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CONFERENCE PAPER

SUSTAINABLE EDGE COMPUTING - ENABLING GREEN AND INTELLIGENT FUTURE TECHNOLOGIES

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Abstract

The rapid proliferation of Internet of Things (IoT) devices, artificial intelligence (AI), and data intensive applications has significantly incre ased the energy demands of conventional cloud computing systems, resulting in higher carbon emissions and operational inefficiencies. Sustainable computing aims to minimize energy consumption and environmental impact; however, traditional cloud infrastructures rely heavily on energy-intensive data centres powered by non-renewable sources.To address these challenges, this paper proposes a sustainable edge computing framework that enables localized data processing, thereby reducing latency, bandwidth usage, and energy consumption. The framework integrates renewable energy-powered edge nodes and AI-driven task scheduling to optimize system performance and resource utilization. Mathematical models for energy consumption, latency, and transmission are developed and validated through numeric al analysis, demonstrating energy savings of up to 60 - 99% compared to cloud-based systems. Secure data storage and retrieval mechanisms are also incorporated to ensure data reliability and privacyThe proposed approach is evaluated across real-world applications, including smart cities, healthcare,agriculture, and industrial systems.The results confirm that sustainable edge computing significantly enhances energy efficienc y and reduces carbon emissions, making it a key enabler for environme ntally responsible and intelligent future technologies.

Introduction:-

The increasing reliance on real-time applications and connected devices has exposed limitations in traditional cloud computing, particularly in terms of latency, energy consumption, and bandwidth usage. Centralized data centres require significant power, contributing to environmental concerns.Edge computing addresses these challenges by enabling localized data processing near the source of data generation. This reduces transmission distance, lowers energy consumption, and improves response time.

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From a sustainability perspective, integrating renewable energy sources and intelligent task scheduling further enhances system efficiency and reduces carbon footprint.

Literature Survey:-

Existing research highlights the advantages of edge computing in reducing latency and improving system efficiency. Studies have explored energy-aware scheduling, task offloading, and integration with IoT systems. Some works have also investigated renewable energy-powered computing infrastructures.

However, limitations still exist:

- Lack of unified frameworks combining energy optimization, sustainability and artificial intelligence.
- Limited numerical validation of energy savings
- Insufficient focus on secure data handling
- This paper addresses these gaps by proposing a comprehensive, energy-efficient, and secure edge computing framework.

Objectives and Contributions

Objectives: Design a sustainable edge framework to improve energy efficiency and performance by reducing cloud dependence, minimizing latency, integrating renewable energy, optimizing AI-based scheduling, and ensuring data security.

Contributions: Proposes an energy-efficient edge-cloud architecture with modelling, performance gains (60 - 99% savings), improved latency-energy efficiency, secure data handling, and real-world applicability.

Proposed Framework

Architecture

The proposed sustainable edge computing framework is designed as a multi-layer architecture consisting of three primary layers: **IoT layer, edge layer, and cloud layer**, integrated with renewable energy support and intelligent control mechanisms.

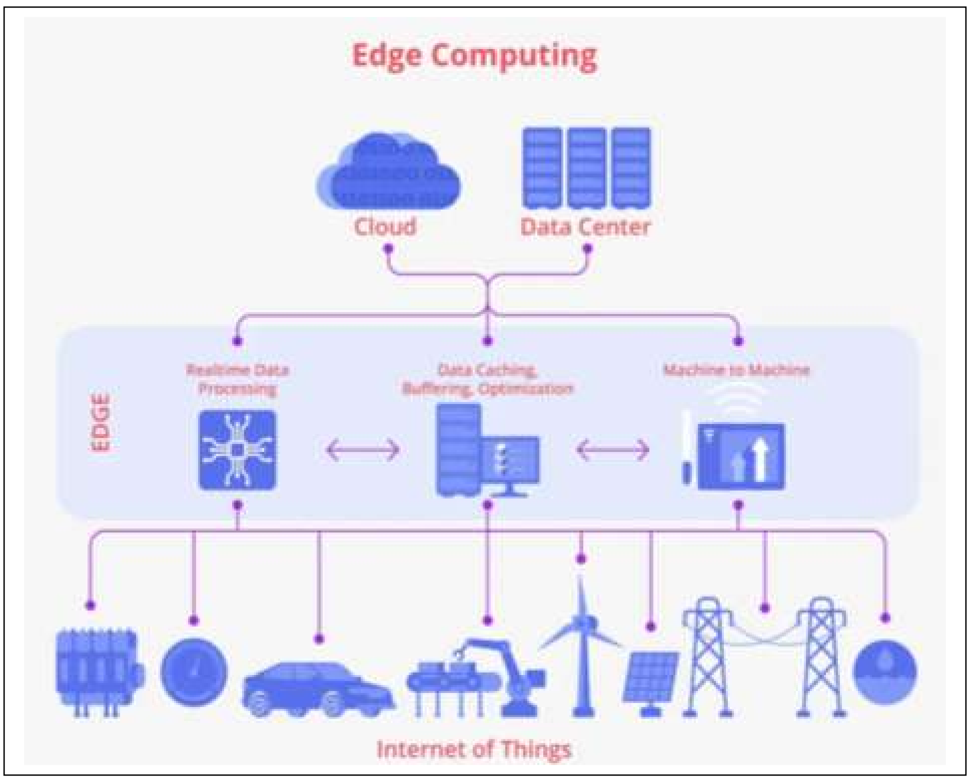

Figure 1: IoT Layer, Edge Layer , Cloud Layer

- **IoT Layer (Data Generation Layer) :** Generates real-time data from sensors and devices.
- **Edge Layer (Processing Layer) :**Processes, filters, and analyses data locally using AI and renewable energy.
- **Cloud Layer(Storage and Analytics Layer):** Stores and performs advanced analysis on selected data.
- **Security Layerand Communication Layer:** Ensures secure data transmission and privacy.

Working Mechanism:
The proposed framework operates through a structured workflow that ensures efficient data processing, reduced energy consumption, and enhanced sustainability.
Step 1: Data Generation**-**IoT devices generate data.
Step 2: Data Transmission**-** Data is sent to nearby edge nodes.
Step 3: Local Processing**-**Edge processes data locally.
Step 4: Data Filtering & Forwarding **-**Only important data is sent to cloud.
Step 5: Renewable Energy Utilization**-** Renewable energy powers edge nodes.
Step 6: AI-Based Task Scheduling**-**AI optimizes task scheduling.
Step 7: Secure Storage & Retrieval**-**Data is securely stored and retrieved.

Mathematical Modelling and Numerical Analysis:
Energy Consumption Model

$$\boldsymbol{E_{total} = E_{proc} + E_{tx} + E_{idle}}$$

The total energy consumption in a computing system consists of:
- E_{proc} : Energy used for processing tasks
- E_{tx}: Energy used for data transmission
- E_{idle} : Energy consumed during idle state

Cloud Energy Consumption Calculation
Assumptions (Cloud System)
Due to centralized processing and long-distance communication:
- $E_{proc} = 1200J$(high computation in data center)
- $E_{tx} = 700J$(long-distance transmission)
- $E_{idle} = 100J$

Calculation : $\boldsymbol{E_{total} = 1200 + 700 + 100 = 2000J}$

Result: Cloud system consumes 2000J total energy

Edge Energy Consumption Calculation

Assumptions (Edge System)

Due to local processing and short-distance communication:
- $E_{proc} = 500J$
- $E_{tx} = 200J$
- $E_{idle} = 100J$

Calculation: $\boldsymbol{E_{total} = 500 + 200 + 100 = 800J}$

Result: Edge node consumes 800J total energy

Energy Saving Analysis
$EnergySaving = 2000 - 800 = 1200J$
$PercentageSaving = \frac{1200}{2000} \times 100 = 60\%$

Edge computing saves 60% energy compared to cloud computing

Transmission Energy Model

$$E_{tx} = k \times d^2$$

Transmission energy depends on:

- k =Distance between nodes
- d^2 =Device-specific constant

Example

Let$k = 0.5$

Cloud (distance = 100m):$E = 0.5 \times 100^2 = 5000J$

Edge (distance = 10m):$E = 0.5 \times 10^2 = 50J$

Result: Energy reduced from **5000J → 50J (99% saving)**

Latency Model

$$Latency = T_{tx} + T_{proc}$$

Latency is the total delay consisting of:

- T_{tx} =Transmission delay
- T_{proc} =Processing delay

Example

Cloud:$T_{tx} = 6s, T_{proc} = 4s$, $Latency = 6 + 4 = 10s$

Edge:$T_{tx} = 1s, T_{proc} = 2s$, $Latency = 1 + 2 = 3s$

Result: Latency reduced by **70%**

Carbon Emission Model

$$CO_2 = E \times EF$$

Carbon emission depends on:

- E = Energy consumed
- EF = Emission factor (kg CO_2 per unit energy)

Example

Let$EF = 0.9$

Cloud:$CO_2 = 2 \times 0.9 = 1.8kg$

Edge:$CO_2 = 0.8 \times 0.9 = 0.72kg$

Result:60% reduction in carbon emission

Storage Optimization Model

$$S_{saved} = S_{raw} - S_{filtered}$$

Storage saving is achieved by filtering unnecessary data at edge.

Example

Let:Raw data = 100MB &Filtered data = 20MB

$$S_{saved} = 100 - 20 = 80MB$$

Result:80% storage saving

5.6 Efficiency Ratio Model

$$Efficiency = \frac{\text{Output}}{Energy\ Consumed}$$

Example

Cloud:$Efficiency = \frac{100}{2000} = 0.05$

Edge:$Efficiency = \frac{100}{800} = 0.125$

Result:
Edge is **2.5× more efficient**

Graphical Analysis and Visualization

Energy Consumption Analysis

Python Code for Graphs

```
import matplotlib.pyplot as plt
systems = ['Cloud', 'Edge']
energy = [2000, 800]
plt.figure()
plt.bar(systems, energy)
plt.title('Energy Consumption Comparison')
plt.xlabel('System')
plt.ylabel('Energy (Joules)')
plt.savefig('energy_comparison.png')
plt.show()
```

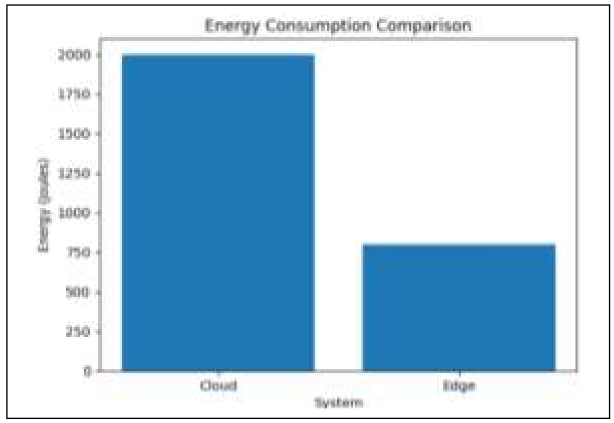

Figure 2: Energy Consumption Comparison

Transmission Energy Analysis

```
import matplotlib.pyplot as plt
transmission_energy = [5000, 50]
plt.figure()
plt.bar(systems, transmission_energy)
plt.title('Transmission Energy Comparison')
plt.xlabel('System')
plt.ylabel('Energy (Joules)')
plt.savefig('transmission_energy.png')
plt.show()
```

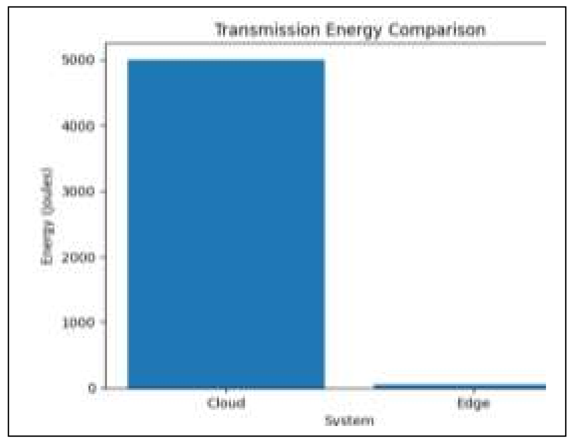

Figure 3: Transmission Energy Comparison

Latency Comparison Analysis

```
import matplotlib.pyplot as plt
latency = [10, 3]
plt.figure()
plt.bar(systems, latency)
plt.title('Latency Comparison')
plt.xlabel('System')
plt.ylabel('Time (seconds)')
plt.savefig('latency.png')
plt.show()
```

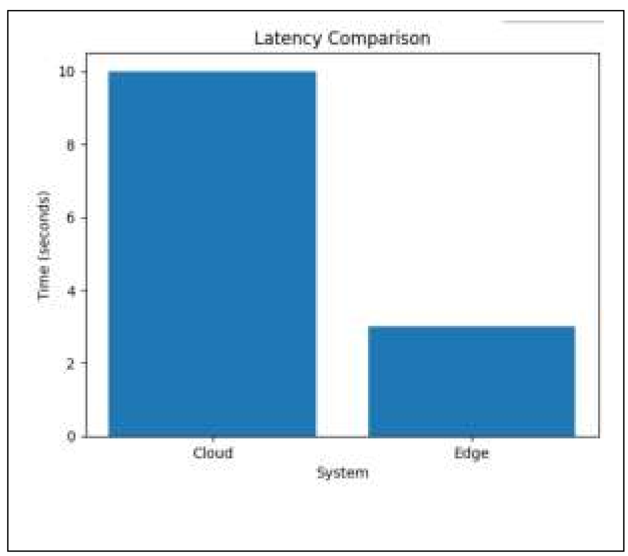

Figure 4: Latency Comparison

Carbon Emission Analysis

- Evaluates environmental impact using energy consumption
- Cloud: 1.8 kg CO_2, Edge: 0.72 kg CO_2 .
- Achieves 60% reduction in emissions

```
import matplotlib.pyplot as plt
carbon = [1.8, 0.72]
plt.figure()
plt.bar(systems, carbon)
plt.title('Carbon Emission Comparison')
plt.xlabel('System')
plt.ylabel('CO2 (kg)')
plt.savefig('carbon_emission.png')
plt.show()
```

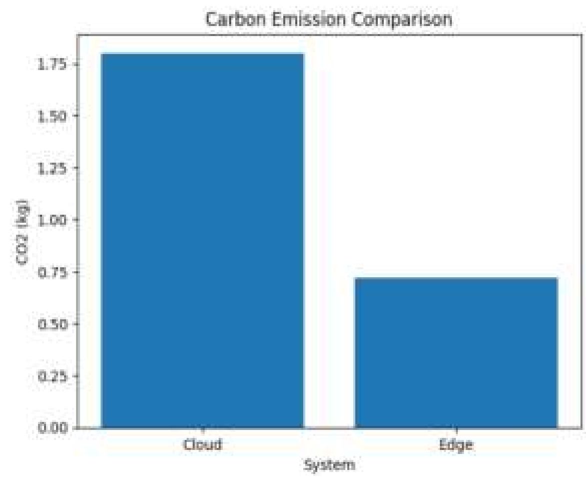

Figure 5: Carbon Emission Comparison

Storage Optimization

```
import matplotlib.pyplot as plt
storage_labels = ['Raw Data', 'Filtered Data']
storage_values = [100, 20]
plt.figure()
plt.bar(storage_labels, storage_values)
plt.title('Storage Optimization at Edge')
plt.xlabel('Data Type')
plt.ylabel('Storage (MB)')
plt.savefig('storage.png')
plt.show()
```

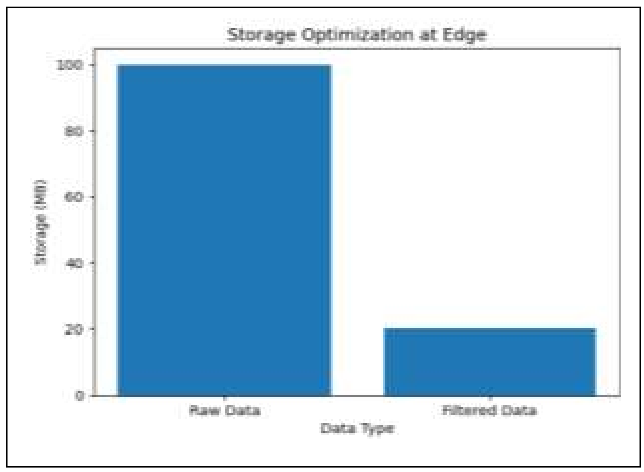

Figure 6: Storage Optimization at Edge

Efficiency Comparison

- Measures system performance per unit energy.
- Edge system is 2.5× more efficient

```
import matplotlib.pyplot as plt
efficiency = [0.05, 0.125]
plt.figure()
plt.bar(systems, efficiency)
plt.title('Efficiency Comparison')
plt.xlabel('System')
plt.ylabel('Efficiency')
plt.savefig('efficiency.png')
plt.show()
```

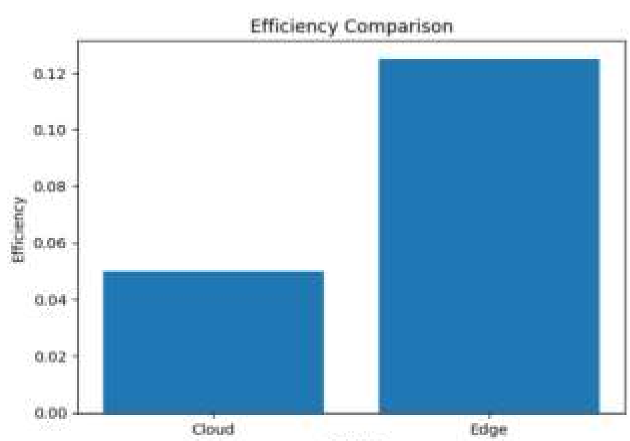

Figure 7: Efficiency Comparison

Latency and Sustainability:

Latency affects energy use.Higher delay increases processing time and power consumption. It saves energy through local processing, shorter transmission distance, efficient resource use, reduced runtime, and integration of renewable energy sources.

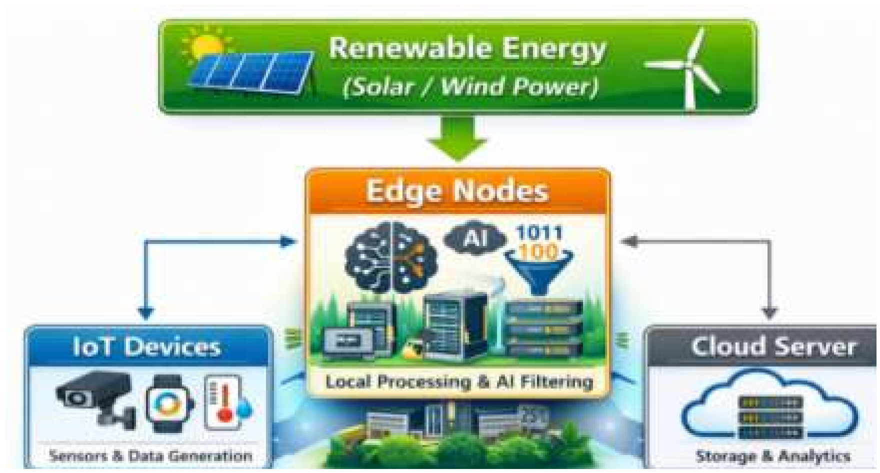

Figure 8: Edge Computing uses Renewable Energy and Reduces Latency

How Sustainable Edge Computing Saves Energy

Figure 9: Sustainable Edge Computing Advantages

Applications of Sustainable Edge Computing

Sustainable edge computing is applied in smart cities (traffic, lighting, waste), healthcare (patient monitoring), agriculture (irrigation, crop monitoring), and industrial IoT (predictive maintenance, energy efficiency).

Result Analysis and Comparison:-

The performance of the proposed sustainable edge computing framework is evaluated by comparing it with traditional cloud computing using key parameters such as energy consumption, transmission energy, latency, carbon emission, storage efficiency, and system efficiency.

Table 1: Comparative Result Analysis

Parameter	Cloud Computing	Edge Computing	Improvement
Total Energy Consumption	2000 J	800 J	↓ 60%
Transmission Energy	5000 J	50 J	↓ 99%
Latency	10 sec	3 sec	↓ 70%
Carbon Emission	1.8 kg	0.72 kg	↓ 60%
Storage Requirement	100 MB	20 MB	↓ 80%
Efficiency Ratio	0.05	0.125	↑ 2.5×

Conclusion:-

A sustainable edge computing framework improves energy efficiency, reduces latency and carbon emissions using renewable energy and AI scheduling. Numerical results show better performance than cloud systems, making edge computing key for sustainable and intelligent systems. It reduces energy use, transmission distance, and carbon footprint through local processing, while lower latency further decreases power consumption and enhances sustainability.

Future Scope:

- Integration with 5G/6G networks
- AI-driven autonomous optimization
- Carbon-aware computing models
- Self-powered edge devices
- Large-scale smart infrastructure deployment

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