GreenStream Routing: Dynamic Data Allocation from Edge Devices to Multi-Cloud Based on Renewable Energy Utilization.

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Vamshi Goutham Akabote
Student ID:X22203010

School of Computing
National College of Ireland

Supervisor: Yasantha Samarawickrama

National College of Ireland

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GreenStream Routing: Dynamic Data Allocation from Edge Devices to Multi-Cloud Based on Renewable Energy Utilization.

Vamshi Goutham Akabote
X22203010

Abstract

The rapid growth of data centres to support the increasing digital service has led to significant energy consumption and environmental impacts, primarily due to reliance on non-renewable energy (brown energy) sources. This research introduces Adaptive Renewable Energy Resource Allocation (ARERA) algorithm, which is designed to dynamically route tasks from the edge devices to cloud data centres based on distinct factors like renewable energy availability, current load distance, and urgency of task. By integrating ARERA with iFogSim simulation toolkit, this study aims to optimize energy usage and reduce carbon emission. The results produced by the simulation demonstrates that the ARERA effectively prioritizes data centres powered by renewable energy, significantly reducing carbon emissions while maintaining performance and efficiency. For example, during simulation process the tasks routed to data centres with higher renewable energy availability had significantly lower carbon footprint which some scenarios achieving up to 100% renewable energy usage. This study not only explains the theoretical understanding of sustainable cloud computing but also provides a practical solution for greener data centre operations, which can be used for both academic research purpose and industry practice. Future work will focus on real world implementation, addressing dynamic workloads and expanding decision making criteria to enhance robustness and adaptability of ARERA mechanism

1 Introduction

In this digital era, the rapid growth of various kind of devices has significantly increased the energy consumption of data centres exacerbating their environmental impact. Data centres now account a substantial portion of global electricity usage, with major cloud service providers like Amazon Web Services (AWS), Google Cloud Platform (GCP) and Microsoft Azure rigorously expanding their operations to accommodate the growing demand for data processing and storage.

Data centres are among the largest consumers of electricity worldwide. Data centres account from 1 to 1.5% of the global electricity use (International Energy Agency,2024). According to Central Statistics Office (2023), in Ireland the electricity consumption between 2021 and 2022 by data centres increased from 31%. There was an 400% increase from 2015-2022 and according to the International Energy Agency (2024), all the data centres combined consumed approximately 460

TWh of electricity in the year 2022. Despite improvements in the energy efficiency, the rapid growth in the digital service has led to substantial increase in energy use in this sector. This has significant environmental implication concerning carbon emissions. The carbon footprint of data centre is notable with the data centres and data transmissions networks responsible for about 330 million metric ton of carbon dioxide equivalent in 2020 this represents 0.9% if energy related to greenhouse gas emissions globally. According to the International Energy Agency,2024 and Asad and Chaudhray (2016) , Figure 1, illustrates the trend in total energy use, renewable energy use, and carbon emissions for data centres from 2010 to 2022. The total energy consumption by data centres has significantly increased from 200 TWh in 2010 to 340 TWh in 2022 this has increased because of the rapid growth in digital services and data processing needs. But the use of renewable energy in data centres has increased accounted for 120 TWh in 2022 compared to just 20 TWh in 2010. Even after all these advancements, carbon emissions associated with data centres have continued to rise reaching 450 million tons of CO2 equivalent in 2022.But there is a necessity for further integration of renewable energy sources and efficiency improvements to mitigate the environmental impact of data centres.

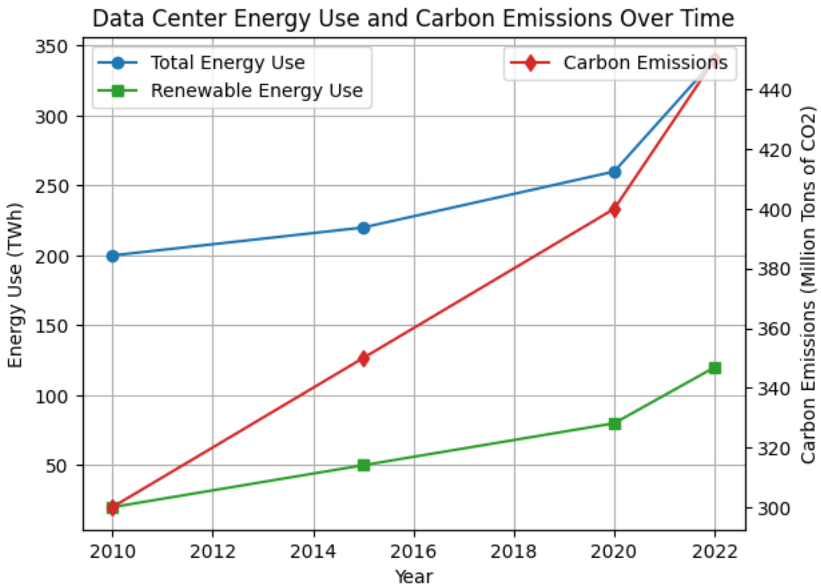

Figure 1: Data Centre Energy Use and Carbon Emissions Over Time

Dr. Patrick Breshnihasn’s research pinpoints the sever impact of the data centres on local resources indicating that the average data centres consume as much of the energy in one day as town size of Kilkenny which is approximately 60 MW. Also, for cooling the servers in the data centres these centres use over 500,000 litres of water dairy for colling purposes with consumption potentially rising to 5 million litres during heatwaves. This intensive use of energy and water significantly contributes to the carbon footprint of these facilities. In the responses to these environmental challenges, there is a growing movement towards making these data centres greener. According to Menear (2021), Ireland has set target for 80% of its electricity consumption to come from renewable energy sources by 2030. Although as of 2020, only 42% was sourced from renewable energy like wind and hydropower. Many tech giants are also committing to sustainability goals. Google is aiming to make its data centres carbon free by 2030. Additionally, partnerships like the one between Microsoft and SSE Airtricity aim to offset energy usage by installing solar panels at all the schools across Ireland. These initiative by top cloud provider highlights the industry efforts to reduce its environmental impact and carbon footprint.

In recent studies, da Silva *et al.* (2023) and Xu *et al.* (2019) their studies have researched on ways to reduce carbon footprint and enhance in cloud and IoT (Internet of Things) infrastructure. da Silva *et al*. (2023), focus on the virtual machine allocation in the mini data centres, optimizing the resources by leveraging renewable energy resource. Xu *et al*. (2019),proposed method to shift workload between the multi cloud data centres, this approach is based on the availability of the renewable energy geographically. There remains a gap in dynamically routing data from different devices to multi cloud environments based on renewable energy despite this advancement.

This research seeks to explore the innovative methods to optimize data centres operations for better energy efficiency and to reduce the carbon footprint. The primary research question driving this study is: **How can data from edge devices be preferentially routed to multi-cloud data enters powered by renewable energy to enhance sustainability?**
This research aims to develop the Adaptative Renewable Energy Resource Allocation (ARERA) API which will dynamically allocates computational tasks to data centres based on the real time factors such as green energy availability, current load, distance, and urgency. By integrating his ARERA API with the iFogSim, a fog computation simulation toolkit, the performance and environmental impact of my approach and providing empirical evidence on its effectiveness. This research contributes to the field of sustainable cloud computing by introducing novel dynamic allocation algorithm that prioritizes renewable energy usage. With the integration of ARERA API with iFogSim will allow for detailed simulation and analysis offering insights into potential for significantly reduction in the energy consumption and carbon emissions. This research will not only advance theoretically understanding but also provides solutions for more greener data centres operations.

1.1 Structure of the Report

This research report is organized into key sections: Introduction, Related Work, Methodology, Experiment and Results, Discussion and Conclusion, and Future Work. Each section builds on the previous one, providing comprehensive understanding of the research, its findings, and its implications for sustainable cloud computing.

2 Related Work

In the evolving landscape of digital technology, edge computing has emerged as crucial extension of cloud computing paradigm. The main benefit of this innovative approach is to reduce the latency and enhance data processing efficiency by bringing computational and data storage more closed to the location where it is needed. All the collated data is stored across various data centres which are managed by multiple cloud providers, exemplifying the flexibility and convenience of multi cloud approach. But now the integration of edge and cloud computing is advancing into the phase where sustainability is the primary focus, addressing the energy consumption and environmental impact of data centres. With the push towards sustainable operations has sparked interest in routing data through multi cloud environments which are powered by green energy sources. Reflecting this shift, significant efforts have been made to decrease reliance on non-renewable energy un data centres by routing the data from the edge devices to multi cloud data centres which are powered by

renewable energy. All this change aligns with global sustainability goals and increasing recognition of environmental impact associated with digital infrastructure. This literature review focusses on the current developments in edge and cloud computing, how the role of virtualization plays key role in efficient resource management and initiatives which are aimed at utilizing green energy to create more sustainable data centre operations.
This literature review will also provide a full examination of new technological advancements and research efforts are moving to change towards greener and efficient computing infrastructure. All these changes are in line with the global sustainability goals.

2.1 Renewable Energy Integration in Cloud Infrastructure

To make use of more renewable energy at data centres, Xu *et al.* (2019) presented a study which focus on the use of Markov Decision Process (MDP) to manage the microservices dynamically. This study addresses the significant issues of energy consumption and its associated carbon emissions. With the help of MDP, authors have introduced a structured and probabilistic framework which handles the variability in energy supply and demand. Authors have integrated real world solar data and workload traces which enhances the practical relevance of the findings. This research also introduces tuning parameter to balance the trade-off between workload execution and non-renewable energy usage which in turn offers flexibility to system administrators. The MDP based algorithm has shown up to 30% improvements in balancing brown energy usage and workload execution compared to baseline algorithms. However, the limitations related to exclusive focus onsite solar energy, battery performance assumptions, concerns related to scalability, and they have omitted external factors which suggest that there is still room for further improvements. A paper by Xu Buyya (2020) focuses on ways to reduce carbon emission by optimizing the use of more renewable energy sources and making improvements in the energy efficiency through self-adaptative approach. The proposed methodology involves self-adaptive system which is capable of dynamically managing both interactive and batch workloads in cloud data centres by making used of an microservices architecture and green energy sources. They have also proposed a method which emphasise the use of green energy by predicating its availability and adjusting workload management strategies accordingly. Also, they have designed a prototype system to demonstrate the effectiveness of this approach in reducing the carbon footprint of the data centres. Without compromising the performance or availability of cloud services, study has shown significant improvements in energy efficiency and renewable energy usage. But this research does not extensively explore the optimization of data routing from edge devices through fog to the cloud.

With the help of AI energy consumption can be optimized in data centres. A study by Yang *et al.* (2019) explored ways on integrating AI technologies for resource scheduling and refrigeration control offers an effective solution to reducing energy usage and operational costs. But, the complexity of implementation, focus on specific energy sources, scalability concerns and limited consideration of external factors highlights areas for future research. Similarly, in research by Cioara *et al.* (2015), they have contributed significantly to the field of more green data centre operations by presenting robust methodology for optimizing the use of locally produced green energy. All the innovations in the paper are noteworthy as they have focused on dynamic energy demand shifting and integrated flexible mechanism.

To switch the data centres from using fossil fuels to green energy sources like solar and wind.
Deng *et al*. (2014) have provided an extensive review of making use of green energy at the cloud computing data centres. Also, highlighted the advantage of using renewable energy like using renewable energy electricity costs is reduced drastically and there will be reduce of carbon emissions which are associated with large scale cloud computing data centres. There focus was on

the need of integrating green energy sources with existing grid power by making use of techniques like the automatic transfer switches and grid ties to manage power dynamically. Also, the study digs deeper into many different strategies for optimizing the energy use, like geographical load balancing and utilizing energy storage solution. The paper calls for future research to address many gaps and develop more comprehensive solutions for more sustainable cloud computing, highlighting the need for innovative power supply architecture and effective demand side management techniques.

These gaps highlight the need for additional research which can incorporate a broader range of green energy sources, adding more realistic batter performance edge devices and scalable solutions which can be applicable for larger and more diverse data centres environments. My research integrates dynamic and adaptive routing algorithm which prioritizes data centres. Also, my approach integrates a broader range of renewable energy source like wind, hydro and solar power. Unlike previous studies as they often focus on specific energy sources or rely heavily on idealized condition, my research will include real time adaptive routing algorithms that will dynamically prioritizes data centres based on the actual availability of green energy.

2.2 Adaptive Algorithm for Cloud Resource Management.

Critical things for optimizing performance and energy consumption are the efficient allocation and management of resources in cloud environments. A study by Sharif *et al.* (2023), introduced an adaptive resource allocation mechanism called Adaptive and Priority based resource allocation (A-PBRA) it is designed to optimize resource utilization in mobile edge computing (MEC). The main aim of this mechanism is to allocated resources based on nature and priority of requests coming in, ensuring only high priority tasks receive resources while optimizing overall resource use. They have compared A-PBRA mechanism with other traditional resource allocation strategies like first come, first served, shortest job first and the results are that A-PBRA is far better than these traditional resource allocations. But this paper does not tackle the sustainability aspects. They have not mentioned how to dynamically shift computational loads based on green energy availability. As the IoT devices are increasing day by day this means data centres are computing more data and using more energy. Ke *et al*. (2019), studied ways to enhance the efficiency of IoT devices through optimal data offloading and allocation of resource by making use of renewable sources. The proposed method includes a combine optimization of data offloading and renewable energy aware bandwidth allocation of IoT devices based on reinforcement learning. But they have not fully how good is the performance of the proposed method in real world scenarios.

For optimizing task scheduling and managing the recourse in fog and edge computing environment, Domanal, Gudetti and Buyya (2020) have proposed a bio inspires hybrid algorithm. This algorithm combines features from different bio inspired approached to reduce time and enhance resource utilization. The proposed approach NBIHA will process tasks as they arrive not like the traditional method where tasks are treated as first come, first served (FSFS). Here each task lay down a measure of attractiveness on the path to computational node. By the time goes by, the NBIHA algorithm finds the best path, making sure the tasks are allocated to the best available resources. Research by Haratian *et al.* (2019) presented an innovative approach that makes use of adaptive and fuzzy logic to manage resource in cloud environments. This logic is highly effective where information is uncertain. This is especially useful for managing unpredictable workloads and resource availability. Also, this allows system to adapt to changes when resource is in demand and real time availability which in turn enhances the efficiency and responsiveness. But in all this research there is lack of integration with renewable energy sources as they have only focused on brown energy and insufficient scalability. To address these gaps, my research will develop comprehensive and adaptable framework which integrated a diverse range of renewable energy resources also tackles scalability issues.

2.3 The Impact of Data Routing

Data routing can enhance the energy efficiency of cloud data centres, Mandal *et al*. (2023) have made use of renewable energy aware service migration to enhance energy efficiency. This study focuses on the main challenge of integrating renewable energy source into cloud operations to reduce reliance on non-renewable energy and decrease carbon emission. The proposed methodology focuses on migrating virtual machines (VMs) to data centres powered by renewable energy leveraging the flexibility of cloud infrastructure to optimize energy use. They use the live VM (virtual machines) migration to relocate energy demand from data centres making use of non-renewable energy to those powered by renewable sources. They tried this out in U-S wide cloud network infrastructure show that using VM migration techniques where up to 30% of non-renewable energy can be replayed by renewable energy. Similarly, Karagiannis and Schulte (2021) have proposed a routing approach called edgeRouting, which aims to optimize the transmission of IoT data by leveraging compute nodes located at the network edge. They designed a method to address the latency issue which was encountered when sending data which was generated from IoT devices to the cloud data centres which are often geographically far from the data sources. edgeRouting, main strength is that it will significantly reduce communication latency. This is done by routing data through the closest edge compute node before sending it to final cloud compute node, edgeRouting exploits both the low propagation delay of edge nodes and the high bandwidth available between edge and cloud nodes.

Hybrid Optimization Based Secure Routing Protocol (HOSRP) designed by designed by Vatchala and Preethi (2022) which is used to enhance the efficiency and security of the data routing in cloud computing environments. This protocol combines particle swarm optimization (PSO) for clustering and firefly optimization for selection of routes, making sure there is a minimal delay and maximum packet delivery ration. Also, in this paper they have employed cryptographic techniques to secure data transmission. To reduce carbon footprint in the cloud computing environment, Gattulli *et al.* (2014) proposed a method to dynamically routing data through IP-over-WDM networks to data centres powered by renewable energy sources. The proposed approach aims to mitigate the environmental impact of cloud services by optimizing the use of renewable energy.

While previous studies have significantly contributed on enchaining the energy efficiency and cloud data centres security, but my research aims to address some of the remaining gaps like focusing more on renewable energy aware data migration by integrating broader range of renewable energy sources and develop a more dynamic and real time resource allocation framework. By integrating these advance routing mechanisms with adaptive resource management and security protocol, my research focus on providing a holistic solution that will enhance the sustainability, efficiency, and security of cloud computing operations.

Table 1: Summarization of related works.

Article	Methodology	Research Domain	Achievements	Limitations	Differentiation
Xu *et al*. (2019)	Markov Decision Process (MDP) for dynamic microservices management	Cloud infrastructure and renewable energy	Up to 30% improvement in balancing brown energy usage and workload execution	Focus on-site solar energy, battery performance assumptions, scalability concerns	Integration of real-world solar data and workload traces

Article	Methodology	Research Domain	Achievements	Limitations	Differentiation
Xu and Buyya *et al*. (2020)	Self-adaptive system managing interactive and batch workloads using microservices architecture and green energy sources	Cloud data centres and renewable energy	Significant improvements in energy efficiency and renewable energy usage	Limited exploration of data routing optimization from edge to cloud	Self-adaptive approach for workload management with green energy prediction
Yang *et al*. (2018)	AI technologies for resource scheduling and refrigeration control	Data centres energy optimization	Reduction in energy usage and operational costs	Complexity of implementation, focus on specific energy sources, scalability concerns	Integration of AI for resource scheduling and refrigeration control
Cioara *et al*. (2015)	Robust methodology for optimizing locally produced green energy use	Green data centre operations	Dynamic energy demand shifting and integrated flexible mechanisms	Limited scalability considerations	Focus on dynamic energy demand shifting and local green energy use
Deng *et al*. (2015)	Review of integrating green energy sources with grid power	Cloud computing data centres and renewable energy	Reduced electricity costs and carbon emissions	Need for innovative power supply architecture and demand side management techniques	Comprehensive review of green energy integration strategies
Sharif *et al*. (2023)	Adaptive and Priority-based Resource Allocation (A-PBRA)	Mobile edge computing (MEC)	Optimization of resource utilization, better than traditional strategies	Lack of sustainability aspects and dynamic computational load shifting	Prioritization of high-priority tasks in resource allocation
Ke *et al*. (2019)	Combined optimization of data offloading and renewable energy-aware bandwidth allocation using reinforcement learning	IoT devices and renewable energy	Enhanced efficiency of IoT devices	Performance in real-world scenarios not fully explored	Reinforcement learning for data offloading and bandwidth allocation
Domanal *et al*. (2020)	Bio-inspired hybrid algorithm (NBIHA)	Fog and edge computing	Reduced time and enhanced resource utilization	Lack of integration with renewable energy sources, insufficient scalability	Bio-inspired approach for task allocation
Haratian *et al*. (2019)	Adaptive and fuzzy logic for resource management	Cloud environments	Enhanced efficiency and responsiveness in managing unpredictable workloads	Focus on brown energy, insufficient scalability	Use of fuzzy logic for managing uncertain information
Mandal *et al*. (2013)	Renewable energy-aware service migration using VM migration	Cloud data centres and renewable energy	Up to 30% replacement of non-renewable energy with renewable energy	Limited exploration of broader range of renewable energy sources	Live VM migration for energy optimization
Karagiannis and Schulte (2021)	edge Routing for optimizing IoT data transmission	IoT and edge computing	Significant reduction in communication latency	Limited focus on renewable energy sources	Routing through closest edge compute node before cloud node
Vatchala and Preethi (2022)	Hybrid Optimization Based Secure Routing Protocol (HOSRP)	Cloud computing and data security	Minimal delay, maximum packet delivery ratio, secured data transmission	Limited focus on renewable energy integration	Combination of PSO and firefly optimization for routing
Gattulli *et al*. (2014)	Dynamic routing through IP-over-WDM networks	Cloud computing and renewable energy	Mitigated environmental impact of cloud services	Need for more dynamic and real-time resource allocation framework	Optimization of renewable energy use in routing

3 Research Methodology

This section provides detailed explanation of methodology employed in the development and evaluation of Adaptive Renewable Energy Resource Allocation (ARERA) and integration with iFogSim to simulated edge and cloud computing environments. The proposed methodology is meticulously structured to ensure comprehensive understanding of each phase of the research process. The methodology is divided into several sub-topic: GreenStream Routing Architecture, Routing Algorithm system components, ARERA API Development, ARERA Integration with iFogSim (Edge side), Data Retrieval and comparison with multi cloud techniques.

3.1 Greenstream Routing Architecture

Greenstream Routing Architecture is comprehensive framework which is designed to optimize the allocation of several types of data tasks to the cloud data centres based on availability of renewable energy, current computational load, geographical distance, and urgency of tasks. This architecture integrates edge devices, ARERA API and cloud service providers to create an efficient data routing system. The main goal of this research is to enhance the sustainability, minimize carbon footprint and energy consumption while maintain high performance and low latency in data processing efficiency of data processing.

The proposed architecture integrates multiple edge devices, the Adaptive Renewable Energy Resource Allocation (ARERA) routing decision Engine, and various cloud service provider. The edge devices include a wide range of IoT devices like mobile phones, laptops and camera that generate large amount of data at the network's edge. The data generated from the edge devices is then transmitted to ARERA routing decision engine which will evaluate and decide the optimal data centres for processing based on time indicators. The data which is selected will processes the data prioritizing those powered by renewable energy sources to ensure sustainability.

A) Greenstream Routing Components

Fig 1 shows the greenstream routing components. The role of each component is described below.

- Edge Nodes: This is where the generation of data starts, which includes edge devices like smartphone, laptops, camera and other IoT devices. All these devices collect and preprocess data locally to reduce volume and complexity of data that needs to be transmitted. These edge nodes require secure and backup interface which can read, modify, and delete the data that is stored in the devices at any point of time. Privacy plays vital role as each node should be protect so that no edge devices can access other edge devices data. All these should be achieved without compromising the performance.
- ARERA Routing Decision Engine: All the data which are pre-processed from the edge devices is transmitted to ARERA Routing Decision Engine. This engine is the main component of the architecture. This engine is responsible for making routing decision based on few parameters. To decide best data centres to send the data, ARERA used the following parameters:
    - Renewable Energy indicator (RE): This parameter provides information about the availability of renewable energy sources at different data centres. The ARERA routing decision engine will prioritize data centres with high availability of renewable energy to reduce the carbon footprint.

    - Current Load (CL): The ARERA engine assesses the current computation load on each data centre. The engine prefers data centres with lower loads to avoid overloading of the data and ensure efficient resources utilization.

- Distance(D): In this, engine will consider the distance between the edge devices and data centres. Here the closer data centres are favoured to minimize latency and energy consumption during data transmission.

- Task Urgency(U): Here the urgency of the tasks being processed is evaluated. More urgent tasks are given higher priority to ensure timely processing.

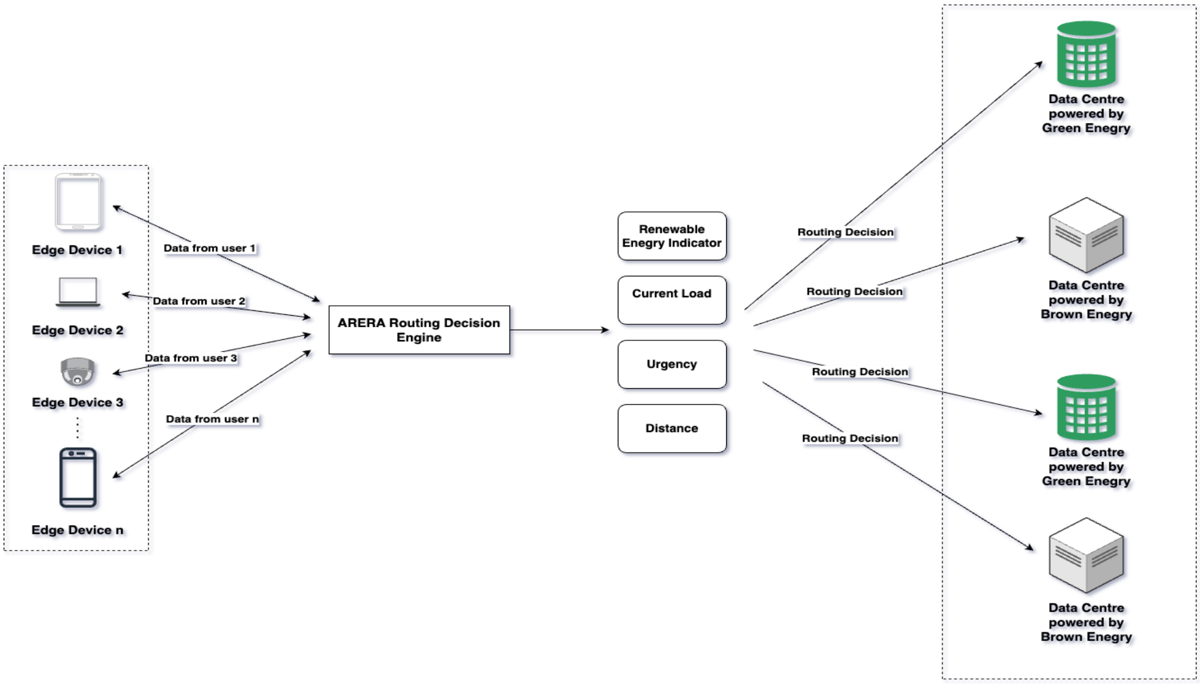

Figure 2: Greenstream Routing Engine.

3.2 ARERA Routing engine

The ARERA Routing Decision employs weighted multi-criteria decision making (MCDM) algorithm to calculate total score for each data centre based on above factors. The data centre with highest score will be selected for task allocation. Linkov *et al.* (2004)have derived multi criteria decision making.

- ARERA Equation Derivation: The equation used in ARERA API for calculating the total score for each data centres are derived from weighted multi-criteria (MCDM) approach. In this criterion renewable energy availability, current load, distance, and urgency of the task. Each of these criteria are assigned weight based on its relative importance, ensuring balanced and comprehensive evaluation.
  - Renewable Energy (RE), Current Load (CL), Distance(D) and Urgency(U) are the factors that ARERA equation is dependent on.
  - Now, normalizing the above factors to bring them onto common scale, typically between 0 and 1. This will help in combining them into a single score. With the help of min-max normalization is done. But for this research, for simplicity I have assumed that each factor is already normalized between 0 and 1.
  - Assigning weights to each factor, assign weights to each factor based on their importance. Let,
    - $w_{RE} = Weight\ for\ Renwable\ Enegry.$
    - $w_{CL} = Weight\ for\ Current\ Load.$
    - $w_D = Wright\ for\ Distance.$
    - $w_U = Wight\ for\ Urgency.$

Therefor the sum of the weight should be 1, i.e. $w_{RE} + w_{CL} + w_D + w_U = 1$.

- Calculate the Score for Each Data Centre, combine the weighted factors to compute score for each data centre. The data centre with the highest score is selected. The score(S) for data centre is calculated as:

$$S = (w_{RE} * RE) + \left(w_{CL} * (1 - CL)\right) + \left(w_D * (1 - D)\right) + (w_U * U)$$

Here, subtract CL and D from 1 because lower values of CL and D are preferred (lower load and shorted distance).

- Processing at Cloud Service Providers: Now at the cloud service provider all the data generated from the ifog sim is processed according to the requirements. The selected data centre most preferably powered by renewable energy, which handles computational tasks. By prioritizing data centres with renewable energy, the architecture ensures that the processing is both efficient and environmentally friendly.

ARERA Side

ARERA API, this brain of Greenstream routing architecture. It is designed in such a way that it provides seamless and efficient interface for evaluating and routing data tasks to the best data centres. The ARERA is designed in such a way that it guarantees high speed decision making, reliability and scalability.

- High speed Decision Making

The API is designed in such a way that it provides rapid processing of incoming data from the edge devices. With the use of advance algorithm and data structure, it makes sures that routing decision are made extremely fast. This in turn minimizes the latency and enhances the system performance. The API makes use of MCDM approach to evaluate data centres based upon availability of renewable energy, current load, distance, and task urgency. It evaluates these factors which are randomly generated from ifog sim, providing swift and accurate routing decision.

- Scalability and Flexibility

API has been designed in such a way that it can scale with growing number of edge devices and data centres. Its modular architecture allows easy integration of additional parameters or changes in weights, making it adaptable to growing requirements and technological advancements. ARERA API can handle large volumes of data and numerous concurrent requests, ensuring robust performance even under high load conditions.

- Reliability and Fault Tolerance

To ensure reliability, the ARERA API incorporates fault tolerant mechanism. It uses redundant systems and data validation techniques to maintain the accuracy and consistency in decision making. Any failure or anomaly in one part of the system the API will continue to function seamlessly, thereby providing uninterrupted service.

- Renewable Energy Prioritization

The primary objective of this research is to minimize the carbon footprint by prioritizing data centres which is powered by renewable energy. The API continuously monitors the renewable energy indicators of all connected data centres and adjusts routing decisions accordingly. By doing this, it not only enhances the energy efficiency but also promotes sustainable computing practices.

B) Greenstream Edge Side

In this section, my focus will on the edge side of the Greenstream Routing Architecture, how the data is generated, pre-processed, and transmitted to ARERA Routing Decision Engine. In this research, it has been considered to setup any 4 edge devices and their interaction with the ARERA engine and cloud data centres.

- Data Generation: Each edge device generate data with random values for key parameters (RE, CL, D and U).
- Pre-Processing: Each edge device will perform local pre-processing to reduce the volume and complexity of the data before the transmission. This includes Data filtering, here the redundant or irrelevant data is filtered, In Data Compression, data size is reduced for efficient transmission.
- Transmission: All the generated data is transmitted from the edge devices to the ARERA Routing Decision Engine. Each data packet includes key parameters like urgency, timestamp, current load, and renewable energy availability.

C) Greenstream Cloud Side

In this section, Cloud side of Greenstream Routing Architecture, explaining how the received data is processed at the selected data centres. This involves knowing the role of the cloud data centres, what are the criterions for their selection by ARERA Routing Decision Engine and what is the impact of this section of data centres on energy consumption and carbon footprint. In this research simulation only four generic data centres configured within iFogSim environment. All four data ceres are designed to simulate the processing of data routed from the edge devices.

Each data centres have different capacities, current load, and energy sources (renewable or non-renewable). The four data centres are labelled as 'dc1'. 'dc2'. 'dc3' and 'dc4'.

4 Design Specification

This section discusses about the design specification of the GreenStream. This Routing Architecture underpins the implementation and associated requirements for optimizing data routing in the cloud computing environment. This section will contain details the system architectural framework, this has been specially crafted to reduce energy consumption and minimize the carbon footprint of data centres by making use of renewable energy resources. The components of routing architecture are edge devices, ARERA Routing Decision Engine and cloud data centres.

4.1 Techniques and Architecture

The Greenstream design starts with generation and pre-processing of data from the edge devices locally, before sending it to the ARERA engine. The ARERA acts as the brain of this architecture which evaluate multiple factors like availability of renewable energy, current load, distance, and task urgency to make the routing decision. The data centre which are selected for processing each task are prioritized based on renewable energy usage to ensure efficient and environment friendly operation.

The three layer architecture of fog computing consist of Edge devices like smartphones, laptops, cameras and IoT devices they all serve as the primary data generators in this architecture. All these devices are responsible for collecting and preprocessing data, and it is done locally. The most crucial step is pre-processing where it reduces the volume and complexity of the data making it more efficient for transmissions. At this stage output will be data packets that are pre-processed which contain key parameters like as urgency, timestamp, current load, and renewable energy availability. Fog layer, it acts as intermediary, where the initial ARERA based routing decision is applied and it minimizes the latency and optimizes data handling closer to source. Finally, Cloud data centres as they are the backbone of the cloud infrastructure, receiving and processing data based on the ARERA engine routing decision. In these multiple data centre is considered with some powered by renewable energy and other by non- renewable sources. The ARERA engine will prioritizes data centres with high renewable energy usage, ensuring that the processing is both efficient and environmentally friendly, making use of data centres which are powered by renewable energy sources to minimize carbon footprint.

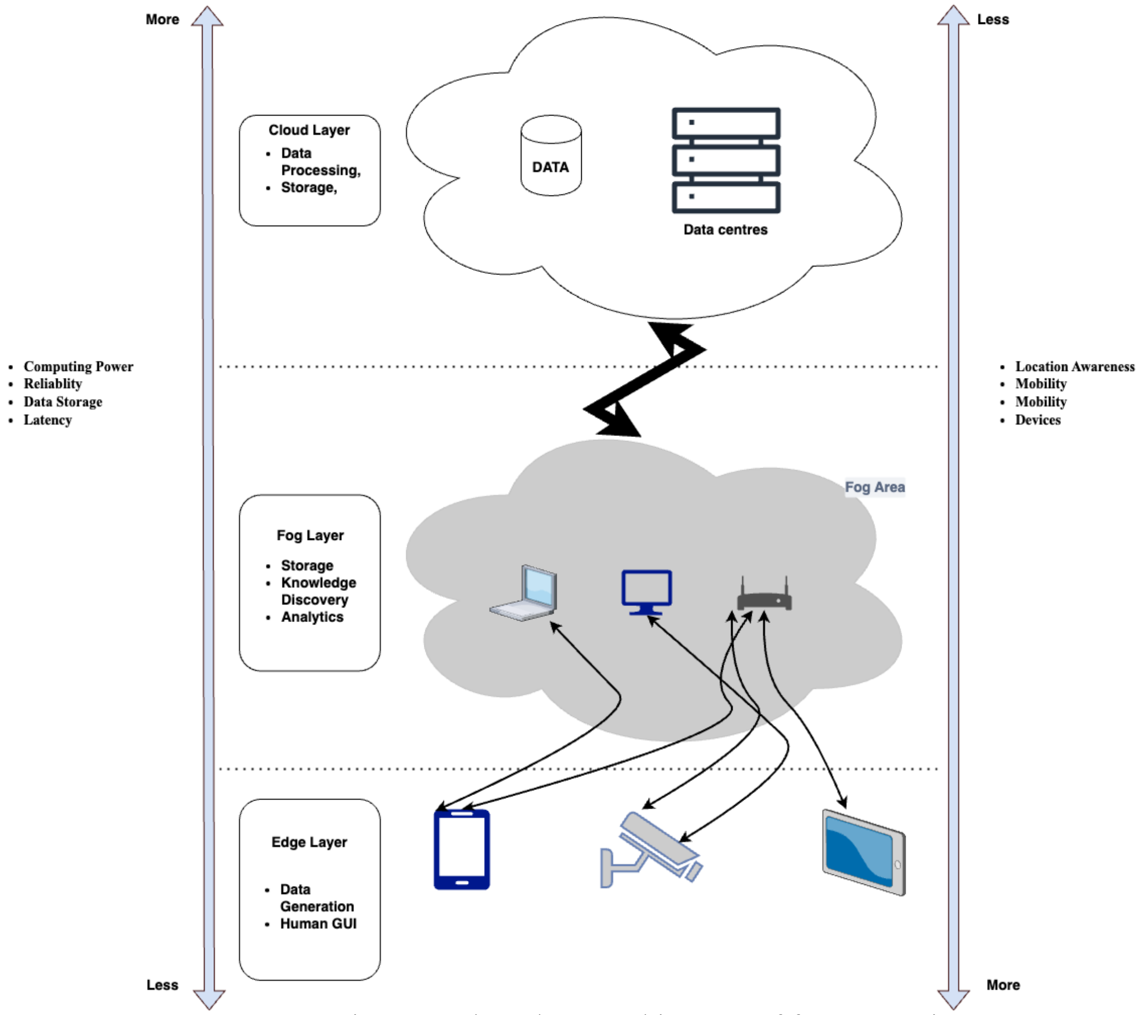

Figure 3: Three-layer architecture of fog computing

4.2 Framework and Tools

iFogSim

iFogSim has been used to stimulate the behaviour of edge devices and cloud data centres and model the int between them. In the iFogSim, four edge devices and four data centres are simulated to evaluate the performance and efficiency of the ARERA algorithm. The iFogSim generates random values for RE, CL, D and U providing diverse dataset for testing the robustness of the ARERA engine.

ARERA API

ARERA API receives data from the edge devices which are created by the simulation tool iFogSim, and the ARERA will calculate scores for data centres and return optimal data centre for task allocation. Also, integrated ARERA with iFogSim, enabling dynamic simulation and evaluation. The implementation of ARERA API is done using JavaScript and node.js. The API leverages HTTP methos to receive data, process it and return results. The core logic is calculating scores based on the given criteria and returning optimal data centre.

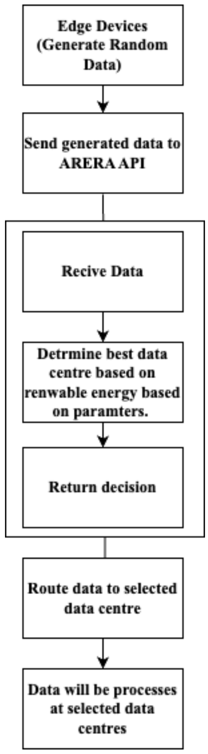

Figure 4: Flow diagram of Greenstream

4.3 Data Generation

In the iFogSim simulation environment, all the values for each parameter which are renewable energy (RE), urgency (U), current load (CL) and distance (D) are generated dynamically. This makes sure that the randomly generated data is realistic and varied for testing ARERA API. For the stimulation purpose varying availability of renewable energy across different data centers, the value is generated randomly. These randomly generated values will help in testing robustness of routing decision algorithm under different energy availability scenarios. For urgency (U), the values are generated randomly, which will represent varying levels of priority for different data packets. By doing so it will help in evaluating how routing decision energies prioritize tasks based on the urgency. Now, the current load and distance values are also generated randomly. The cloud load value will represent computational fluctuation on all four data centers. With this ARERA engine can distribute load to prevent overloading any single data center. Distance, this will represent changing physical distance between edge devices and data centers. Randomness of each value will help in analyzing the impact of distance on latency and energy consumption.

5 Implementation

Let us now discuss implementation process of Greenstream Routing Architecture and Adaptive Renewable Energy Resource Allocation (ARERA) API. In the implementation stage, ARERA API integration with iFogSim has been done to simulate integration between edge devices and cloud data centres. Also, evaluated the effectiveness of the proposed algorithm in optimized data routing decisions. For scalability and reliability purpose, ARERA API has been hosted on AWS elastic beanstalk. The final stage of implementation involved creating robust and scalable system that cloud can simulate real world-based scenarios of data routing for edge devices to cloud data centres. This will involve configuring iFogSim simulation, developing ARERA API, integrating both the components and preparing for deployment on AWS Elastic Beanstalk. This primary aim is to assess the ARERA algorithm efficiency in selecting the optimal datacentres based on renewable energy availability, current load, distance, and task urgency.

5.1 Outputs Produced

In the final stage if the implementation, several key outputs are produced and each contributing to detailed understanding oof the system performance and ARERA algorithms effectiveness. Transformed data, simulation environment generated data representing various parameter for each data centres like renewable energy (RE), current load (CL), distance (D) and urgency (U). All this data were dynamically produced during simulation to reflect direct scenarios and conditions. In the simulation results, a detailed results for the simulation including energy consumption metrics, execution time and specific data centres selected for the task allocation can been seen. These results play crucial role in analysing the efficiency and sustainability of routing decision mode by the ARERA algorithm. In addition, results provided a breakdown of score for each data centres, this shows how the ARERA evaluates different parameters to determine the best routing decisions. The ARERA API generated JSON response that include details about the selected data centres. Each response contained data centre ID, carbon footprint, detailed score components and energy usage (total energy, renewable energy, non-renewable energy). The obtained response played crucial role in validating the decision made by the ARERA algorithm and understanding impact on energy consumption and caron footprint.

5.2 Tools and Language Used

Various tools and programming languages were used to implement the functionality and performance required. To create simulation environment, I have used iFogSim which will mimic the behaviour of edge devices and cloud data centres. also, used for modelling of interactions between these components, providing a platform to test and evaluate the ARERA algorithm. The iFog Sim framework is implemented in java, which enables detailed simulation of fog computing environments. The ARERA API which serves as the core component for implementing the routing decision engine. This API will process data from edge devices, evaluated data centres based on ARERA algorithm and will return the optimal routing decisions. The creation of API was developed using JavaScript and Node.js. This provides scalable and efficient server-side solution. By selecting JavaScript allowed a rapid development and integration with the simulation environment. For ARERA API deployment I have used AWS Elastic Beanstalk as it provides scalable and managed environment. Elastic Beanstalk simplifies the deployment process and offers automatic scaling, load balancing and monitoring which in turn ensure high availability and reliability of API.

Algorithm 1: ARERA Routing Decision Algorithm

```
// Step 1: Initialize Variables
Set maxScore to -1
Set selectedDataCenter to null
// Step 2: Iterate through Data Centers
for each dataCenter in dataCenters do
    // Calculate renewable energy factor based on timestamp
    renewableFactor = calculateRenewableFactor(dataCenter.RE, T)
    // Calculate score components
    renewableEnergyScore = weights.RE * (renewableFactor / 100)
    currentLoadScore = weights.CL * (dataCenter.CL / dataCenter.C)
    distanceScore = weights.D * (dataCenter.D / maxDistance)
    urgencyScore = weights.U * U
    // Calculate total score for the data center
```

```
    totalScore = renewableEnergyScore - currentLoadScore - distanceScore
+ urgencyScore
    // Update selected data center if current score is higher
    if totalScore > maxScore then
        maxScore = totalScore
        selectedDataCenter = dataCenter.id
    end if
end for
// Step 3: Return the selected data center
return selectedDataCenter
```

5.3 Process of Integration and Deployment

Both integration and deployment process involved several critical steps to make sure the successful operation of the system:

- Setup of Simulation Environment: The iFogSim environment is configured with four edge devices and four cloud data centres. With this setup generation of relevant data points was possible like as renewable energy, availability, current load, distance, and urgency.
- Development of API: The primary goal to develop ARERA API was to implement routing decision engine. It is designed to receive data from the edge device, process the data using the ARERA algorithm and return response with the routing decisions.
- Integration: This involves establishing communication between the iFogSim simulation environment and the ARERA API. Also, HTTP client libraries facilitated this integration by allowing edge devices to send data to the API. Now, the API processes the data, determine the optimal data centres based on the calculated score and return routing decision to the simulation environment.
- Deployment on AWS Elastic Beanstalk: ARERA API was packaged and deployed on AWS Elastic Beanstalk. This involved configuration of the elastic beanstalk environment, setting up necessary variable and ensuring proper connectivity with iFogSim simulation.
- Testing and Validation: Once deployed, the system thorough tested to validate the integration and ensure that the API is making correct routing decision. also, performance metrics was collected to analyse the system efficiency and effectiveness of ARERA algorithm.

Component	Description
Edge Devices	4
Cloud Data Centers	4
Fog Devices	2 (Cloud and Proxy Server)
Simulation Runs	8
Data Generation	Randomized values for RE, CL, C, and D
Urgency Levels	Randomized between 1 and 5
Renewable Energy (RE)	Values between 0 and 100
Current Load (CL)	Values between 0 and 10,000 kWh
Capacity (C)	Values between 10,000 and 20,000 kWh
Distance (D)	Values between 0 and 70
Programming Language	Java (iFogSim), JavaScript (ARERA API)
Frameworks	Apache HTTP Client, JSON

Table 1: iFogSim Simulation Specification

6 Evaluation

The main purpose of this section is to provide comprehensive analysis of results obtained and main findings of this research, as well as implication of these findings from both academic and practitioner perspectives. Here I will present all the key findings, result that support my research question and objectives, offering in-depth and rigorous analysis. Tools are employed to critically evaluate and assess experimental research outs and theory level of significance. With the help of graphs, charts and plots are used to displays the results, making that data more accessible and comprehensible. In this research, I have utilized ARERA algorithm to optimize allocation of computational tasks to cloud data centres which is based on several key factors like renewable energy availability, current cloud, distance, and task urgency. The iFogSim framework was employed to simulate the edge devices and cloud data centres behaviour. I have run eight simulation runs, each generating randomized values for parameters to test robustness and effectiveness of ARERA algorithm.

In this research, Key findings indicate that the ARERA algorithm effective reduces the carbon footprint by prioritizing data centres with higher renewable energy availability which was our primary goal of this research. The proposed algorithm ensures efficient energy utilization by balancing load across data centres, preventing overloading of data, and optimizing resource use. Moreover, the proposed algorithm minimizes latency by considering the distance between edge devices and data centres which is crucial for real time application.

Simulation	Urgency Score	Current Load Score	Renewable Energy Score	Distance Score	Total Energy (kWh)	Renewable Energy (kWh)	Non-Renewable Energy (kWh)	Carbon Footprint (kg CO2)
1	0.1	0.023	0.168	0.128	772	324.24	447.76	223.88
2	0.5	0.105	0.392	0.005	6730	6595.4	134.6	67.3
3	0.3	0.069	0.308	0.062	2407	1853.39	553.61	276.8
4	0.4	0.121	0.4	0.031	7117	7117	0	0
5	0.2	0.068	0.252	0.082	2633	1658.79	974.21	487.1
6	0.3	0.075	0.148	0.097	4238	1568.06	2669.94	1335
7	0.2	0.085	0.156	0.062	5362	2091.18	3270.82	1635.41
8	0.2	0.013	0.224	0.1	822	460.32	361.68	180.84

Table 2 : Each simulation result

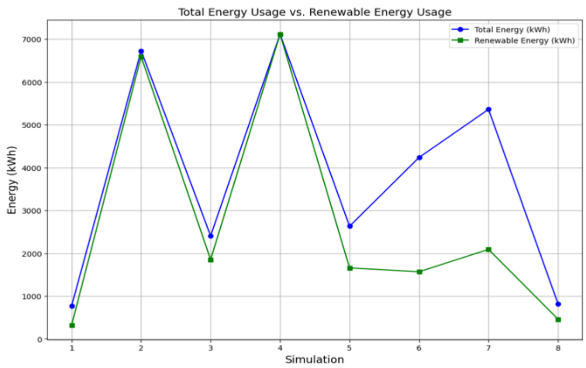

Figure 5: Total Energy Usage vs. Renewable Energy Usage.

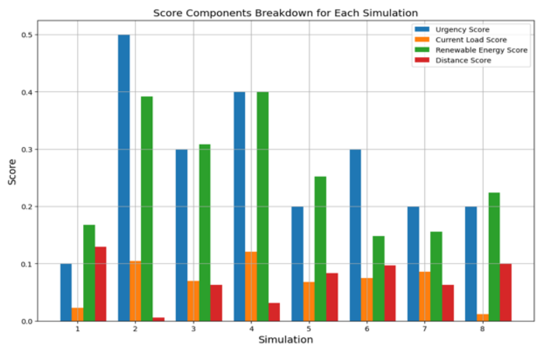

Figure 6: Score Components Breakdown for Each Simulation

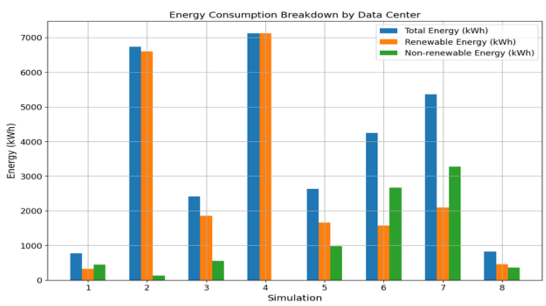

Figure 7: Energy Consumption Breakdown by Data Centre.

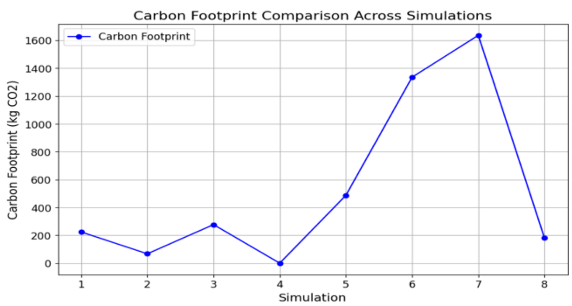

Figure 8: Carbon Footprint Comparison Across Simulation

6.1 Total Energy Usage vs Renewable Energy Usage

This metric will help us understand the proportion of renewable energy that has been utilized in comparison to the total energy consumption across different simulation. In the first graph, this graph illustrates total energy usage compared to renewable energy usage across eight different simulations. This highlights proportion of renewable energy utilized in each simulation. Simulation number 2 and 4 in figure 5, renewable energy usage matches closely to the total energy usage which in turn indicates high reliance on renewable sources. But significant discrepancies in simulation 1,2 and 7 suggest considerable portion of energy is derived from non-renewable sources. This metric helps in identifying simulation where renewable energy is maximized which in turn informing potential improvements in routing decision to enhance sustainability.

6.2 Score Components Breakdown for Each Simulation

This metric provides insights on how several factors like urgency, current load, renewable energy availability and distance will contribute to routing decision made by ARERA routing engine algorithm. In the second graph it provides detailed breakdown of each scoring components that influence the ARERA algorithm decision making process. These components include urgency, current load, renewable energy, and instance score. From figure 6, the renewable energy score and urgency score are dominant factors in most simulations. Distance score contributes minimally to simulations where data centre that is selected is closer to the edge devices. By understating the contribution of each component will allow for fine tuning the weights assigned to these factors which will optimize the decision-making process.

6.3 Energy Consumption Breakdown by Data Centre

This metric shows the energy consumption of each data centres divided into total energy, renewable energy, and non-renewable energy. This will help in understanding how effectively renewable energy are utilized by different date centres. In the third graph, the energy consumption of each data centre across different simulation divides into total energy, renewable energy, and non-renewable energy. Data centres with higher renewable energy consumption is preferred as they align with the sustainability goals. The distribution of energy consumption will help in identifying data centres that are more efficient in utilizing renewable energy. This analysis will help in understanding the energy efficiency of each data centre, informing decisions on where to route data task to minimize impact on the environment. Also helps in planning infrastructure investment, like enhancing renewable energy capacity at specific data centres.

6.4 Carbon Footprint Comparison

This metric measures the carbon emission which are produced by each simulation, providing insights into environmental impact of the routing decisions. In the carbon footprint graph, its tracts the carbon emissions produced by each simulation, providing clear picture of environmental impact. With the lower carbon footprint indicate more environmentally friendly routing decision, demonstrating the effectiveness of the ARERA algorithm in emissions. All the variations in carbon footprint across simulation highlight the impact of different routing strategies on sustainability. This metric is crucial for validating the ARERA algorithm performance in achieving the primary goal of this research. Also helps in setting benchmarks for future improvements, aiming to further reduce carbon emissions in cloud date centre operations.

6.5 Graph Comparison

The relation between figure 6 and figure 5 shows how ARERA algorithm makes decisions. Higher renewable energy in figure 6 leads to higher renewable energy usage in figure 5, by this we can say that the algorithm prefers data centres with more green energy. Also, the current load score helps to spread tasks to less busy data centres eventually avoiding overload. The distance score will ensure that data is sent to the closer data centres to save energy. In ARERA algorithm, not all factors contribute to the routing decision. The renewable energy score and current load score are most impactful, this is because algorithm prioritizes data centres that use more green energy, and which are less busy. Also, distance and urgency play crucial role but are secondary compared to load and energy use. The score in figure 6 shows how each factor contributes to overall decision. In figure 7, shows how much total renewable and non-renewable energy at each data centre uses. So, when data centre has higher renewable energy score and low current load score, and this will be selected, this can be shown by higher renewable energy use in figure 5 as mentioned in figure 8 by this it is evident that data centres with more renewable energy and less load is prioritized by the data centres and ARERA algorithm effectively reduces overall carbon emissions.

6.6 Discussion

The Adaptive Renewable Energy Resource Allocation (ARERA) was evaluated by running eight simulation which demonstrated its ability to optimize allocation of task to cloud data centres based on multiple factors like renewable energy availability, current load, current load, distance, and task urgency. The findings from simulation indicate that ARERA can significantly influence energy consumption patterns and carbon footprint of data centres, providing sustainable solution for cloud computing operations. From the result produced by eight different simulations, the result showed a wide variating in total energy usage and renewable energy consumption across different simulations. In simulation 4, it showed an exemplary case where the total energy usage was entirely derived from renewable sources, leading to zero carbon footprint. By this it is evident that the potential of ARERA in prioritizing to send data to the data centre, which is using renewable energy, thereby minimizing environmental impact. In the previous studies, like those by Deng *et al*. (2014), have similarly emphasized the importance of integrating renewable energy in cloud data centres to achieve sustainability goals.

The breakdown of score components for each simulation showed the balanced consideration of urgency, current load, renewable energy, and distance. It can be seen in the simulation that ARERA algorithm effectively prioritizes tasks based on urgency while also still factoring in the other criteria to ensure an optimal and sustainable decision. This multi-criterion decision-making approach algins with the methodologies which was proposed by Linkov *et al*. (2004), in this paper the authors have emphasised the importance of comprehensive evaluation framework in resource allocation. The variations in carbon footprint across eight simulations underscores the impact of ARERA in reducing CO2 emission. The simulation where the data centres with highest renewable energy availability were selected resulted in significantly lower carbon footprint. But this has certain limitation as this research uses randomly generated data for simulation rather than employing realistic data from the actual data centre and edge devices. This can affect the accuracy of the results, as randomly generated data may not accurately reflect the complexity of real workloads, energy availability, and network conditions.

For implementing Greenstream routing algorithm in real world scenarios involves several practical consideration and challenges. Collection of real time data, accurate and real time data on energy availability, data centre loads, and network distance are crucial for the effective functioning of ARERA. To achieve this sensor can be used which will continuously monitor and transmit data ensuring ARERA algorithm can make informed decision based on the latest information. Also adhering to regional regulation and compliance standards regarding data transmission, energy usage and environmental impact is essential. Working with regulatory bodies to ensure the deployment of ARERA aligns with legal and environmental guideline is crucial. Like, data centres in the European unio must comply with GDPR and other environmental regulations.

7 Conclusion and Future Work

This research aimed to explore and implement sustainable and efficient routing mechanism for cloud computing data enters using Adaptive Energy Resource Allocation (ARERA) algorithm. My primary research question was: **How can data from edge devices be preferentially routed to multi cloud data centres powered by renewable energy to enhance sustainability?** Here main objectives included minimizing carbon footprints, optimizing energy usage, and ensuring efficient resource utilization in cloud environment. The ARERA algorithm was integrated with iFogSim to simulate real world scenarios and evaluate its performance. The results obtained from the simulation validated the effectiveness of ARERA based routing mechanism. The approach demonstrated significantly improves the energy efficiency and carbon footprint reduction compared to traditional methods. By prioritizing data centre powered by renewable energy and considering factors like urgency, current load, and distance, ARERA was able to make informed routing decision that minimize energy consummation and environmental impact. There are, however, some limitations to the research. All the experiment is done on simulation environment while beneficial for controlled testing, does not fully capture the complexities of real-world data centres and workloads. By using static workloads in simulation may not reflect dynamic nature of real-world computational tasks accurately. Additionally, this study focus on limited number of data centres suggests that future research should consider more extensive and diverse set of data centres to provide more comprehensive evaluation.

Future work includes real world implementation of ARERA in actual data centres to assess its practical performance and challenges. By integrating dynamic and fluctuating workloads in future experiment would provide more realistic evaluation of ARERA adaptability and performance. Also, in future decision-making criteria can be expanded to include factors like cost, network, latency, and data security cloud enhance the robustness of ARERA mechanism. Integrating machine learning techniques could improve ARERA's predictive capabilities and decision-making process. Additionally, data generated by the edge devices can be encrypted and then it can be sent to the ARERA routing engine to find the best data centre to send the data to.

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