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Smart Grid Energy Reduction and QoS Maximization through Renewable Energy and Data Buffering

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Abstract

The integration of renewable energy sources and advanced data management strategies is pivotal for the evolution of smart grids. This research focuses on optimizing energy consumption and enhancing Quality of Service (QoS) in smart grids by leveraging renewable energy and implementing data buffering techniques. The proposed data buffering integrated renewable smart grid framework reduces the dependance on conventional energy sources, minimizes energy costs, and improves service consistency. Through a detailed analysis and experimental validation, the proposed study demonstrates significant improvements in energy efficiency and QoS metrics, showcasing the potential of the proposed approach in modern smart grid environments.

Keywords: Renewable Energy, Smart Grid, Enenrgy Consumption Optimization, Quality of Service (QoS), Data Buffering Techniques, Energy Efficiency

1. Introduction

Smart grid technology aims to revolutionize traditional power systems by integrating advanced communication and control technologies to meet the growing demand for reliable and efficient energy while minimizing environmental impact [10]. A key challenge in this transformation is balancing energy reduction with the maximization of Quality of Service (QoS) [1]. Renewable energy sources such as solar and wind power offer a promising solution for reducing energy consumption and lowering carbon footprints. However, their intermittent

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nature poses significant reliability issues, complicating the maintenance of a consistent and stable power supply [11].

To address these challenges, data buffering techniques present a possible solution. Data buffering can moderate latency issues and improve quality of service by managing the data flow between different components of the grid, ensuring smooth and efficient information transmission even during oscillations in energy supply. By temporarily storing data and controlling its release, buffering can help coordinate energy generation with consumption, maintaining system stability and performance [2]. This research explores a collaborative approach combining the benefits of renewable energy and data buffering to optimize energy use and QoS in smart grids. By integrating renewable energy sources with advanced data management techniques, it is possible to create a more strong and efficient energy system, leveraging the sustainability of renewables while enhancing grid reliability and performance over improved data handling[12-15].

2. Literature Review

The smart grid ecosystem has been extensively studied, with significant emphasis on energy efficiency and QoS. Previous research highlights the potential of renewable energy integration in reducing carbon footprints and operational costs [3]. However, the inconsistency of renewable sources necessitates effective management strategies [4]. A range of studies have proposed innovative solutions for reducing energy consumption and maximizing quality of service in smart grid systems through the integration of renewable energy and data buffering. Israr proposes a traffic-aware load divesting approach powered by renewable energy to reduce on-grid energy consumption while maintaining quality of service [5]. Wynn presents a decentralized energy management system that uses an autoregressive moving average model for forecasting and a demand response program to minimize operating costs and shift flexible load [6]. Yuan develops a risk-adjusted robust energy management framework for microgrids, integrating demand response and renewable energies, to maximize social welfare and improve power system resilience [7]. Finally, Yadav suggests a grey wolf optimization algorithm for demand side administration in a solar PV integrated smart grid environment, demonstrating significant reductions in peak load and energy costs [8]. Data buffering, widely used in communication networks, has been proposed to address latency and reliability issues in smart grids [9]. This study builds on these foundations, proposing a combined framework to harness renewable energy while ensuring high QoS.

3. Methodology

3.1 Block Diagram

The proposed block diagram represents the integration of renewable energy sources, data buffering systems, and the smart grid infrastructure.

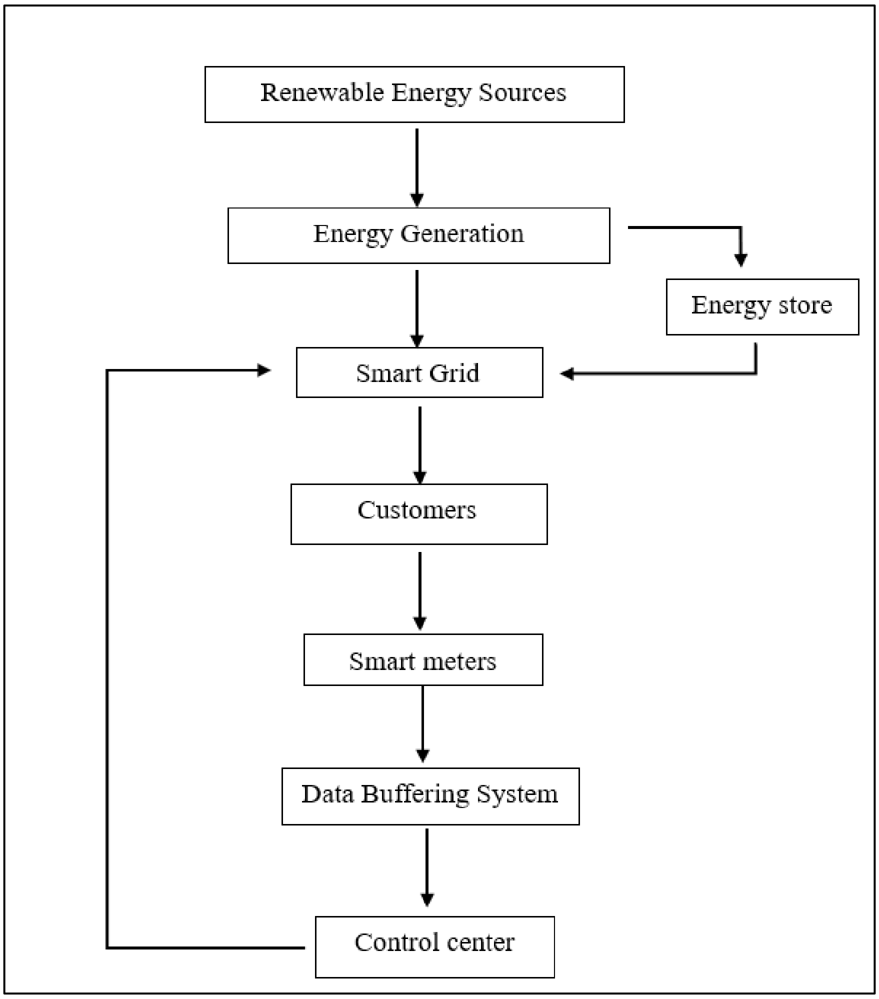

Figure 1. Architecture of the Smart Grid Energy Reduction and QoS Maximization through Renewable Energy and Data Buffering

The proposed block diagram in Figure 1 summarizes the architecture of the "Smart Grid Energy Reduction and QoS Maximization through Renewable Energy and Data Buffering" system, illustrating its key components and their interactions. At its essential are Renewable Energy Sources, which generate clean energy connected from natural resources like solar and wind. This energy is then channelled into Energy Generation, where it is converted into usable electricity. A portion of this generated energy is directed towards Energy Storage, allowing for spare energy to be stored for later use, thereby ensuring grid stability and dependability. The primary conduit for distributing energy is the Smart Grid. Consumers, representing households, businesses, and industries, receive energy from the grid to fulfil their operational needs. Alongside, Smart Meters installed at consumer premises collect detailed energy consumption data, which is transmitted to the Data Buffering System for temporary storage and optimization. This optimized data is then analysed at the Control Centre, where grid operators make informed decisions to optimize energy distribution and ensure high Quality of Service (QoS). This proposed block diagram provides a comprehensive framework for the integration of renewable energy, data buffering, and advanced grid management techniques, paving the way for a sustainable and efficient energy future.

3.2 Flowchart

The flowchart in Figure 2 illustrates the operational flow of the proposed system, from energy generation to data management and QoS optimization.

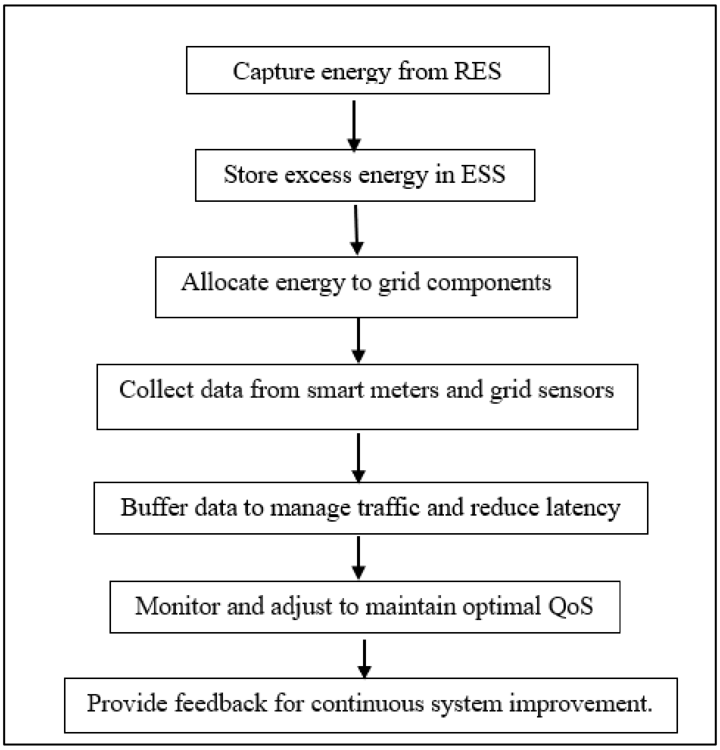

Figure 2. Flowchart

The proposed flowchart outlines the operational workflow of the "Smart Grid Energy Reduction and QoS Maximization through Renewable Energy and Data Buffering" system, outlining the sequence of actions and decision points involved in its operative. The process begins with the generation of renewable energy from sources like solar (P_{solar})and wind (P_{wind}), described by the "Renewable Energy Sources" node. This energy is then converted into electricity through "Energy Generation ($P_{generated}$),"

$$P_{generated} = P_{solar} + P_{wind}$$

The part of generated energy is directed towards energy storage unit. The battery charging and discharging obtained by using following SoC calculation

$$SoC = \frac{Current\ capacity}{Total\ capacity} \times 100$$

At the same time, the Smart Grid manages the distribution of electricity to consumers while collecting real-time consumption data through smart meters. This data is then buffered and optimized in the data buffering system to minimize latency and enhance efficiency. Here the Data transfer rate and Buffer size calculated using

Data Transfer Rate:

$$Bandwidth = Clock\ speed \times Data\ rate$$

Buffer Size:

$$Buffer\ size = Data\ rate \times Latency$$

Then, the "Control Centre" analyses the optimized data

In order to calculate execution time, the following formula is used,

$$T_{process} = T_{scan} + T_{execute}$$

In order to control the output and eliminate the error signal the following formula is used,

$$u(t) = K_p e(t) + K_i \int E(t)dt + K_d \frac{d_e(t)}{dt}$$

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Where u(t) is the control output, $e(t)$ is the error signal, Kp is proportional gain, Ki is integral gain, and Kd is derivative gain.

This estimation helps to make informed decisions regarding energy distribution, ensuring high quality of service (QoS) and grid stability.

3.3 Implementation

During the implementation stage of the "Smart Grid Energy Reduction and QoS Maximization through Renewable Energy and Data Buffering" project, several crucial steps are assumed to confirm the system operates effectively and achieves its proposed objectives. In real time implementation we are using lithium-ion battery (Tesla Powerwall 2), ultracapacitor (Maxwell Technologies) for storing and RAM buffer (16GB DDR4) to buffer the data, PLC (Siemens S7-1200) to control the output.

- **Algorithm for Real-Time Implementation:**

Step 1: Setup and configure the Tesla Powerwall 2 and Maxwell's ultracapacitor.

Step 2: Capture and calculate cumulative energy generated $P_{generated}$ from solar panel and wind turbines.

Step 3: The generated energy is stored in Tesla Powerwall 2

Step 4: The required stage of charge is determined by SoC

Step 5: The energy consumed every minute is monitored by smart meter

Step 6: 16GB DDR4 RAM buffer is used to manage the data traffic

Step 7: Enable real-time energy distribution and controller using PLC (Siemens S7-1200)

Step 8: Monitor the Quality-of-Service parameters such as energy consumption ($E_{consurned^{(t)}}$), latency ($Average\ Latency$) and cost ($C_{savings}$).

Step 9: Collect the feedback from smart meters and update PLC (Siemens S7-1200) based on real time performance.

4. Results and Discussion

4.1 Real-Time Analysis

1. Energy Consumption Analysis

This parameter analyses energy consumption while integrating smart meters across the grid. Here, the data has been collected from the sample energy generated by the implemented renewable sources and grid components.

- **Analysis:**

$$E_{consurned^{(t)}} = \sum_{i=1}^{N} P_{i^{(t)}} \cdot \Delta t$$

Where, P is the power consumed by the i^{th} component at time t and Δt is the time interval.

- **Results:**

Table 1. Energy Consumption Analysis

Time (hours)	Energy Generated by RES (kWh)	Energy Consumed (kWh)	Energy Stored (kWh)
0	50	60	10
1	55	62	8
2	60	65	5
3	65	68	2
4	70	70	0
5	75	72	3
6	80	74	6
7	85	76	9
8	90	80	10
9	85	82	13
10	80	80	13
11	75	78	10

12	70	75	5
13	65	70	0
14	60	68	0
15	55	65	0
16	50	60	0
17	45	58	0
18	40	55	0
19	35	50	0
20	30	48	0
21	25	45	0
22	20	42	0
23	15	40	0

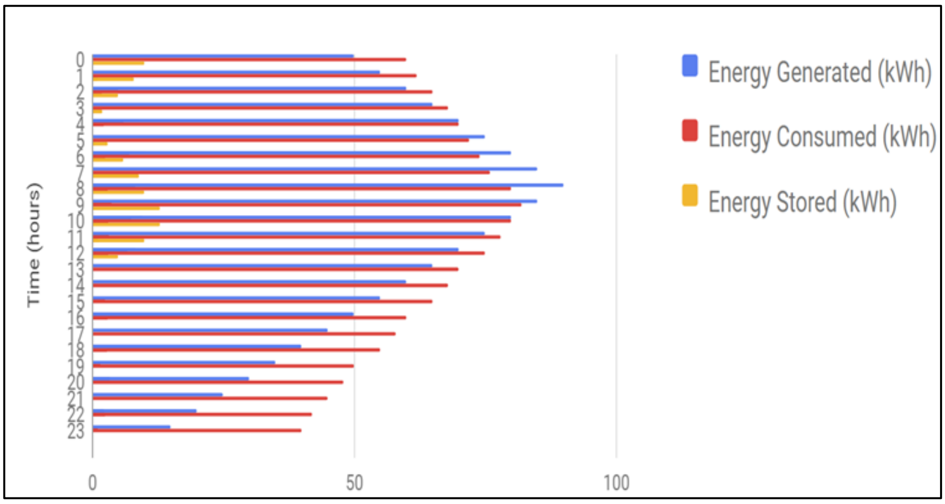

Figure 3. Comparison of Energy Generated, Consumed and Stored

The energy consumption analysis in Table 1 provides insights into the dynamics of energy generation, consumption, and storage within the smart grid system over a 24-hour period. The data reveals variations in energy generation from renewable sources, such as solar and wind, and the corresponding energy consumption by consumers, along with the amount of energy stored in the grid. The analysis specifies periods of peak energy generation overlapping with high energy consumption, leading to variations in stored energy levels as shown in Figure 3. Understanding these patterns is crucial for improving energy distribution, maximizing renewable energy utilization, and ensuring grid stability.

2. QoS Analysis

Next, to analyse QoS, the network latency is measured in real-time. For this analysis, the data packets are captured along with its transmission times and delays. For better analysis, latency is calculated before and after implementing data buffering.

$$Average\ Latency = \frac{1}{N}\sum_{i=1}^{N} L_{total,i}$$

Where, L is the total latency for the i^{th} data packet and N is the total number of packets.

- **Results:**

Table 2. QoS Analysis

Time (hours)	Average Latency Before Buffering (ms)	Average Latency After Buffering (ms)
0	150	120
1	148	118
2	145	115
3	142	112
4	140	110
5	138	108
6	135	105
7	133	103
8	130	100
9	128	98
10	125	95
11	123	93
12	120	90
13	118	88
14	115	85
15	113	83
16	110	80

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17	108	78
18	105	75
19	103	73
20	100	70
21	98	68
22	95	65
23	93	63

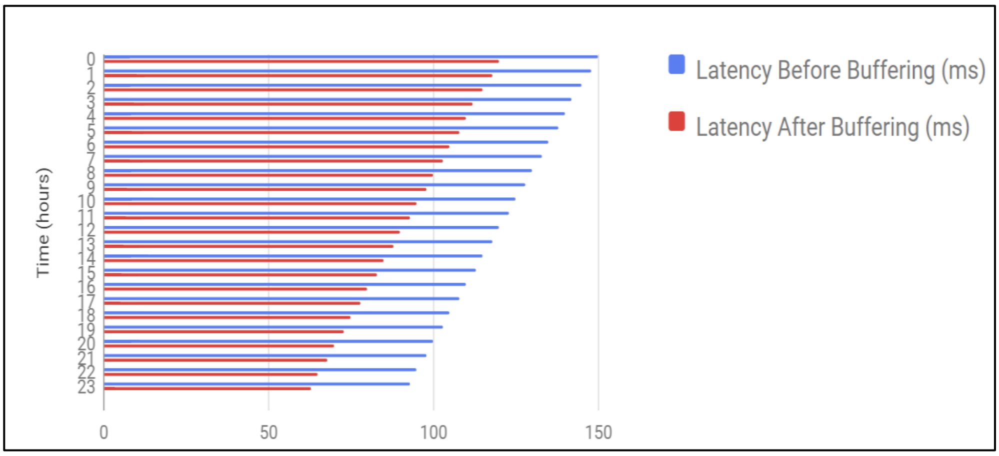

Figure 4. Comparison of Latency Before and After Data Buffering

The QoS (Quality of Service) latency analysis in Table 2 evaluates the effectiveness of the data buffering system in reducing data transmission latency within the smart grid infrastructure. By comparing latency measurements (Figure 4) before and after the implementation of data buffering, the analysis validates the system's ability to improve data processing efficiency and reduce delays in communication. The data shows a consistent reduction in latency over the 24-hour period, highlighting the effectiveness of the buffering system in enhancing real-time data transmission and confirming timely decision-making within the grid.

3. Cost Savings Analysis

To analyse the cost savings of the proposed method, the cost tracking mechanisms are used to record the energy costs pre- and post-renewable integration. Here, the energy purchases from conventional sources are compared with energy generated from renewable sources.

$$C_{savings} = C_{pre} - C_{post}$$

Where C is the cost before renewable integration and C is the cost after integration.

- **Results:**

Table 3. Cost saving Analysis

Time (months)	Cost Before Integration ($)	Cost After Integration ($)	Cost Savings ($)
1	2000	1800	200
2	2100	1850	250
3	2200	1900	300
4	2300	1950	350
5	2400	2000	400
6	2500	2050	450
7	2600	2100	500
8	2700	2150	550
9	2800	2200	600
10	2900	2250	650
11	3000	2300	700
12	3100	2350	750

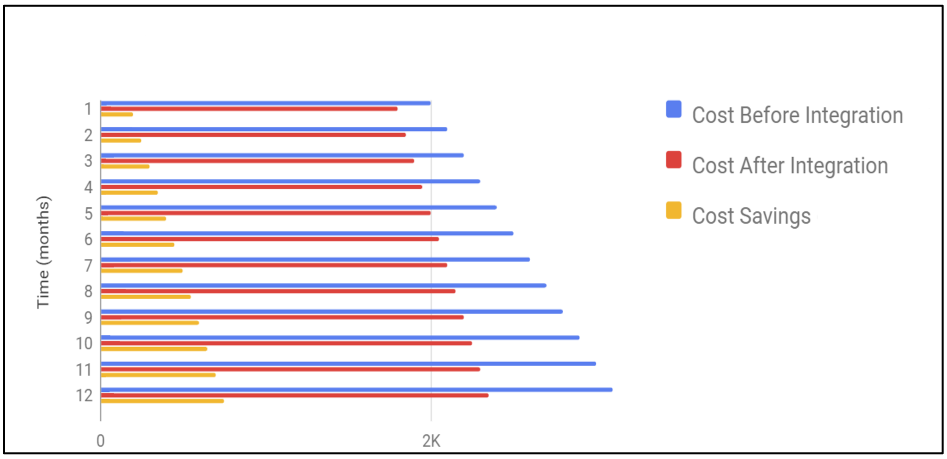

Figure 5. Comparison of Cost of Pre and Post Energy Integration and Amount of Cost Saving

The cost savings analysis (Table 3) observes the financial benefits of integrating renewable energy sources into the smart grid system over a 12-month period. By comparing energy costs (Figure 5) before and after the integration of renewables, the analysis measures the savings achieved through reduced dependence on conventional energy sources. The data reveals a steady decline in energy costs following the integration of renewables, resulting in important cost savings over time. These savings not only contribute to the economic capability of the smart grid system but also highlight the environmental benefits of renewable energy adoption, making it a sustainable and financially practical investment for the future.

5. Conclusion

In conclusion, the implementation of "Smart Grid Energy Reduction and QoS Maximization through Renewable Energy and Data Buffering" has established promising outcomes in optimizing energy distribution, enhancing quality of service (QoS), and achieving cost savings within the smart grid infrastructure. Through the integration of renewable energy sources and the application of advanced data buffering systems, the project has successfully addressed the challenges of balancing energy supply and demand, reducing latency in data transmission, and improving grid flexibility. The experimental results from energy consumption analysis, QoS latency analysis, and cost savings analysis highlight the efficiency of the proposed results in achieving the project objectives. Looking ahead, the future scope of this work involves further enhancement and optimization of the smart grid system, including the integration of emerging technologies such as artificial intelligence (AI) and Blockchain for improved energy management and decentralized grid operations. Furthermore, constant research and development efforts focused on improving renewable energy generation technologies, energy storage systems, and data analytics abilities will more improve the efficiency, reliability, and flexibility of future smart grid implementations, paving the way for a more sustainable and resilient energy future.

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