



Edge Computing for Smart Grid: An Overview

Prajali Bafila^{1*} and Mohit Lal Sah^{2**}

^{1*}Department of Electrical Engineering, Indian Institute of Technology Jodhpur, Nagaur Road, Karwar, Jodhpur, 342037, Rajasthan, India. ^{2**}School of Computer Science & Applications, IFTM University, Lodhipur Rajput, Moradabad, 244102, Uttar Pradesh, India.

*Corresponding author(s). E-mail(s): p24ee0207@iitj.ac.in; Contributing authors: mohitsaho@gmail.com;

ABSTRACT

Edge computing has a big impact on smart grids. It cuts down on delays by handling data near where it comes from. This lets grids make choices immediately, which is key for quick and reliable operations. It's different from old cloud systems, where data goes to main servers for checking. This new way speeds up data work, makes things safer, uses bandwidth better, and helps the system bounce back from problems. Edge computing cuts down on hold-ups from busy networks and doesn't need always to be online. It makes grid jobs like finding faults, answering demand, and guessing loads faster and more exact. This paper looks at how edge computing stacks up against cloud computing for smart grids. It checks how this affects how well the grid works overall. The findings show that edge-based setups help modern power networks to adapt and recover. This means they can better handle the spread of energy sources and changing energy needs.

KEYWORDS

Smart Grid, Edge Computing, Cloud Computing

1 Introduction

The main aim of smart grids is to enhance transmission and distribution and energy generation through various technologies involving two-way communication, intelligent monitoring, control, and The ability to heal oneself. Smart devices such as smart meters, sensors, and intelligent electrical appliances improve the smart grid's ability to generate data through various applications and services. Recently, many smart grids have started using cloud computing to store, analyze, and manage this data, which will facilitate future control commands and decision-making processes. Nevertheless, existing legacy cloud computing platforms might have many downsides, including slow response time, networks, and arrangement problems. All of these factors limit their use in real-time applications. Edge computing was introduced recently to solve these issues productively in conventional cloud computing. A game-changing way to beat the flaws of regular cloud computing in real-time decision-making is to bring edge computing into smart grids. Edge computing offers not only just enhancing grid reliability and providing a range of technical benefits. It's has becoming a powerful alternative to cloud-based applications. In this paper, we'll dive into the many advantages of edge computing, explore how it strengthens grid reliability, compare it with cloud computing, and also discuss the challenges that come with implementing it.

2 Literature Review

By integrating of edge computing with smart grids is a growing area of research that solves several problems associated with cloud computing, eg. security risk, delays, data localization and high bandwidth usage. There are many studies which have explored how edge computing can make smart grids more efficient, fast and reliable, especially as these grids depend more and more on real-time data processing and decision-making.

Paper by Peng Zeng, Hao Liang, Ying Zhang, and Chunhe Song (2023) emphasize on how edge computing is improving smart grid. The authors explain that edge computing helps optimize grid operations by improving things like load analysis and fault detection. The paper focuses on recent advances in edge computing that have been applied to smart grids. It also addresses issues like optimization, load analysis, and fault detection, along with security. [1]

Similarly, Sen Yang and Ruijuan Zheng (2023) The paper is on reducing latency when we use edge computing in place of cloud computing by placing devices near terminals and user sides. It emphasizes on reducing data privacy and the burden of storage in the cloud data centers. Their research shows that this approach eases the load on cloud data centers which leads to quicker response times. It also helps with privacy since sensitive data stays local, and reduces the need for massive storage in the cloud.[2]

Another important paper by Y. Zhu (2023) here the author focuses on the cyber security aspect of the smart grid and different types of cyber attacks. It also proposes a framework that includes a batch polluting strategy that syncs updates the attack points. As smart grid systems becoming more complex, they become more vulnerable to cyber-attacks. Zhu proposes using edge computing for real-time monitoring and response to these threats, which can make the grid more secure.[3]

S. Singhal (2023) examines how edge computing helps smart grids by using fog nodes for load balancing. His research shows that edge computing can cut down operational costs by 6%, reduce turnaround time by 15%, lower energy consumption by 29%, and cut processing time and delays by 14%, compared to other algorithms. This highlights how effective edge computing is for real-time load balancing in smart grids.[4]

Singhal (2023) also looks at a hybrid optimization algorithm for edge computing in smart grids, using a technique called grey wolf differential evolution. RHO algo on cloud analyst simulator is being used by the author to show the effective categorized fog node for utilization. The proposed load-balancing algorithm demonstrates significant improvements in performance metrics, achieving a reduction in cost by 6%, response time by 15%, energy consumption by 29%, processing time by 26 %, and delay by 14% compared to static and dynamic algorithms.[5]

F. Alsokhry (2022) in this paper simulation is conducted on MATLAB, and logo is used here as a Hybrid grey wolf differential evolution optimization algorithm. The blog is compared with particle swarm optimization and differential evolution. It shows a response time of 54 ms, 82.1 ms, and 81.6 ms, faster respectively. It also manages the data transactions effectively in smart grids.[6]

D. N. Molokomme (2022) discusses the integration of the smart grid with machine learning technologies to optimize the resources. They introduced edge intelligence (EI), which means the edge devices are not just meant for the relay of information but taking benefits of AI advancement and enabling edge devices to take decisions by themselves[7].

The paper by J. Li (2022) explores the synergy between edge computing and cloud computing in smart grids. As the number of intelligent devices in smart grids increases, managing them becomes challenging. The paper discusses how edge computing helps alleviate the burden on cloud systems by enabling real-time data processing and enhancing security [8].

This integration is vital for improving grid performance and managing the increased complexity of modern energy systems[?].In 2020, L. U. Khan examined how edge computing addresses latency issues in smart cities, particularly in applications that generate large amounts of data, such as those found in smart grids. The paper identifies edge computing as a promising solution to the latency problems associated with cloud systems and emphasizes its role in enabling faster decision-making [9].S. Zahoor (2018) proposed a cloud-fog-based model to improve resource management in smart grids. By adding fog computing alongside cloud services, this model optimizes the use of smart devices and data processing capabilities. The paper demonstrates the scalability, flexibility, and cost-effectiveness of fog computing in smart grid applications, highlighting its ability to enhance load balancing and reduce energy consumption [10].

Recent trends in edge computing for smart grids demonstrates that localized data processing at the edge can significantly enhance the performance and security of grid operations. Edge computing reduces the dependence on centralized cloud systems, addresses privacy concerns by keeping sensitive data local, and enables real-time decision-making, which is crucial for maintaining grid stability. Several studies also show how edge computing can be integrated with other technologies, such as IoT, machine learning, and fog computing, to further improve smart grid performance. However, challenges remain in scaling edge computing solutions for larger grids, ensuring seamless integration with existing cloud systems, and addressing issues related to the security of distributed edge devices. As the research continues to evolve, edge computing is expected to play an increasingly important role in enabling the development of more resilient, efficient, and secure smart grids.

3 TECHNOLOGICAL ADVANTAGES OF EDGE COMPUTING

Edge computing has drawn significant attention as a solution that can address some of SG's real-world challenges. Under the assumptions laid down in the literature, we must minimize data transmission time and expedite local decision making instead of depending on center control and command systems, which may be inaccessible at that point or in contact. Given AI expansion within real-time systems, we attempt to enhance Edge computing benefits for smart grids. Overview of Smart Grid and Edge Intelligence Edge computing suggests the move of some computation and storage capacities from the center data center closer to the location of the data source [14]. Here, we are trying to analyze maximum data closer to the data source (which we mark as network edge here), generating devices rather than sending them to the server and then waiting for a central decision on that data.[15]. Edge computing is often mistaken with other terminology, and some authors use it interchangeably.

Table 1 ASSESSMENT OF CLOUD & EDGE COMPUTING (Data generated by the author)

Parameters	Cloud	Edge
Type of Deployment	Centralized	Decentralized
Location	Away from Location	Nearby
Processing Power	Vast	Limited
Efficiency	High	High

Delay in Communication	High	Low
Processing at	Central Virtual Server	Edge Server
Storage	Huge	Very Limited
Privacy and Security	High	Low
Mobility Support	No	Yes

4 CRITICAL ENABLING TECHNOLOGIES FOR EDGE COMPUTING

4.1 (i) Containerization

4.2 (ii) Orchestration

4.3 (iii) Mobile Network Fifth Generation (5G)

4.3.1 1) Technological Benefits of Edge Computing

Lowered Delay and Real-time Processing: Edge computing excels in real-time data processing, significantly reducing delays by processing data closer to its source. The delay reduction can be quantified as:

$$\Delta T = T_{\text{cloud}} - T_{\text{edge}}$$

Where: - ΔT is the reduction in delay, - T_{cloud} is the delay in cloud-based processing, - T_{edge} is the delay in edge computing processing.

This formula demonstrates how edge computing reduces delay compared to cloud computing by processing data closer to the source, crucial for maintaining efficiency and stability in applications such as smart grids [11] [12].

4.4 Smart Grid Bandwidth Utilization

Table 2 Bandwidth Comparison between Edge and Cloud Computing (Data generated by the author)

System Type	Data Sent to Cloud (MB)	Bandwidth Utilization
Edge Computing	10	Low (Efficient)
Cloud Computing	100	High (Inefficient)

In edge computing, bandwidth are minimized because data is processed locally at the edge using micro controllers which reducing the amount of data transmitted to the cloud. This local data processing is particularly beneficial in smart grids, where multiple IoT devices can overwhelm the cloud infrastructure. By reducing bandwidth consumption, edge computing not only improves network performance but also reduces operational costs [13].

4.5 Improvements to Security and Privacy

Edge computing enhances security by processing sensitive data locally or near its source, reducing the need to transmit it to a centralized cloud server. This additional layer of local processing helps mitigate risks associated with data breaches commonly seen in cloud-based setups. By keeping data processing closer to the source, edge computing enhances privacy and lowers vulnerability to attacks.

4.6 Integration of Lightweight Machine Learning Models

Edge computing provides an excellent platform for integrating lightweight machine learning models, which enhance the data processing and decision-making capabilities of edge devices. These models enable real-time data analysis, which is crucial for applications like smart grids, where immediate responses are essential [11] [12].

4.7 Scalability and Autonomy

Edge computing contributes to the scalability and autonomy of smart grids. By distributing processing to the edge, smart grids reduce their reliance on centralized cloud infrastructure, leading to increased flexibility. The scalability and self-sufficiency offered by edge computing enhance the grid's overall stability, particularly in situations where there may be network disruptions or fluctuations [14].

5 IMPACT ON GRID RELIABILITY

5.1 Real-Time Monitoring and Fault Detection

Edge computing provides a way to monitor actions on the grid in real-time, which helps minimize disruption and allows for more rapid fault identification and isolation. This is a critical aspect for maintaining reliability and minimizing impacts of grid failures. For example, fault detection systems using edge computing can isolate faults before they spread and disrupt the power delivery to users and customers. The fault detection time T_f can be expressed as:

$$T_f = \frac{D}{V_{fd}}$$

Where:

- T_f is the fault detection time,
- D is the distance or the area affected by the fault,
- V_{fd} is the speed of fault detection (in meters per second).

5.2 Enhanced Resilience to Failures

The decentralization of data processing and decision-making in edge computing also allows a smart grid to be more flexible during failures. For example, if there is a situation of a cloud

outage, then edge computing devices can independently clip to the adjacent edge application. Input to core functions can remain utilizing edge computing to maintain grid reliability in the interim [14].

The resilience factor R of edge devices during failures is:

$$R = \frac{N_{\text{active}}}{N_{\text{total}}}$$

Where:

- N_{active} is the number of operational edge computing devices during a failure,
- N_{total} is the total number of edge computing devices deployed in the grid.

5.3 Effective Restoration Methods

Edge computing also permits the development of intelligent restoration methods and systems that can automatically recover the grid in the case of failure or attack. This consideration is an important aspect of reliability and restoration in case of disturbance [15]. The effectiveness of the restoration system $E_{\text{restoration}}$ can be calculated as:

$$E_{\text{restoration}} = \frac{T_f - T_r}{T_f} \times 100$$

Where:

- $E_{\text{restoration}}$ is the efficiency of the restoration system (percentage),
- T_f is the fault detection time,
- T_r is the restoration time.

5.4 Improved Operational Efficiency

The ability to process live data through edge devices will minimize operational inefficiencies for smart grids. The ability for predictive maintenance capabilities and on-demand response management will help fleet grid operators better allocate and manage resources and consume less energy [12]. The cost savings C_s from operational efficiency improvements can be expressed as:

$$C_s = \frac{R_{\text{reduced}} \times C_{\text{operation}}}{T_{\text{total}}}$$

Where:

- R_{reduced} is the reduction in resource consumption due to predictive maintenance,
- $C_{\text{operation}}$ is the operational cost per unit of energy consumed,
- T_{total} is the total time under analysis.

6 IMPLEMENTATION CHALLENGES

6.1 Resource Management and Allocation

Resource allocation and management are fundamental challenges in implementing edge computing in smart grids. Edge devices typically have limited processing and storage capabilities, making it essential to optimize resource usage for efficient performance. This includes techniques like load balancing, resource provisioning, and adaptive scheduling to ensure that the available resources are used effectively without overloading the devices.

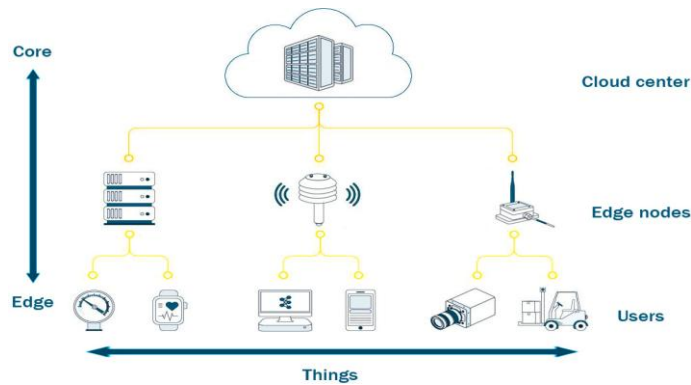


Fig. 1 Comparison of Resource Allocation in Edge vs. Cloud Computing. Source: Adapted from [16].

6.2 Security Issues

While edge computing enhances security by processing data at the edge, it introduces new security challenges. Edge devices are vulnerable to cyber threats, including unauthorized access, data breaches, and denial-of-service attacks. Protecting edge devices and ensuring secure communication between devices are critical for maintaining grid stability.

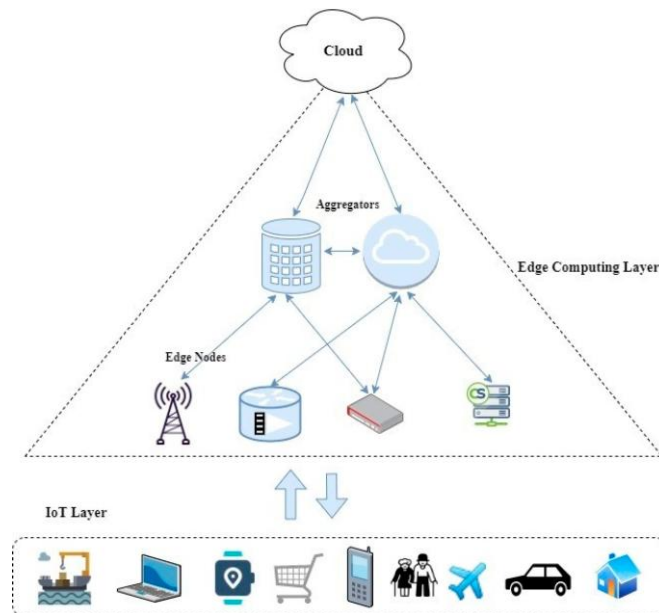


Fig. 2 Potential Security Threats in Edge Computing [17].

6.3 Interoperability and Standardization

Implementing edge computing in smart grids requires interoperability and standardization across different systems and devices. Edge computing systems must be compatible with various communication protocols, hardware, and software architectures. Effective interaction between edge devices and cloud infrastructure is essential to maximize the benefits of edge computing. Standardizing protocols such as IEEE 802.15.4 for low-power wireless communication and IEC 61850 for grid communication is a step in the right direction.

6.4 Network Congestion and Latency

Edge computing offers many benefits; however, network latency and congestion can still create challenges, particularly in large-scale smart grids. To ensure reliable data transmission and processing, network congestion must be mitigated through optimized routing and prioritization of critical data.

Table 3 Standards for Interoperability in Edge Computing for Smart Grids(Data generated by the author)

Standard	Application in Edge Computing
IEEE 802.15.4	Low-Power Wide-Area Networks (LPWAN) Communication
IEC 61850	Smart Grid Communication Standard
MQTT	Lightweight Messaging for IoT Devices

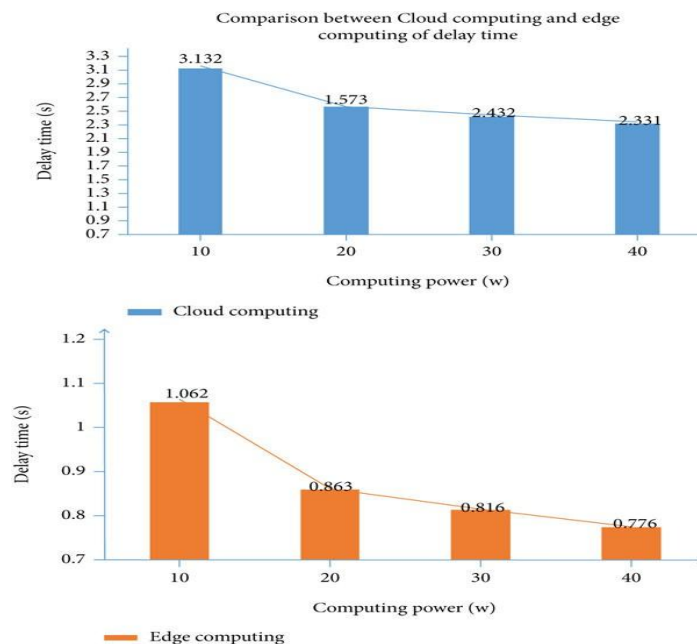


Fig. 3 Comparison of Network Latency in Edge vs. Cloud Computing for Smart Grids. Source: ARToolKit Target Tracking and Animation Fusion Technology Based on Edge Computing and Augmented Reality [18].



Additionally, network latency, especially in remote or rural areas, needs to be minimized through technologies such as 5G and low-latency networks.

7 CONCLUSION

This article discusses the limitations of cloud computing, contrasting it with edge computing and highlighting the role of edge computing in enhancing grid reliability. Edge computing impacts real-time oversight in smart grids by reducing delays, making better use of bandwidth, improving security, and ensuring grid stability.

While cloud computing still has its place in some scenarios, edge computing offers a more reliable and effective way to monitor and manage grids in real-time. Edge computing helps minimize latency, optimize bandwidth usage, and provide better security, contributing to a more resilient smart grid.

However, to fully realize the potential of edge computing in smart grids, we must address several key challenges:

- Efficient resource management and allocation to handle limited processing power and storage on edge devices.
- Overcoming security challenges such as cyber threats and ensuring secure data communication.
- Standardization and ensuring interoperability between diverse devices and systems across edge and cloud platforms.
- Mitigating network congestion and latency issues, particularly in large-scale deployments.

By tackling these issues, edge computing can significantly enhance the performance, efficiency, and reliability of smart grids, making them more adaptive and resilient in the face of growing energy demands and network complexities.

CRedit Author Contribution Statement:

Prajali Bafila: Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing.

Mohit Lal Sah: Data Curation, Formal Analysis, Funding Acquisition, Investigation, Project Administration, Resources, Software, Supervision, Validation, Visualization.

Competing Interests:

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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