairly across them. This ensures that no resource is overloaded. By making better use of available resources, we can keep power consumption per work from going up due to underutilization.

- **Scheduling using Predictive Algorithms:** These algorithms employ and incorporate past workload data and workload prediction models to anticipate future workload trends. By projecting future resource demands, task scheduling may proactively allocate resources. Because of this, less energy is lost as a result of under- or over-provisioning of resources.
- When planning tasks, energy-aware algorithms think about things like communication overhead and data localization features to see how to cut down on power use. You may lower the amount of energy consumed for network connectivity and the associated energy consumption by scheduling jobs that require large data transfers on resources that are closer to the data source. It is possible to reduce energy usage by colocating tasks that need a high degree of connectivity, which in turn reduces data transmission distances.
- Energy-aware task scheduling algorithms can prioritise jobs based on their significance or due dates. This feature is known as task prioritisation. Assigning higher priority tasks to resources with better energy efficiency is one way to reduce energy consumption for time-sensitive or essential workloads.

Finally, it is essential to understand the workload characteristics, resource capabilities, and energy consumption profile distribution in depth in order to build task scheduling algorithms that are energy sensitive. By optimising decisions on job allocation, cloud computing systems might potentially bring about higher energy efficiency, lower carbon emissions, and enhanced sustainability.

4.2 Dynamic Resource Provisioning and Allocation for Green Cloud Computing

Achieving the objectives of green cloud computing relies heavily on dynamic resource allocation and provisioning. By carefully controlling their resources, cloud service providers may greatly reduce their carbon emissions, optimise the utilisation of their resources, and decrease their energy consumption. Here is a rundown of some of the numerous approaches utilised by green cloud computing to dynamically provide and allocate resources:

- To ensure the most efficient utilisation of resources, load balancing involves distributing workloads over many servers or virtual machines. By using dynamic load balancing, cloud service providers may keep their servers from being overwhelmed and cut down on energy waste. Load balancing algorithms consider several factors, such as CPU utilisation, memory use, and network traffic, to allocate resources appropriately.
- By merging several VMs into one smaller set of servers, virtual machine (VM) consolidation aims to reduce the number of physical servers that are being used. The merging of virtual machines makes this possible. Utilising this technology leads to a decrease in energy consumption and an increase in resource utilisation by eliminating underutilised or idle servers. In order to consolidate virtual machines (VMs) in a way that maintains performance and service level agreements, dynamic VM consolidation algorithms are responsible for continuously evaluating resource demands and making intelligent decisions.
- **Considering Power Consumption in Task Scheduling** When allocating resources to jobs, power-aware task scheduling algorithms consider both performance and energy consumption factors. By strategically allocating tasks to power-efficient servers or virtual machines (VMs), cloud providers may improve resource allocation while reducing overall energy consumption. In order to make ef-

efficient and effective scheduling decisions, these algorithms examine several factors, such as server power profiles, work priorities, and communication costs.

- Allocation of Resources Bearing Renewable Energy Sources in Mind By factoring in the availability and utilisation of renewable energy sources, resource allocation algorithms may promote sustainability in green cloud computing. The ability to dynamically allocate resources to data centres powered by renewable energy sources allows cloud service providers to maximise the usage of clean energy while decreasing their reliance on power networks fuelled by fossil fuels. Energy availability, energy cost, and workload allocation among renewable energy data centres are only a few of the criteria taken into consideration by these algorithms.

Hence, Providers of cloud services may improve resource utilisation, decrease energy consumption, and limit carbon emissions in green cloud computing environments by using these dynamic resource provisioning and allocation approaches. The reason behind this is that these techniques enable the dynamic allocation and delivery of resources. The overarching goal of creating efficient and environmentally friendly cloud services is advanced by these tactics.

4.3 Energy-Efficient Virtual Machine Placement for Green Cloud Computing

Efficient deployment of virtual machines (VMs) is an important aspect of environmentally conscious cloud computing. In this aspect of green cloud computing, virtual machines (VMs) are best allocated to real servers in a way that maximises resource utilisation and minimises energy use. When deciding how to deploy virtual machines, it's important to think about things like server power consumption, workload characteristics, and resource requirements. In green cloud computing, some energy-efficient methods for deploying virtual machines are:

- Placement Based on Consolidation: This approach aims to reduce the power consumption of virtual machines by putting them all on a smaller number of physical servers. Virtual machines (VMs) with similar resource requirements and workload characteristics can be pooled together to increase total server utilisation. Underutilised servers may crash or be consolidated as a result of this. Virtual machine (VM) placement algorithms take into account VM resource requirements, allocate them to servers that can fulfil those demands, and all the while keep performance and SLAs intact.
- Load-Aware Placement: Utilising the current workload distribution across physical servers, load-aware placement algorithms generate informed placement recommendations. Avoiding server overload, which might lead to higher energy usage, is the objective of these algorithms. Virtual machines (VMs) run on servers with evenly distributed loads, allowing this to happen. The goal of load-aware placement is to distribute virtual machines among servers that have available resources by taking measures like CPU utilisation, memory use, and network traffic into account.
- One method is power-aware virtual machine placement, which involves allocating VMs to servers based on their power consumption characteristics. This technique finds servers or server states that use little power, and then distributes virtual machines (VMs) based on their power profiles. To reduce overall energy consumption and maximise overall efficiency, power-aware placement algorithms install virtual machines (VMs) on servers that are efficient with energy.

- **Thermal-Aware Placement:** Algorithms used to manage VM placement take server thermal characteristics into consideration and strive to distribute the heat produced by VMs evenly across the data centre. Improving cooling efficiency and reducing energy consumption related to cooling infrastructure may be achieved by thermal-aware deployment. To do this, we disperse the virtual computers in a way that keeps certain regions from getting too hot. Among the many factors considered by these algorithms when deciding where to put things is the server's temperature, as well as its cooling capacity and thermal constraints.
- Using predictive models, certain advanced virtual machine placement tactics may foresee resource needs and workload patterns. Dynamic placement with predictive models is one solution in this category. By looking at historical data and taking things like time of day, seasonality, and workload patterns into account, these models are able to predict future resource needs. Optimising energy efficiency and tool utilisation is possible through proactive allocation of virtual machines (VMs) and modification of resource provisioning made possible by dynamic placement algorithms that use predictive models.

Last but not least, green cloud computing's virtual machine deployment strategies might significantly help with energy efficiency, resource conservation, and green practice promotion. By using these strategies, cloud service providers may meet their clients' demands for performance and service while also reducing their energy use.

5. GREEN CLOUD APPLICATIONS AND CASE STUDIES

5.1 Green Cloud Gaming

The phrase "green cloud gaming" describes the use of eco-friendly methods and tools in the cloud gaming industry. Reducing the energy consumption and carbon footprint of gaming services is the main goal of this industry. By connecting to distant servers, users may stream games through cloud gaming. This removes the need for high-end gaming gear and minimises the amount of energy used by each user. Here are some key points to consider and ways to implement eco-friendly practices in cloud gaming:

- **Energy-Efficient Data Centres** Providers of gaming services in the cloud may focus on operating data centres with little energy usage. Using energy-efficient technology, optimising cooling systems, and implementing power management techniques are all part of the plan to reduce energy use. Data centres may achieve greater overall energy efficiency by implementing state-of-the-art technologies such as server virtualization, consolidation, and energy-efficient components.
- **Using Server Technology and Making the Most of Available Resources:** Maximising server usage is important for cloud gaming to get maximum energy efficiency. Using load balancing and resource allocation methods, providers can potentially improve the efficiency of server-side game instance distribution. This ensures that server resources are utilised efficiently and stops them from being underutilised, which leads to reduced carbon emissions and energy savings.
- **Networking that is conscious of power usage:** For online multiplayer gaming to be successful, a solid networking infrastructure is required. Providers can mitigate network bandwidth require-

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ments and energy consumption during data transmission by employing energy-aware networking techniques like traffic optimisation, data compression, and quality of service (QoS) management.

- Cloud software gaming systems rely on virtual machine (VM) technologies, which are important to their functioning. One such technology is virtual machine consolidation. Providers can improve resource utilisation and reduce energy consumption by consolidating several game instances onto a smaller number of physical servers or virtual machines (VMs). In order to reduce energy waste, virtual machine (VM) consolidation algorithms constantly track resource utilisation and improve the distribution of VMs. The usage of renewable energy sources to power data centres can be prioritised by cloud gaming providers. This allows for the integration of renewable energy. Using renewable energy credits and investing in renewable energy purchase might significantly lower cloud gaming services' carbon impact. Providers may also look at investing in renewable energy generation on-site or establishing agreements with green energy suppliers.
- User Education and Being Aware of the Product: and Spreading awareness about the energy-saving advantages of cloud gaming and encouraging energy-conscious conduct can have a positive impact. In order to help gamers reduce the amount of energy they waste when gaming, gaming devices and platforms should have energy-efficient settings, automatic shutdowns, and low-power modes.
- Even if cloud gaming does away with the necessity for top-tier hardware, encouraging the usage of power-efficient monitors, headphones, and other gaming accessories can contribute to more environmentally friendly gaming habits. More and more people are turning to cloud gaming as their preferred method of playing online games. The promotion of energy-efficient gaming consoles, peripherals, and accessories with built-in energy-saving features can contribute to a decrease in the amount of energy consumed during video game play.
- Gaming gear must be properly managed over its whole existence if it is to be sustainable. An integral part of lifecycle management is recycling as well. By promoting the proper disposal and recycling of old gaming gear, we can help bring down the amount of electronic waste and get closer to a circular economy.

As a result, cloud gaming providers may help promote sustainability in the gaming business by reducing their energy consumption, contributing to more environmentally friendly practices, and so on. Green cloud gaming allows players to enjoy their favourite games without negatively impacting the environment.

5.2 Green Cloud in Industry Verticals (e.g., Healthcare, Finance)

Green cloud computing has the ability to improve energy efficiency and environmental sustainability across several industrial sectors. Here are a few examples of potential sectors that might benefit from green cloud:

- The healthcare industry stands to benefit greatly from the digitization of patient data management, imaging systems, and medical records if green cloud computing materialises. Healthcare organisations may store and retrieve patient records on energy-efficient cloud infrastructure, eliminating the need for paper records and physical storage. Additionally, telemedicine systems hosted in the cloud can enable remote consultations, reducing patient travel and the associated energy consumption and carbon emissions.

- The banking and financial services business is one that may greatly benefit from green cloud computing's ability to streamline data centre operations and infrastructure. There is no longer any need for physical branches or paper transactions thanks to cloud-based financial technology like smartphone applications and internet banking. Moving financial apps and services to more energy-efficient cloud platforms can help financial firms save money and lessen their environmental effect.
- Cloud computing provides the ability to enable smart manufacturing with supply chain optimisation, which might lead to smart manufacturing overall. Cloud analytics and data management allow firms to track and improve energy use across all industrial processes, leading to less waste and more efficient use of resources. The use of cloud-based supply chain management solutions has the ability to maximise inventory management while simultaneously reducing transportation-related emissions by increasing supply chain visibility, coordination, and collaboration.
- Retail and e-commerce: E-commerce platforms and inventory management systems in the retail industry might be made more energy efficient with the use of green cloud computing. Online storefront optimisation, server energy consumption minimization, and demand-based dynamic scalability are all possible with cloud-hosted retail systems. Furthermore, logistics operations may be enhanced using cloud-hosted supply chain analytics through the optimisation of delivery routes and the reduction of carbon emissions in the last mile of delivery.
- The use of cloud computing in the education sector might pave the way for the development of greener online classrooms. There may be less need for printed textbooks and other educational resources if cloud-based e-learning systems provide instructors and students with remote access to these resources. Learning management systems, online collaboration tools, and virtual classrooms housed in the cloud provide the ability to enhance education delivery while decreasing the energy normally associated with physical infrastructure.
- Government Agencies and Public Services: By using green cloud computing, government agencies and public services may enhance service delivery and make the most of their resources. Using digital platforms that provide online government services and citizen service portals hosted in the cloud can reduce the need for in-person visits and paperwork. In addition, public administration may be able to save energy and become more sustainable with the use of cloud-based data analytics for evidence-based policymaking, resource planning, and infrastructure optimisation.

To sum up, these examples show how green cloud computing can be used to many different types of industries, which in turn helps to reduce carbon emissions, increase energy efficiency, and open up new avenues for sustainable practices. The specifics of implementation and benefits will vary across industries because every market has its own quirks and needs.

6. GREEN CLOUD SECURITY AND PRIVACY

6.1 Energy-Aware Security Mechanisms for Green Cloud Computing

Green cloud computing prioritises energy-aware security techniques that aim to maintain strong security while reducing energy consumption and environmental impact. The goal of these methods is to set up

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efficient security processes while making the most of the resources that are already accessible. Here are a few energy-efficient security measures related to green cloud computing:

- Computationally expensive and energy-intensive are two characteristics of traditional encryption methods. As an alternative to such cumbersome techniques, lightweight cryptography can be used. Using lightweight cryptographic algorithms designed for low-resource environments allows us to reduce power consumption without sacrificing security. These techniques keep the necessary level of security while minimising computational overhead and energy consumption. Cloud computing relies heavily on virtualization technologies, one of which is virtualization security. Ensuring the safety of virtual machine (VM) instances while concurrently decreasing the security overhead is a key goal of energy-aware secure virtualization. Implementing a number of solutions, including as secure booting, hardware-assisted virtualization, and hypervisor-based security measures, can optimise resource utilisation and energy efficiency while simultaneously increasing security.
- Users' permissions to access resources in the cloud are controlled by access control systems. We are talking about energy-aware access control here. In energy-aware access control, the quantity of energy utilised is considered while granting access to resources. Optimising energy use while maintaining security may be achieved by dynamically adjusting access privileges and resource provisioning according to energy availability and user requirements. Wasteful resource allocation may be prevented and energy waste can be decreased by utilising this strategy.
- Intrusion Detection and Prevention: Energy-aware intrusion detection and prevention systems (IDPS) seek out and remove any security threats while cutting down on energy use. Using efficient algorithms, these systems are able to monitor and analyse system logs and network traffic in real time. There is a way to reduce energy consumption associated with security monitoring without sacrificing good threat detection. Reducing the amount of false positives and improving the detection algorithms can achieve this.
- Minimising Energy Consumption for Security Monitoring: Optimisation of security monitoring system deployment and maintenance is an important aspect of energy-aware security monitoring. Included in this is the strategic positioning of surveillance cameras and other security devices. The objective is to reduce power usage without sacrificing coverage during their installation. More energy-efficient security monitoring is feasible with the help of technologies like distributed monitoring and edge computing, which decrease the amount of data processing and transmission needed.
- Secure Data transfer: To guarantee efficient data transfer, energy-aware secure data transmission prioritises improving encryption techniques and procedures. It is feasible to decrease the amount of energy spent during data transmission without compromising security by utilising energy-efficient encryption techniques, reducing encryption overhead, and reducing the number of encryption operations. To further aid in the energy-efficient transfer of encrypted data, techniques such as data compression and encryption offloading can be employed.
- Compliance with Green Security Policies: Ensuring that security measures align with the goals of energy efficiency and sustainability is made possible via the establishment of green security policies and compliance frameworks. Organisations can institute rules that promote energy-conscious security practices and support the use of energy-efficient security devices. Security measures in green cloud computing can be guided by compliance standards. Indicators of energy efficiency, security measures, and environmental criteria can all be found in these frameworks.

With security solutions that are cognizant of energy consumption trends, organisations may find a middle ground between security requirements and energy efficiency in cloud computing environments. Through these methods, we may achieve robust security, preserve sensitive data, reduce energy usage, optimise resource utilisation, and promote sustainability all at once.

6.2 Green Cryptography and Privacy Preservation

The main focus of green cryptography and privacy preservation is to apply privacy-enhancing techniques and cryptographic algorithms in an energy-efficient and environmentally friendly way (Meghna, Amit Kumar Tyagi, 2023) (Amit Kumar Tyagi, 2023). While reducing energy use, these solutions are meant to secure sensitive information and preserve privacy. When it comes to environmentally friendly encryption and privacy protection, these are some of the most pressing issues and solutions:

- **Energy-Starting Cryptographic Methods** A key component of “green” encryption is the utilisation of algorithms that minimise power consumption. While lowering the amount of computational overhead and energy consumption, these techniques provide stringent security. Using methods like lightweight cryptography, which were developed for devices with minimal resources, can help achieve energy economy without compromising data safety.
- **Key Administration and Distribution:** Reducing energy use and increasing security protection are two outcomes of effective key management systems. Key distribution approaches that are energy-aware, such elliptic curve cryptography (ECC) with smaller keys, might potentially decrease the computational power needed for key production, distribution, and encryption. Further decrease in energy consumption by key management operations is achieved through the use of energy-efficient key update and revocation strategies.
- **Privacy-Preserving Protocols:** Protecting private data while lowering computing and data transport energy requirements are two main objectives of privacy-preserving methods. Various techniques, including secure multiparty computing (SMC), homomorphic encryption, and differential privacy, allow computations to be executed on encrypted data. The confidentiality of the supplied information can be ensured using these techniques. Reducing energy consumption without compromising user data privacy is possible using privacy-protecting protocols.
- **Protocols for energy-efficient secure communication** may be developed to improve data transfer while limiting energy consumption. This allows for energy-aware secure communication. Utilising strategies like energy-aware routing, efficient encryption algorithms, and compressed encryption methods can help reduce the energy overhead associated with secure communication. Using strategies like opportunistic encryption and packet bundling, energy efficiency in secure communication may be optimised even further.
- **Technologies that Enhance Privacy:** These technologies are designed to minimise data collection and usage in order to safeguard user privacy. Methods like data minimization, data anonymization, and pseudonymization can help reduce the amount of personal information that is collected and kept. Reduced energy consumption associated with processing and storing massive amounts of personal data without compromising data confidentiality is possible with the help of privacy-enhancing technology.
- **Control of Access That Considers Energy Consumption** In order to determine who has access to what resources, energy-aware access control systems consider energy use. It is feasible to avoid

the allocation of unnecessary resources and energy waste by dynamically changing access permissions based on energy availability and user requirements. Reduced computational overhead is another benefit of energy-aware access control when it comes to control checks.

- **Data lifetime management:** Effective data management throughout all stages of data lifecycles contributes to privacy protection and energy efficiency. Data retention restrictions, data anonymization techniques, and secure data deletion protocols can help reduce the energy waste associated with storing and processing unnecessary data. An effective data lifecycle management system facilitates a middle ground between energy efficiency goals and privacy requirements.
- **Energy-efficient hardware:** To make cryptographic procedures more energy efficient, one may use low-power processors, cryptographic accelerators, or hardware security modules (HSMs). By using energy-efficient hardware components, cryptographic calculations may be performed with little power consumption and strong security.

Implementing green cryptography and privacy preservation solutions allows businesses to strike a compromise between data security, privacy protection, and energy efficiency. These solutions not only minimise energy consumption, increase resource utilisation, and promote sustainability, but they also guarantee excellent cryptographic security and privacy protection.

7. OPEN ISSUES TOWARDS GREEN CLOUD COMPUTING

While green cloud computing has come a long way in promoting sustainability and energy efficiency, there are still certain issues and concerns that have not been fully overcome. It is necessary to identify and address these problems and obstacles. Some major questions in the realm of environmentally friendly cloud computing remain unanswered, and they are as follows:

- **Common practices and evaluation criteria:** Environmental impact assessment methods, sustainability standards, and energy efficiency metrics are all now in the works of becoming standardised. There aren't any universally accepted metrics for comparing and assessing the environmental performance of different cloud service providers. To ensure accurate reporting, comparison, and assessment of ecologically responsible cloud computing activities, it is important to establish commonly accepted standards and metrics.
- **Still, efficient energy management in dynamic cloud environments is challenging.** It is necessary to resolve the challenge of dynamic energy optimisation. A topic that is now receiving a lot of attention from researchers is how to dynamically optimise power management, job scheduling, and resource allocation without sacrificing performance or user experience. We must prioritise the development of smart energy optimisation algorithms and frameworks that can adjust to evolving workload patterns and resource needs.
- **Where to Find Data Centres and Power Plants:** To what extent cloud computing contributes to environmental degradation may depend importantly on the location and energy consumption of data centres. Data centres must be situated in areas with access to renewable energy sources and their energy mix must be considered if true sustainability is to be achieved. Reducing reliance on fossil fuels while increasing usage of renewable energy sources is a continuing problem.

- **Methods and Tools for Building Green Data Centres:** Data centre design, cooling technologies, server architecture, and energy-efficient technology must undergo continuous innovation. Research is ongoing in several areas, including the improvement of server utilisation and performance, the creation of more energy-efficient cooling systems, and the examination of new technologies like liquid cooling. New eco-friendly data centre technologies are expected to be a major factor in significantly reducing the energy consumption of cloud computing infrastructure.
- **Difficulties with Personal Data Protection and Online Security:** The preservation of user confidentiality and safety in environmentally conscious cloud computing environments remains a major concern. Finding a happy medium between energy-saving procedures and regulations pertaining to data privacy and security could be challenging. Encryption techniques that are efficient, require little CPU overhead, and provide robust security, as well as protocols for the secure transport of data, remain a focus of ongoing attention.
- The education of users and the adoption process are ongoing challenges; one of them is getting individuals and businesses to embrace cloud computing in an eco-conscious way. The benefits of energy efficiency and sustainability, along with the part that users may play in reducing their environmental effect, must be educated to users. Green alternatives, user-friendly tools and interfaces to enable green choices, and behavioural changes are areas that require further attention.
- Cloud computing infrastructure and devices generate a great deal of electronic trash, or e-waste, which has not yet been adequately addressed in terms of lifecycle management. Reusing, recycling, and properly disposing of hardware components is important for reducing the environmental impact of cloud computing. The promotion of proper disposal and recycling practices, the creation of long-term strategies for handling electronic waste, and the ideas behind circular economies are all ongoing challenges.

Because of this, industrial players, academic institutions, governments, and consumers all need to collaborate to find answers to these unanswered questions. For green cloud computing to successfully promote the adoption of energy- and environmentally-efficient practices, it needs constant research, new ideas, information sharing, and policymaking.

8. FUTURE DIRECTIONS AND EMERGING TRENDS TOWARDS GREEN CLOUD COMPUTING

8.1 Green Cloud Computing Research Roadmap for Future Research

Research roadmaps provide an overview of the main areas of focus and objectives that academics and industry practitioners should think about to advance green cloud computing. An approach to clean cloud computing based on proposed research is as follows:

- The energy-efficient resource management effort aims to optimise energy consumption, ensure performance, and satisfy users through the development of advanced solutions for resource management. Allocating workloads dynamically, intelligently placing virtual machines, and using energy-aware scheduling algorithms that account for workload specifics, energy profiles, and performance requirements are all part of this.

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- Research state-of-the-art data centre designs and cooling technologies that lessen energy consumption and improve energy efficiency; this will help create green data centres. This encompasses the study of thermal management strategies, heat reuse, novel cooling systems, and liquid cooling. Our objective is to maximise data centre cooling efficiency while minimising the use of traditional cooling technologies wherever feasible.
- Researchers should look at ways to integrate renewable energy sources into cloud computing infrastructures so that they can be used effectively. Research on new possibilities for the production and storage of renewable energy inside data centres, as well as methods for optimally matching energy use with the availability of renewable energy, should be undertaken.
- Network equipment, switches, routers, and communication protocols are all part of the network infrastructure that the Green Network Infrastructure programme aims to address with an emphasis on energy efficiency. It is important to look at ways to improve network speed, reduce latency, and optimise energy use without compromising network security or reliability.
- Investigate ways to handle, store, and retrieve data in cloud systems that are more energy efficient; this is part of the green data management and storage initiative. Studying techniques for data compression, intelligent data placement, effective data retrieval, and data deduplication is important for reducing energy usage and optimising storage utilisation.
- The primary measure to guarantee the security and confidentiality of green cloud computing solutions is to establish robust privacy and security protocols tailored to green cloud computing. Research on protocols that protect users' privacy, energy-efficient encryption techniques, and secure data transfer technologies that minimise energy use without sacrificing security or privacy should be considered.
- E-Waste Reduction and Lifespan Management: Provide long-term solutions to the problems associated with managing electronic waste in cloud computing through the development of environmentally friendly practices for component recycling, responsible disposal, and hardware lifespan management. As a result, this will contribute to the resolution of issues caused by cloud computing. Examining the ideas of circular economies, refurbishing techniques, and environmentally friendly manufacturing practices can help reduce the negative impacts of cloud computing infrastructure on the environment.
- User awareness and Adoption: Look at several options for increasing user awareness and getting others to adopt green cloud computing practices. In order to persuade businesses and individuals to embrace green and energy-efficient cloud computing practices, studies on user education, behavioural change, and persuasive tactics are important.
- Metrics and Standardisation: Contribute to the development of defined measures, frameworks, and processes for assessing and contrasting cloud computing systems' energy efficiency and environmental effect. There are a number of potential avenues for harmonising green computing standards and laws across nations, which could facilitate standardisation of practise and benchmarking.
- Frameworks for the economy and businesses: The cost-effectiveness of energy-efficient approaches, the impact on business operations, and the potential income models are only a few of the economic and financial ramifications of green cloud computing that should be investigated. To encourage the usage of green cloud computing, research on the function of market mechanisms, subsidies, and incentives is important.

This study's results provide a comprehensive review of the key areas for future research that could lead to innovations in green cloud computing. To address these research challenges and promote the implementation of sustainable and energy-efficient practices, collaboration among academics, industry practitioners, legislators, and end-users is important.

8.2 Emerging Technologies and Innovations Towards Green Cloud Computing

Innovations in green cloud computing are being propelled by new technology, which opens the door to more sustainable and energy-efficient activities. The following are some of the most important innovations and technologies that have helped make cloud computing greener:

- **Machine learning and artificial intelligence:** Cloud computing is utilising ML and AI techniques to enhance resource allocation and energy usage. In order to achieve higher energy efficiency and reduce operational costs, intelligent algorithms can dynamically modify resource utilisation, job scheduling, and cooling systems. Optimising energy usage is another potential outcome of AI-powered predictive analytics that include both historical trends and current data.
- **The phrase “edge computing”** describes the trend towards locating data processing and storage facilities closer to the point of generation. This gets rid of the requirement to send data to the cloud several times. It is possible to lessen the amount of energy required for data transmission. Data processing at the edge of the network makes this possible. In addition to reducing reliance on resource-intensive cloud infrastructure, edge computing enables real-time analytics and reactions.
- **Data Centres with a Green Profile:** Data centres with a green profile employ innovative design and technologies to reduce their energy consumption and environmental effect. Modular data centres, liquid cooling, better power management, and renewable energy source integration are all examples of techniques that fall under this category. The main objectives of environmentally friendly data centres are to optimise energy efficiency, reduce carbon emissions, and make the most of available resources by making full use of them.
- **Energy-efficient hardware:** New central processing units, memory modules, and storage devices have all helped make cloud computing more power efficient. Central processing units (CPUs) with low power consumption, energy-efficient memory technologies (like non-volatile memory), and solid-state drives (SSDs) use less power than traditional hardware components. Utilising dedicated hardware accelerators can improve some computer tasks in terms of performance per watt. Intel® Graphics Processing Units and Field Programmable Gate Arrays are two examples of accelerators in this category.
- **The ability to centrally manage and allocate network resources** is a key feature of software-defined networking (SDN), which allows for efficient optimisation and allocation of network capacity (Meghna, Amit Kumar Tyagi, 2023) (Mishra S., Tyagi A.K., 2022) (T. T. George and A. K. Tyagi, 2022) (Rekha G., Tyagi A.K., Anuradha N, 2020). By using SDN-based solutions, network topologies may be changed dynamically to reduce energy consumption and boost overall network efficiency. Cloud computing uses software-defined networking (SDN) to optimise traffic management and network routing, which in turn reduces communication energy consumption.
- **A greener energy production strategy** is to integrate renewable power sources like solar and wind into cloud computing infrastructures. This will help reduce the impact on the environment. Cloud service companies are acquiring renewable energy through PPAs, which stand for power purchase

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agreements. Renewable energy generation is another area where these suppliers are increasing their investments. One way to lessen the impact on the environment caused by cloud computing is to use renewable energy sources. This will help cut down on our reliance on fossil fuels.

- More energy efficiency and storage optimisation in cloud systems are two outcomes of recent developments in environmentally friendly storage technologies. Data deduplication, compression, and tiered storage systems are beneficial approaches for lowering the energy footprint of storage operations. New storage technologies, such as solid-state drives (SSDs), allow for more storage density with less power usage. Technology such as shingled magnetic recording (SMR) and helium-filled drives are instances of this kind.
- Effective management of workloads and resources in cloud environments is now feasible thanks to technologies like virtualization and containerisation. Containerisation technologies provide lightweight and isolated application environments; two examples are Docker and Kubernetes. Better allocation of resources and less need for unnecessary hardware provisioning are both made possible in these settings. Virtualization technology allows for optimised server usage, which brings about consolidation and energy savings.
- Integration of the Internet of Things (IoT): By combining cloud computing with IoT devices and sensors, energy usage may be better monitored, managed, and optimised in many different contexts (Sheth, H.S.K., Tyagi, A.K., 2022). (Nair M.M., Kumari S., Tyagi A.K. 2021). By providing real-time data for optimisation and decision-making that saves energy, smart grids, IoT-enabled intelligent building management systems, and energy monitoring solutions contribute to energy efficiency and sustainability.
- Models of Service Utilising Green Clouds: Some of the green cloud service models that providers are providing include software as a service (SaaS), infrastructure as a service (IaaS), and platform as a service (PaaS) solutions that are more energy efficient. These models incorporate strategies to better use resources, reduce energy consumption, and ensure long-term viability, all with the goal of providing greener cloud computing solutions to customers.

These emerging technologies and innovations show the current endeavours to make cloud computing greener, more efficient, and less harmful to the environment. Utilising these enhancements, companies can reduce their carbon footprint, increase resource utilisation, and save money—all while taking advantage of the scalability and adaptability that cloud computing services provide—and so reduce their environmental impact.

8.3 Green Cloud Computing in the Context of Sustainable Development Goals

Environmentally friendly cloud computing aligns with many United Nations Sustainable Development Goals (SDGs). The following is a rundown of the SDGs and how they relate to green cloud computing:

- Green cloud computing promotes energy efficiency and the utilisation of renewable energy sources, which contribute to Sustainable Development Goal 7: Affordability and Clean Energy. Using cloud computing makes it easier to switch to cheaper and greener energy sources, which in turn reduces the carbon impact. This is achieved by implementing energy-efficient equipment, making use of renewable energy sources, and optimising energy consumption.

- Goal 9 of the Sustainable Development Agenda: Industry, Innovation, and Infrastructure Cloud computing that is “green” promotes the development of eco-friendly hardware and software. It promotes the development and use of data centres with improved energy efficiency, cutting-edge cooling technologies, and eco-friendly hardware. Green cloud computing promotes technological advancements that help build resilient and long-lasting infrastructure.
- By encouraging resource optimisation and smart data management, green cloud computing helps to reduce electronic waste, which contributes to Sustainable Development Goal 12: Responsible Consumption and Production. Reduced energy consumption and physical infrastructure requirements go hand in hand with its promotion of frugal use of computer resources. Responsible consumption and production may be fostered through the use of environmentally friendly cloud computing, which maximises resource utilisation and supports sustainable habits.
- One way to lessen the impact of climate change is through green cloud computing, which ties into Sustainable Development Goal 13: Climate Action. Cloud computing helps achieve climate action goals by, among other things, optimising energy consumption, using renewable energy sources, and reducing carbon emissions normally linked with computing. With this software’s help, businesses may transition to low-carbon operations and reduce their carbon footprint.
- Partnerships for the Goals, which is Sustainable Development Goal 17: Many different groups and individuals, including governments, businesses, and cloud service providers, must work together to ensure that cloud computing is conducted in an environmentally friendly manner. Collaboration is important for generating innovation, creating industry standards, and encouraging the adoption of energy-efficient practices. Collaborative efforts are important for achieving the environmental conservation and sustainable development-related Sustainable Development Goals (SDGs).

Consequently, businesses may help achieve several SDGs by employing eco-friendly cloud computing practices. The larger aims of sustainable development align with the associated principles of responsible resource utilisation, efficient energy utilisation, and reduced carbon emissions associated with cloud computing (Tyagi, A.K., Sreenath, N., 2023) (Tyagi, Amit Kumar, 2019) (Reddy K.S., Agarwal K., Tyagi A.K., 2021) (Li, J., & Li, B. 2012) (Ren, S., & Tan, Z. (2016). In addition to contributing to the worldwide objective of a more sustainable future, environmentally friendly cloud computing has operational and economic advantages.

9. CONCLUSION

As this chapter has shown, green cloud computing is not without its share of advantages and disadvantages. Concerning sustainability, energy efficiency, and ecological responsibility, these are the possibilities and threats. Bear in mind that there may be many benefits for businesses and the environment by using energy-efficient practices, integrating renewable energy sources, and optimising resources within cloud computing infrastructure. Nevertheless, this chapter has highlighted some challenges that must be conquered before the potential of green cloud computing can be completely realised. Some of the advantages of green cloud computing have already been mentioned. Possible benefits include reduced energy use, better use of resources, cheaper costs, and alignment with sustainable development goals. Businesses can lessen their impact on the environment and help shape a greener future by installing energy-efficient hardware, making smarter use of their resources, switching to renewable energy, and

encouraging responsible consumption. Cloud computing that is less harmful to the environment is, therefore, both a technical challenge and a shared responsibility for a better, more sustainable future.

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