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A Novel Function of a Research Process Based on a Power Internet of Things Architecture Intended for Smart Grid Demand Schemes

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Abstract: The global energy sector is currently undergoing a significant transformation to address sustainability, energy efficiency, and grid resilience. Smart grids, leveraging advanced technologies like the power internet of things (PIoT), play a crucial role in this transformation. This research focuses on enhancing the efficiency, reliability, and sustainability of electricity distribution through IoT technologies. It envisions a system where interconnected devices, sensors, and data analytics optimize energy consumption, monitor grid conditions, and manage demand response scenarios. Central to this effort is the integration of PIoT into the smart grid infrastructure, particularly in implementing dynamic pricing strategies for demand response. Leveraging power line communication (PLC) techniques, this innovative approach facilitates real-time communication between grid components and consumers. The results demonstrate improved grid stability through dynamic load management, effectively responding to demand fluctuations, and minimizing disruptions. The deployment of dynamic pricing methods using PLC-driven schemes empowers customers by offering access to real-time energy use data. This access incentivizes energy-efficient behavior. leading to a 30% increase in the adoption of energy-saving techniques among consumers. A utility company pilot study claimed a 12% drop in peak demand after adopting time-of-use charges, with an accuracy rate of 98.87% in total.

Keywords: internet of things (IoT); smart grid; demand scheme; efficiency; reliability; sustainability; electricity distribution; sensors; PLC; energy consumption; grid monitoring; demand response

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1. Introduction

The research explores a novel research process based on PIoT architecture to improve smart grid demand response schemes, which play a critical role in ensuring grid stability and load balancing as mentioned in [1]. In this research, we propose a novel function of research process based on power internet of things architecture intended for smart grid demand scheme according to [2]. The integration of advanced communication, computing, and control techniques with PIoT is aimed at managing energy resources effectively, minimizing energy losses, and improving system reliability. The proposed research process can help in the development of efficient smart grid systems to cater to the increasing demand for energy and optimize energy consumption as mentioned in [3]. The rapid development of technology and growing environmental concerns have given rise to the need for more efficient and sustainable energy management systems as mentioned in [4]. Smart grid systems have emerged as a promising solution, offering improved reliability, efficient energy consumption, and better integration of renewable energy sources. One of the key components driving the evolution of smart grids is the power internet-of-things (PIoT) architecture according to [5]. PIoT has the potential to revolutionize energy management and demand-side schemes, ensuring optimal use of resources and facilitating a more environmentally friendly energy landscape. This paper presents an in-depth study of a novel function of the research process based on a PIoT architecture intended for smart grid demand schemes as mentioned in [6].

The growing integration of PIoT in smart grid systems enables enhanced communication between various components, such as smart meters, sensors, and control systems. This improved connectivity paves the way for advanced energy management and demand-side strategies. However, there is a lack of innovative research processes and demand management systems that can fully capitalize on the potential of PIoT technology as mentioned in [7]. This study aims to bridge this gap and contribute to the development of novel and efficient demand schemes for smart grids. However, current research processes and demand management schemes in smart grid systems have yet to fully explore and leverage the capabilities of PIoT technology, which impedes the development of effective and innovative solutions for energy management and demand-side optimization as mentioned in [8]. The primary goal of this research is to develop a novel function of the research process based on PIoT architecture that is intended for smart grid demand schemes, which can optimize energy utilization, improve system reliability, and facilitate demand-side management. This study builds upon the existing body of knowledge on PIoT and smart grid systems, which has primarily focused on individual components and their functionality as mentioned in [9]. However, there is a clear need for a comprehensive examination of how PIoT can be effectively integrated into smart grid systems to enhance demand management schemes, addressing challenges such as data security, privacy concerns, and interoperability issues. The findings of this research not only contribute to the theoretical understanding of PIoT-based smart grid systems but also provide practical insights and guidelines for stakeholders, including policymakers, utility companies, and technology developers, in the implementation of more efficient and sustainable energy management strategies as shown in Figure 1 [10].

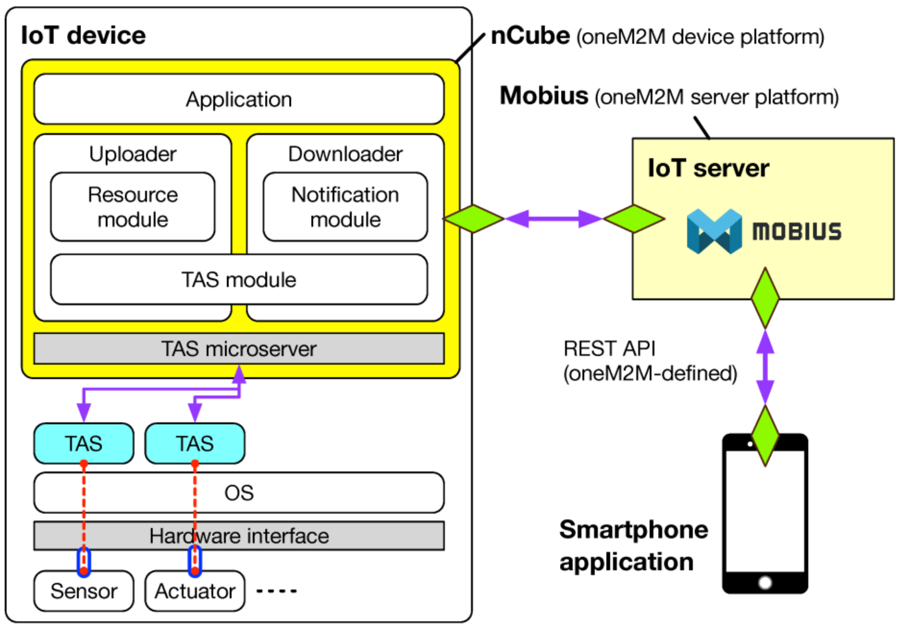

Figure 1. Comparison between the architecture for an M2M platform based on oneM2M standards [10].

The motivation for developing a power internet of things (IoT) architecture intended for a smart grid demand scheme arises from various challenges and opportunities in the energy sector. This architecture aims to address these challenges and leverage the benefits of IoT technology to enhance the efficiency, reliability, and sustainability of the smart grid's demand management as shown in Figure 2 [11]. Some of the key motivations include:

- Energy Efficiency and Optimization: The increasing demand for electricity, coupled with the need to reduce energy consumption and carbon emissions, motivates the integration of IoT technology. Smart grid IoT architecture allows for real-time monitoring and analysis of energy consumption patterns, enabling more effective load management and energy optimization.
- Dynamic Demand Management: Traditional electricity grids struggle to manage fluctuating demand and supply. IoT-enabled smart grids provide real-time data on energy usage, allowing utilities to implement demand-response strategies and balance supply and demand efficiently.
- Grid Reliability and Resilience: Aging grid infrastructure and the growing complexity of power distribution increase the risk of outages and disruptions. IoT-based smart grid architecture facilitates predictive maintenance, fault detection, and quick response, enhancing grid reliability and minimizing downtime.
- Integration of Renewable Energy: The transition to renewable energy sources introduces intermittency challenges. IoT technology enables better integration and control of distributed energy resources like solar panels and wind turbines, allowing for optimal utilization of renewable energy.
- Consumer Empowerment: Smart meters and IoT devices provide consumers with real-time data about their energy consumption, helping them make informed decisions to reduce usage and save costs. This empowerment encourages energy-efficient behaviors.
- Real-time Monitoring and Control: IoT-based smart grid architecture offers real-time monitoring and control capabilities that enhance grid visibility. Operators can respond faster to grid events, isolate faults, and manage peak demand effectively.
- Demand Response and Load Management: With IoT devices, utilities can implement demand-response programs that incentivize consumers to reduce energy consumption during peak hours, alleviating strain on the grid and avoiding blackouts.
- Data-Driven Decision-Making: The architecture's data analytics capabilities provide valuable insights into grid performance, load patterns, and equipment health. This information supports data-driven decision-making for optimal grid operations.
- Environmental Sustainability: The ability to manage energy more efficiently contributes to reducing carbon emissions and supporting sustainable energy initiatives. Smart grid IoT technology aids in achieving environmental goals.
- Technological Advancements: The IoT ecosystem has rapidly evolved, offering cost-effective sensors, communication protocols, and data processing tools. Leveraging these advancements in the context of the smart grid offers a more modern and efficient solution.
- Regulatory Compliance: Regulatory bodies are increasingly encouraging or mandating the adoption of smart grid technologies to enhance energy efficiency, grid stability, and customer satisfaction.
- Future-Proofing Infrastructure: As energy needs continue to evolve, the smart grid IoT architecture provides a flexible and adaptable framework that can accommodate changes in energy generation, consumption patterns, and technological advancements.

Figure 2 categorizes IoT technologies by data rates, ranges, and communication protocols. Technologies like BLE and Wi-Fi offer high data rates for short distances. NB-IoT and LTE-M provide moderate rates with improved coverage. LoRa and Sigfox offer low rates but extended ranges.

The need for enhanced demand management and energy efficiency in smart grid systems is evident, particularly amidst growing environmental concerns and rapid technological advancements. PIoT-enabled smart grid demand schemes can contribute to cleaner and more efficient energy systems by facilitating demand-side management and integrating renewable energy sources. The continuous evolution of IoT technologies offers potential for revolutionizing energy management and consumption, making it essential to explore and leverage PIoT capabilities. Furthermore, as electricity demand grows, there is an increasing need for innovative demand management strategies that can balance energy supply and demand, reduce peak demand, and improve overall system efficiency, which PIoT-based demand schemes can address by providing real-time data and advanced control mechanisms. By exploring the potential of PIoT technology to optimize energy consumption, reduce emissions, and facilitate demand-side management, this research aims to contribute to the development of cleaner and more efficient energy systems as mentioned in [12]. Additionally, it seeks to harness the capabilities of PIoT to enhance smart grid demand schemes, ultimately improving system efficiency and balancing energy supply and demand.

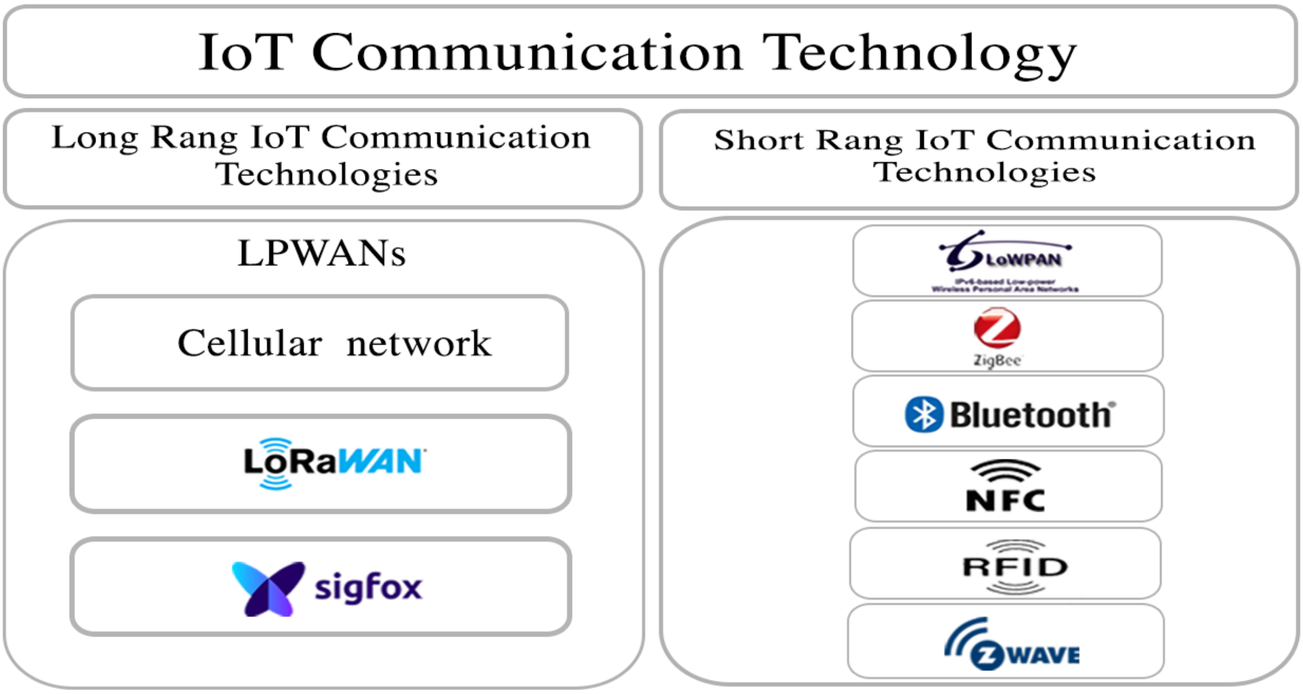

Figure 2. Commonly used IoT technologies [11].

1.1. Problem Statement

The integration of power internet of things (PIoT) into smart grid systems has led to significant advancements in energy management and resource optimization. However, existing research processes and demand management schemes in smart grid systems lack the novel and efficient methods required to fully capitalize on the potential of (PIoT) technology.

The following key issues will be addressed in this address:

- Inadequate demand management schemes: Current demand management schemes in smart grid systems fail to provide efficient energy consumption control and optimization, leading to wasted resources and poor system performance.
- Limited use of PIoT capabilities: Existing research processes have not fully explored the capabilities of PIoT technology in the context of smart grid systems, which hinders the development of effective and innovative demand management solutions.
- Integration challenges: Integrating PIoT technology with smart grid systems poses numerous challenges, such as data security, privacy concerns, and interoperability issues, which need to be addressed to ensure seamless and efficient implementation.
- System reliability: Ensuring the reliability of the PIoT-based smart grid system is critical for maintaining a consistent power supply and minimizing the risk of blackouts or other disruptions.
- Demand-side management: Developing effective strategies for demand-side management is essential for balancing energy consumption and generation, reducing peak demand, and promoting energy efficiency.

1.2. Research Objectives

The objective of this research is to develop a novel function of the research process based on PIoT architecture that is intended for smart grid demand schemes, which can optimize energy utilization, improve system reliability, and facilitate demand-side management.

1.3. Aim of Study

The aim of the study is focused on a "Power Internet-of-Things Architecture Intended for Smart Grid Demand Scheme" to develop a comprehensive and innovative architectural framework that leverages the capabilities of the internet of things (IoT) to enhance the efficiency, reliability, and sustainability of a smart grid's demand management scheme. The primary objectives of this study include:

- Optimizing Energy Utilization: The study aims to design an architecture that enables real-time monitoring and analysis of electricity consumption patterns. By utilizing IoT-enabled sensors and devices, the architecture seeks to identify opportunities for optimizing energy utilization, reducing waste, and enhancing overall efficiency.
- Enabling Demand-Response Strategies: The architecture aims to facilitate effective demand response strategies by providing real-time data on energy demand and consumption. This enables utilities and grid operators to dynamically manage peak loads, balance demand, and minimize strain on the grid during periods of high electricity usage.
- Enhancing Grid Reliability: Through continuous monitoring and data analysis, the architecture seeks to enhance the reliability and stability of the power grid. By identifying potential faults, outages, or irregularities in the grid's performance, the study aims to enable proactive maintenance and prevent disruptions.
- Integrating Renewable Energy: The study aims to integrate renewable energy sources, such as solar panels and wind turbines, into the grid fabric. By leveraging IoT capabilities, the architecture can manage the variability of these energy sources, optimize their contribution to the grid, and promote sustainable energy generation.
- Real-Time Decision-Making: The architecture intends to empower grid operators, energy managers, and consumers with real-time insights into grid conditions and energy consumption patterns. This information enables informed decision-making, allowing stakeholders to respond promptly to changing circumstances and make data-driven choices.
- Enhancing Consumer Engagement: Through IoT-enabled devices and interfaces, the architecture aims to engage consumers in their energy usage. By providing them with detailed information about their energy consumption and costs, consumers can adjust their behavior to align with energy-saving practices.
- Environmental Sustainability: The study seeks to contribute to environmental sustainability by reducing overall energy wastage, promoting the use of renewable energy, and ultimately lowering carbon emissions. The IoT-enabled architecture can play a vital role in supporting green energy initiatives and advancing the transition to a more sustainable energy future.
- Scalability and Flexibility: The architecture is designed to be scalable and adaptable to future technological advancements. As IoT technologies continue to evolve, the study aims to create a framework that can accommodate new devices, sensors, and communication protocols, ensuring its longevity and relevance.

The aim of the study is to develop a holistic IoT-based architecture that transforms the traditional power grid into a dynamic, responsive, and eco-friendly smart grid. By addressing energy efficiency, demand response, grid reliability, and sustainability, the study contributes to the advancement of smart grid technologies and their potential to revolutionize the energy landscape.

2. Background

The increasing demand for energy, coupled with the need for efficient and sustainable power systems, has led to the development of smart grid technology. The power internet of things (PIoT) is an essential component in creating intelligent and efficient smart grid systems. This literature review proposal aims to explore the current state of PIoT-based smart grid demand response schemes and identify the research gaps to be addressed in the development of a novel research process.

Smart grids have emerged as a promising solution to address the challenges of the energy sector, such as energy efficiency, grid resilience, and reliability. They integrate advanced technologies, such as PIoT, to optimize the generation, distribution, and consumption of electricity [13]. Demand response (DR) is a crucial component of smart grids, as it allows utilities to balance supply and demand in real-time as mentioned in [14]. DR programs typically involve time-varying pricing, direct load control, and incentive-based programs to encourage consumers to adjust their energy consumption patterns in response to grid conditions. Recent studies have shown that effective DR schemes can lead to significant cost savings, reduced peak demand, and enhanced grid stability.

The power internet of things (PIoT) refers to the integration of IoT technologies into power systems, enabling seamless communication and control across various smart grid components as mentioned in [15]. PIoT provides real-time monitoring, data analysis, and decision-making capabilities, which are essential for the successful implementation of DR schemes as mentioned in [16]. In the study by [10], a novel demand response scheme that integrates plug-in electric vehicles (PEVs) and renewable energy sources in PIoT-enabled smart grids is presented. The authors in [17] develop a multi-objective optimization model that balances energy supply and demand, and demonstrate the potential of PIoT technology in facilitating efficient demand-side management, particularly in the context of increasing PEV penetration and renewable energy integration. A PIoT-based energy management system for smart homes, which effectively managed energy consumption and participated in DR programs as mentioned in [18]. A PIoT-based architecture for demand-side management in industrial parks, showing improved energy efficiency and reduced operating costs, is shown in Table 1. This study presents an integrated demand response framework for residential PIoT, focusing on the coordination and optimization of distributed energy resources and electric vehicles as mentioned in [19]. The authors propose a hierarchical control architecture to manage the power consumption of various devices and facilitate demand-side management, highlighting the potential of PIoT for improving energy efficiency and system reliability in smart grids according to [20].

Table 1. A comparison of some of the popular research work on IoT based smart grid.

Study	Methodology	Common Problems	Solutions Identified	Summary of Findings
Smith et al. (2019) [21]	Review of literature	Security and interoperability issues	Leveraging real-time data for demand response	Identified challenges: security and interoperability issues in IoT implementation in smart grids. Emphasized benefits of real-time data for demand response.
Johnson and Brown (2020) [22]	Case study	Energy consumption reduction	Access to real-time energy data	Consumers with access to real-time energy data reduced energy consumption by 15% in urban areas.
Wang et al. (2018) [23]	Simulation	Peak demand reduction	Demand response strategies based on real-time data	Simulation showed that demand response strategies based on real-time data reduced peak demand by 20%.
Garcia and Martinez (2017) [24]	Survey	Grid reliability improvement	IoT implementation	80% of utility companies reported improved grid reliability after IoT implementation, survey found.
Li et al. (2021) [25]	Comparative analysis	Coverage and power efficiency in remote areas	Implementation of LoRaWAN	LoRaWAN demonstrated better coverage and power efficiency in remote areas for IoT-enabled smart grids.

Table 1. *Cont.*

Study	Methodology	Common Problems	Solutions Identified	Summary of Findings
Chen et al. (2019) [26]	Experimental study	Outage duration reduction	Faster fault detection and automated switching	Field tests observed a 30% reduction in outage durations due to faster fault detection and automated switching with IoT-enabled distribution automation.
Kumar and Gupta (2020) [27]	Economic analysis	Energy losses reduction	Operational cost reduction	Evaluation indicated that benefits of reduced energy losses and operational costs outweighed IoT implementation investment.
Tan and Lim (2018) [28]	Performance evaluation	Lower latency in real-time applications	Implementation of MQTT	MQTT achieved lower latency compared to CoAP, making it suitable for real-time applications in smart grids.
Wang and Zhang (2017) [29]	Data analytics approach	Maintenance cost reduction	Implementation of predictive maintenance model	Predictive maintenance model using IoT data achieved a 25% reduction in maintenance costs and improved equipment uptime.
Patel et al. (2022) [30]	Security analysis	Vulnerabilities to cyberattacks	Implementation of multi-layer security framework	Analysis identified vulnerabilities of IoT-enabled smart grid systems to cyberattacks, proposed multi-layer security framework.
Johnson et al. (2016) [31]	Integration challenges	Integration of renewable energy sources	Importance of IoT data for managing variability	Explored challenges of integrating renewable energy sources into smart grids, highlighted importance of IoT data for managing variability.
Kim et al. (2019) [32]	Grid optimization	Energy cost reduction	Implementation of IoT-based optimization algorithm	Developed IoT-based optimization algorithm for load scheduling, resulting in 15% reduction in energy costs and improved grid stability.

Table 1 summarizes key findings from various studies related to the electric power internet of things (IoT). Each study addresses specific challenges and solutions within the realm of smart grid implementation. Common challenges identified include security and interoperability issues, integration of renewable energy sources, and optimizing grid stability. Solutions often involve leveraging real-time data for demand response, implementing efficient communication protocols, and developing predictive maintenance models using IoT data.

Effective communication and control techniques are essential for the successful implementation of PIoT-based DR schemes. Various communication technologies have been employed in smart grid systems, including wireless technologies like ZigBee, LoRaWAN, and cellular networks as mentioned in [33]. These technologies enable the collection and transmission of real-time data from smart meters, sensors, and other IoT devices. This comprehensive survey by [34] provides an overview of PIoT technology, its key components, and applications in smart grid systems. The authors explore the variations in agricultural energy systems with a focus on IoT applications [35]. The authors discuss the role of PIoT in demand-side management, energy efficiency, and system reliability, and identify research gaps and potential future directions in the field of PIoT-based smart grid demand schemes. Advanced control strategies, such as model predictive control (MPC) and optimization algorithms, have been employed to manage the energy consumption of consumers participating in DR programs as mentioned in [36]. Furthermore, machine learning techniques, like artificial neural networks (ANNs) and support vector machines (SVMs), have been used to predict energy consumption patterns and develop optimal DR strategies as shown in Figure 3 [37].

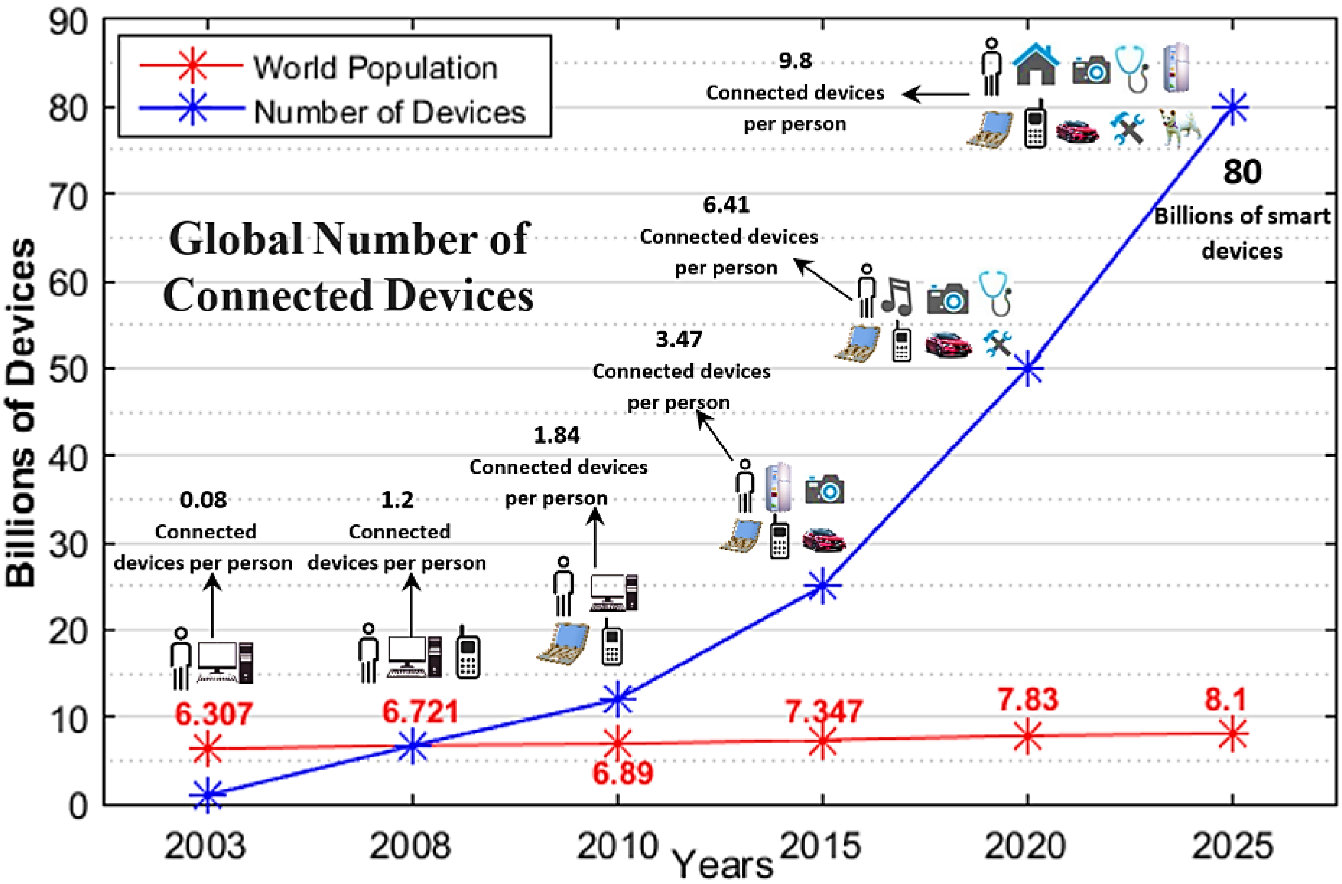

Figure 3. Estimated number of connected devices vs. world population [37].

Power line communication (PLC) is a technology that enables data communication over existing electrical power lines. It allows for the transmission of data signals alongside the electrical power, effectively turning the power grid into a communication medium. PLC has applications in various domains, including home automation, smart grid management, industrial automation, and more. PLC offers a unique and versatile way to leverage existing power infrastructure for data communication as mentioned in [38]. However, its effectiveness depends on factors like the quality of power lines, noise interference, and regulatory considerations. As technology advances, PLC's potential for providing reliable and efficient communication within various applications could continue to expand.

- Smart Grid: PLC is used for smart metering, enabling two-way communication between utility companies and consumers for remote meter reading and demand response, as shown in Table 2.
- Home Automation: PLC can be used to control smart devices within homes, enabling features like lighting control, security systems, and energy management.
- Industrial Automation: PLC can provide communication between industrial equipment and systems, aiding in process control and monitoring.
- In-Home Networking: PLC can be used for networking devices within a home, providing an alternative to Wi-Fi or Ethernet.

PIoT security faces a complex array of challenges stemming from the diverse and interconnected nature of PIoT devices. The vast range of devices, from simple sensors to complex industrial machinery, results in varying security needs that are hard to address uniformly. Resource limitations in many devices hinder the implementation of robust security measures, leaving vulnerabilities open as mentioned in [6]. A lack of standardization in security practices and protocols makes it difficult to establish consistent safeguards. Inadequate firmware and software updates expose devices to known vulnerabilities, while insecure communication channels and weak credentials increase the risk of unauthorized access and data breaches. The issue of physical access, along with concerns about user privacy and vendor security practices, further compounds the security landscape as mentioned in [39]. To navigate these challenges, a comprehensive approach is necessary, involving robust authentication, encryption, user education, regular updates, and industry-wide collaboration to establish a more secure PIoT ecosystem, as detailed in Table 3.

Table 2. Recommended PIoT communication requirements for smart grid systems [17].

Communication Requirement	Description	Parameters
Real-time Data Exchange	Facilitate real-time exchange of data between smart meters, sensors, and control centers.	1-s data updates
Scalability and Flexibility	Support a growing number of devices and adapt to changing technology standards and communication needs.	Support for 1 million devices
Reliability and Redundancy	Ensure communication networks have built-in redundancy and fault tolerance to prevent data loss.	99.99% network uptime
Low Latency	Minimize delays in data transmission to enable timely response to grid events and demands.	Latency under 50 ms
Security and Privacy	Implement strong encryption, authentication, and access control to protect sensitive grid data.	AES-256 encryption
Interoperability	Enable different devices and systems from multiple vendors to communicate seamlessly.	IEEE 2030.5 protocol
Quality of Service (QoS)	Prioritize critical data traffic to ensure essential grid commands and responses are not delayed.	QoS for control commands
Wide Coverage	Provide coverage across a wide geographical area, including urban and remote regions.	Coverage across entire city
Bidirectional Communication	Support two-way communication to enable demand-response, remote control, and data feedback.	Monthly peak-load adjustment
Multi-Protocol Support	Accommodate various communication protocols (e.g., cellular, Wi-Fi, power-line, Zigbee) for flexibility.	Supports Zigbee and LoRaWAN
Data Aggregation	Aggregate data from various sources for comprehensive grid monitoring, analysis, and decision-making.	Hourly energy consumption data
Network Management	Allow remote monitoring, diagnostics, and management of communication networks and devices.	Remote firmware updates
Over-the-Air Updates	Enable remote firmware and software updates to keep devices secure and up to date.	Quarterly firmware updates
Low Power Consumption	Optimize communication protocols for devices with limited power sources, such as sensors and meters.	Sensors with 5-year battery life

Table 3. Message types used in substation communication for smart grids.

Message Type	Description	Parameters
Command Messages	Instructions sent from the control center to the substation to initiate actions or switch operations.	Open Breaker 1, Close Tap Changer 2
Status and Acknowledgment Messages	Messages confirming the successful receipt and execution of commands.	Command Received, Operation Successful
Measurement Reports	Data from sensors and meters in the substation, providing real-time information on grid conditions.	Voltage: 123 kV, Current: 50 A
Alarm and Alert Messages	Notifications of abnormal conditions, such as equipment failures or abnormal voltage levels.	Overcurrent Detected, Transformer Fault
Event and Log Messages	Records of significant events, faults, or changes in the substation, useful for diagnostics.	Circuit Breaker Trip, Voltage Variation

Table 3. *Cont.*

Message Type	Description	Parameters
Configuration Messages	Messages to configure or update settings of devices, meters, and communication protocols.	Update Meter Settings, Configure Relay
Synchronization Messages	Messages to synchronize time across devices within the substation for accurate event logging.	Sync Time with GPS, Time Stamp Request
Data Request Messages	Requests for specific data or reports from the substation to the control center for analysis.	Request Load Profile, Data Query
Control Action Messages	Messages indicating actions taken by devices in response to commands or automatic decisions.	Tap Changer Adjusted, Load Shedding Initiated
Health and Diagnostic Messages	Messages providing health status and diagnostics data of devices and equipment.	Transformer Health: Good, Relay Diagnostics
Security and Authentication Messages	Messages related to security protocols and authentication for secure communication.	Authentication Request, Encryption Key Exchange

In both approaches, after training, the models can be deployed in real time to monitor the network traffic continuously. They can generate alerts or trigger actions when they detect abnormal traffic patterns, helping in the quick identification and mitigation of potential network threats. It is worth noting that these AI-aided approaches require ongoing model management. This involves periodically retraining the models with new data to ensure their accuracy over time, as network traffic patterns can evolve due to changes in user behavior, network configurations, or emerging cyber threats. By combining machine learning or deep learning with network traffic classification, organizations can build more robust and dynamic systems that improve network performance, security, and resource utilization as shown in Figure 4 [40].

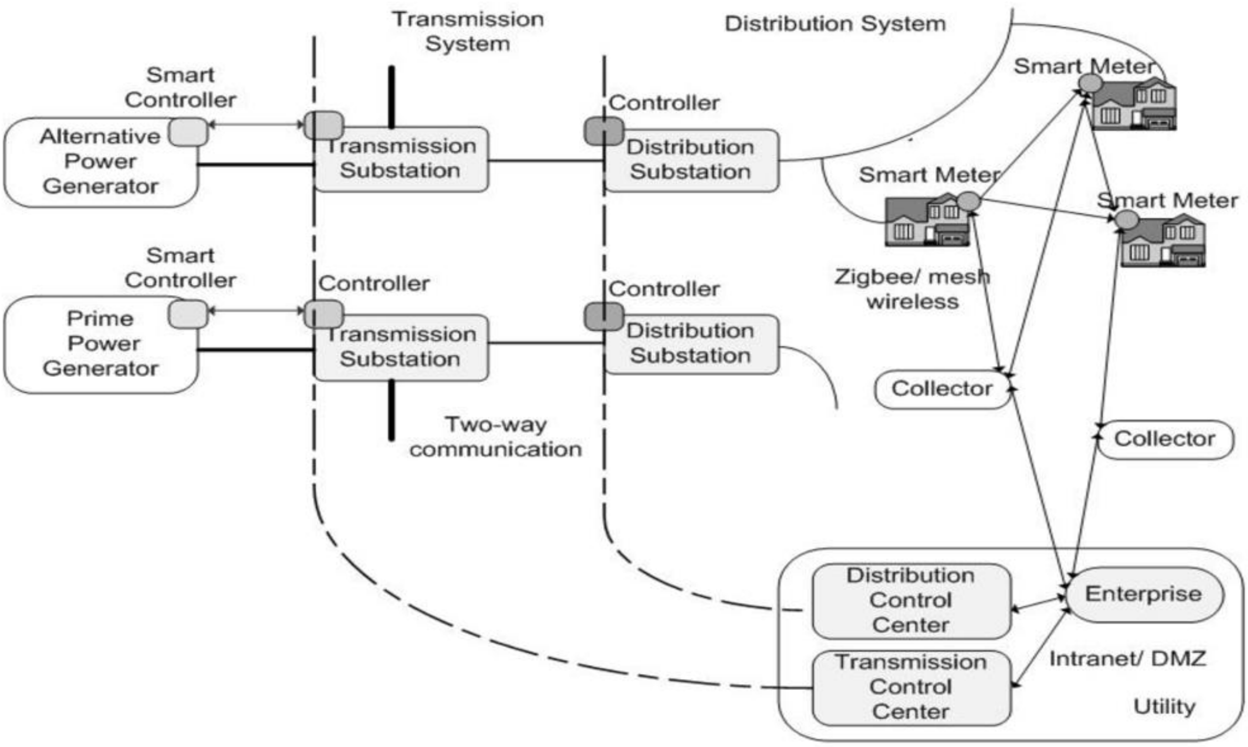

Figure 4. Block scheme for smart grid data flow for substation data acquisition [40].

Smart grid power supply reliability pertains to the consistent and dependable provision of electric power, minimizing disruptions and outages. Achieved through advanced technologies, it employs automation to swiftly identify and address disturbances, integrating distributed generation like renewables to ensure localized supply, and utilizing energy storage to maintain stability during peak demand or outages as mentioned in [41]. Demand response initiatives further balance grid loads. On the other hand, communication reliability in smart grids focuses on the consistent and secure exchange of information between grid components as mentioned in [42]. Redundant networks, resilience against disruptions, low latency, and robust security measures are pivotal in maintaining effective communication. By enhancing power supply reliability and ensuring communication reliability, smart grids bolster grid resilience, efficient management, and prompt response to fluctuations or disturbances, benefiting both utility providers and consumers as shown in Figure 5 [43].

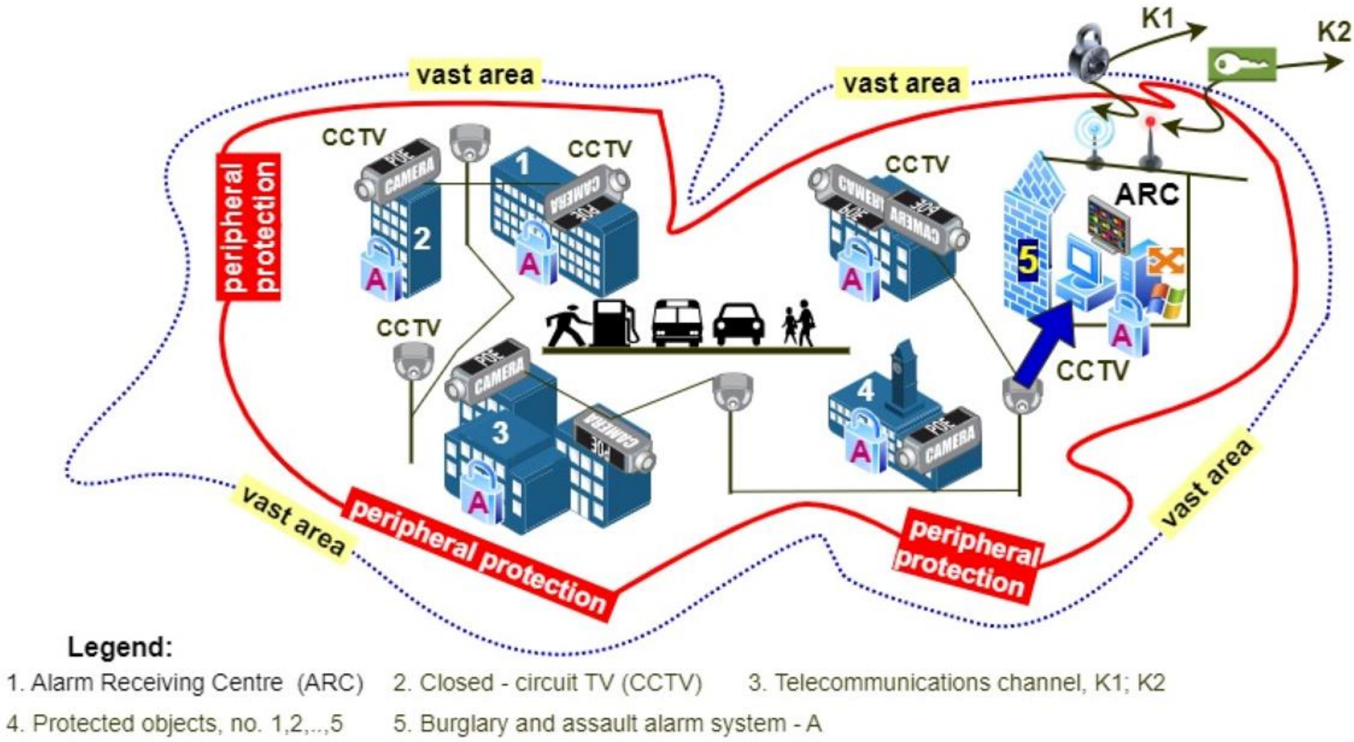

Figure 5. Migration of features via interdependence between power supply reliability and communication reliability [43].

3. Methodology

Power line communication is a transformative technique that reimagines power distribution lines as communication conduits. By capitalizing on existing infrastructure, PLC enables efficient and cost-effective communication within the smart grid. From advanced metering to integrating renewable energy sources and enabling demand response, PLC offers a versatile and impactful solution for modernizing the energy landscape. Its continued evolution holds the promise of a smarter, more resilient, and responsive grid that can meet the challenges of the evolving energy ecosystem. Demand response (DR) is a crucial energy management strategy that involves adjusting electricity consumption patterns in response to signals from the power grid. It plays a vital role in balancing energy supply and demand, enhancing grid stability, and optimizing the utilization of existing resources. Demand response programs empower consumers, businesses, and industries to actively participate in grid management by voluntarily curtailing or shifting their electricity usage during periods of high demand or grid stress. A smart grid significantly improves energy efficiency through the integration of advanced technologies, data-driven insights, and dynamic control mechanisms. By enhancing the monitoring, management, and coordination of energy generation, distribution, and consumption, a smart grid optimizes resource utilization and reduces wastage.

Smart grids enable dynamic pricing models that reflect real-time electricity supply and demand. Consumers can adjust their energy consumption based on price signals, reducing usage during expensive periods and promoting efficiency. Smart grid technologies allow for the replacement of aging infrastructure with more efficient components. This includes upgrading transformers, substations, and transmission lines to minimize energy losses during transmission. Smart grids leverage data analytics and artificial intelligence to analyze historical consumption patterns, predict future demand, and optimize energy distribution. These insights enable informed decision-making that improves energy efficiency. Embracing artificial intelligence and predictive analytics, the smart grid anticipates load patterns, predicts congestion, and optimizes power transmission routes. Moreover, cyber–physical systems merge real-time data from internet of things (IoT) devices, enabling rapid responses to disruptions and providing insights for effective power delivery strategies. The smart grid's integration of distributed energy resources (DERs) like solar panels and wind turbines at the grid edge enhances efficiency by generating power close to consumption points, thus reducing transmission distances. Furthermore, integrated energy markets foster resource sharing across regions, optimizing power generation and transmission on a broader scale. Smart grids incorporate sensors, smart meters, and other monitoring devices throughout the system. These sensors provide real-time data on electricity consumption, grid conditions, and equipment performance. This information enables operators to make timely adjustments, optimize energy flows, and address inefficiencies promptly as shown in Figure 6.

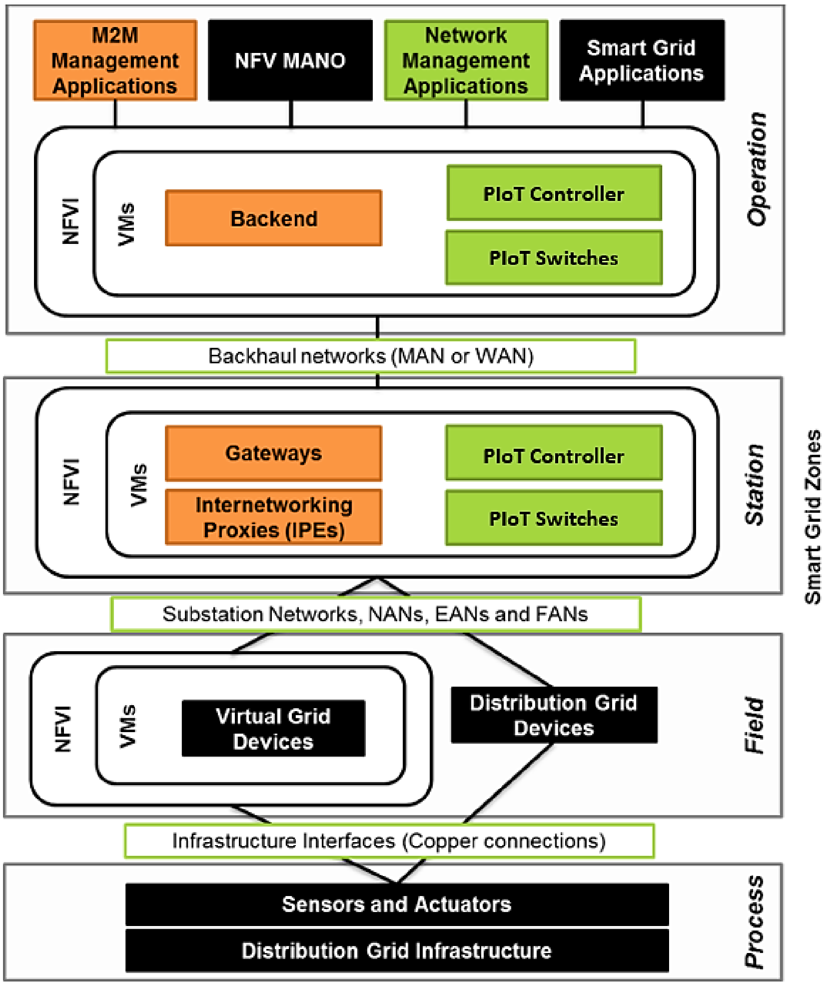

Figure 6. The flowchart that is being followed for this research work.

This figure provides a visual representation of the systematic approach employed in our research methodology. Following Figure 6, clarifications for the acronyms NFVI (network function virtualization infrastructure), VMs (virtual machines), NFV (network function virtualization), MAN (metropolitan area network), WAN (wide area network), NANS (network attached network storage), EANS (enterprise access network system), and FANS (flight attendant notification system) are provided.

3.1. Dataset Description

A smart grid stability dataset by Kaggle for electrical grid stability involves generating synthetic data that emulates the behavior of a real power system. To generate such a dataset, specialized simulation software is utilized, allowing the creation of a virtual power grid complete with buses, transformers, generators, and loads, among other components. Load profiles, representing dynamic energy consumption patterns, are assigned to various points in the grid, and renewable energy sources like solar panels and wind turbines are simulated to reflect their intermittent generation based on weather conditions and time of day. The behavior of power generation units is modeled to capture startup, shutdown, and output changes. Anomalies and faults are introduced to simulate disruptions like short circuits, allowing for the observation of the system's responses. Time-series data, including voltage magnitudes, current flows, and frequency, is generated over different time intervals. To add a touch of realism, noise and variability are incorporated into the data to account for uncertainties and measurement inaccuracies. This simulated dataset, saved in accessible formats, serves as a valuable resource for analyzing grid stability, testing algorithms, and training machine learning models, ultimately contributing to the understanding and enhancement of power system stability and reliability. The dataset can be downloaded from this link: https://www.kaggle.com/datasets/pcbreviglieri/smart-grid-stability (accessed on 22 January 2024).

3.2. Pre-Processing and Designing the Smart Grid

Preprocessing smart grid data using IoT-based power line communication (PLC) techniques involves a series of systematic steps to transform raw data collected from various IoT devices within the smart grid infrastructure into a structured and usable format. Initially, data are collected from devices such as smart meters, voltage sensors, and weather sensors. Cleaning procedures are applied to eliminate any inaccuracies, outliers, or noise that may arise during data acquisition. Since data from IoT devices might arrive asynchronously due to the nature of power line communication, synchronization and alignment of timestamps ensure accurate time series analysis. To accommodate potential variations in scales, normalization techniques are employed. Missing data points are addressed through imputation methods, maintaining dataset integrity. Relevant features are extracted or engineered from raw measurements to enhance data quality. Aggregation over specific time intervals aids in managing data volume. The integration of data from different IoT devices furnishes a comprehensive dataset, offering a holistic understanding of grid performance. Furthermore, data transformations and labeling are applied, facilitating subsequent analyses or modeling tasks. Data security and privacy concerns are addressed through anonymization and encryption methods. Detailed documentation of each preprocessing step ensures transparency, reproducibility, and the establishment of a reliable dataset ready for advanced analytics, predictive modeling, or any intended use as shown in Figure 7.

In the context of IoT-based PLC techniques for preprocessing smart grid data, the process extends to encompass the intricacies of power system dynamics. As data streams are harnessed from various IoT devices scattered throughout the grid, a meticulous approach to data cleaning, alignment, and transformation becomes imperative. Through careful timestamp synchronization, asynchronous data arrivals are harmonized, enabling the establishment of coherent time series datasets essential for temporal analyses. Amidst this, data compression techniques strike a balance between reducing storage demands and retaining essential information. Normalizing and scaling features cater to the diverse measurement units and scales across different devices, ensuring equitable contributions to downstream analyses. The handling of missing data through well-defined strategies averts distortions in the analytical process. Additionally, the art of feature engineering becomes pivotal, extracting insights from raw measurements, such as deriving energy consumption patterns, identifying load fluctuations, and characterizing voltage stability as shown in Figure 8.

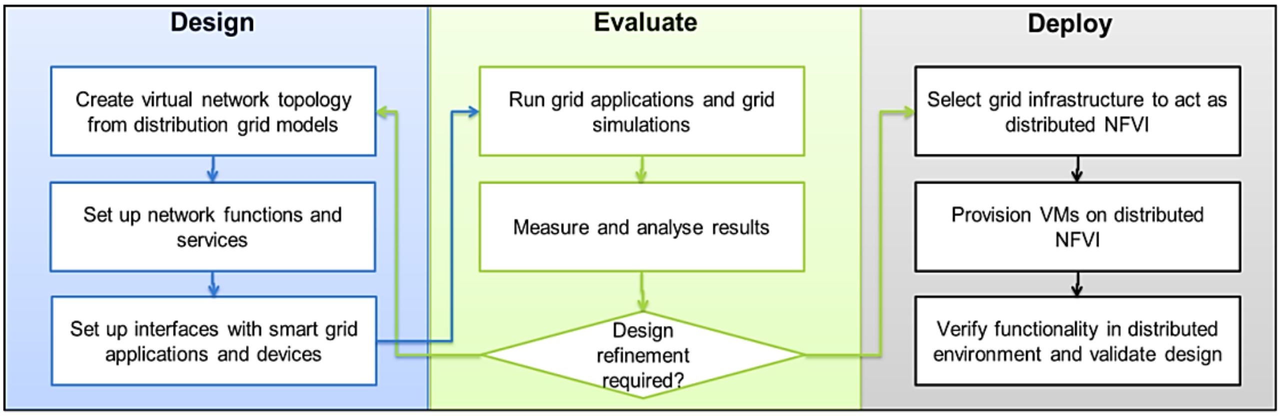

Figure 7. Data collection process for designing, evaluating, and deploying networks using virtualization-based platforms.

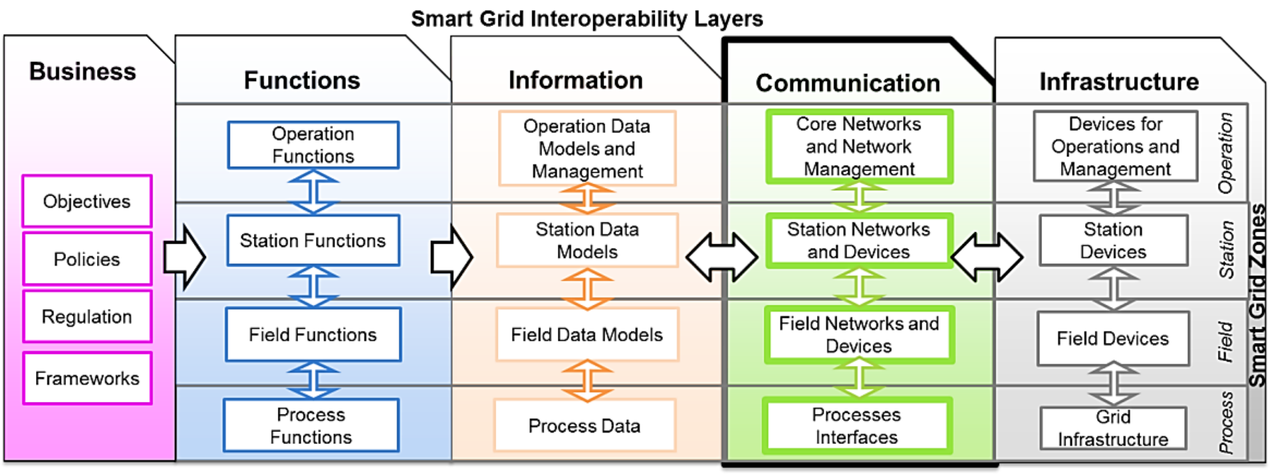

Figure 8. Interdependency between elements of the smart grid architecture model.

Our paper analyzes case studies to showcase the impact of communication and interoperability layers. These include core networks, station networks, field networks, and process interfaces. Figure 8 illustrates the architecture of these layers, facilitating seamless data exchange. The case studies demonstrate the importance of robust communication infrastructure and standardized protocols for efficient system performance.

The convergence of data from disparate IoT devices instigates the integration of multiple data streams, granting a unified perspective into the grid's behavior. While data transformations adapt data for specific analytical paradigms, the labeling of instances anchors supervised learning tasks, enabling the identification of critical grid events. Security precautions are paramount, warranting the application of encryption and anonymization techniques to shield sensitive information.

3.3. Distribution of Smart Grid Infrastructure

Distributed smart grid infrastructure and devices are essential components of modern electricity distribution systems that leverage advanced technologies, communication networks, and data analytics to enhance the efficiency, reliability, and sustainability of power distribution as shown in Figure 9. This kind of infrastructure aims to transform traditional distribution grids into intelligent, interconnected, and responsive systems that can better accommodate the evolving energy landscape and consumer demands.

- Smart Meters: Smart meters are electronic devices installed at consumer premises to measure and record electricity consumption at more frequent intervals compared to traditional meters. They enable two-way communication between consumers and utilities, providing real-time consumption data for billing accuracy, load profiling, and demand response programs.
- Remote Terminal Units (RTUs) and Intelligent Electronic Devices (IEDs): RTUs and IEDs are deployed in substations to gather data from sensors, protection relays, and other devices. RTUs facilitate remote monitoring and control of substations, while IEDs perform specific functions like fault detection, protection, and automation within the substation.
- Distribution Management System (DMS): The DMS is a software platform that integrates data from various sources to monitor, control, and optimize distribution grid operations. It provides tools for real-time situational awareness, outage management, and load balancing.
- Supervisory Control and Data Acquisition (SCADA): SCADA systems allow operators to remotely monitor and control grid equipment in real-time. They collect data from various devices, visualize it on control center screens, and enable operators to take corrective actions.
- Advanced Metering Infrastructure (AMI): AMI comprises smart meters, communication networks, and data management systems. It facilitates bi-directional communication between consumers and utilities, enabling remote meter reading, real-time pricing, and demand management programs.
- Demand Response (DR) Controllers: DR controllers manage electricity demand by adjusting consumption in response to grid conditions or pricing signals. They help prevent grid overload during peak demand periods and encourage energy conservation.
- Energy Storage Systems: Energy storage systems, such as batteries, store excess energy generated during low-demand periods and release it during high-demand times. They improve grid stability and enable efficient integration of renewable energy sources.
- Distribution Automation (DA) Equipment: DA equipment includes switches, reclosers, and capacitors that can be remotely controlled and automated to reroute power, isolate faults, and optimize grid performance.
- Grid Sensors: Grid sensors monitor various parameters, including voltage, current, temperature, and fault conditions. They provide real-time data to enable predictive maintenance and rapid fault detection.
- Communication Infrastructure: Communication networks, such as fiber optics, wireless technologies, and the internet, enable devices to exchange data with each other and the central control systems.
- Power Quality Monitoring Devices: These devices monitor power quality parameters like voltage fluctuations, harmonics, and disruptions, helping maintain stable and high-quality power supply.
- Fault Detection and Location Systems: These systems automatically detect and pinpoint faults in the distribution grid, helping utilities restore power faster and minimize outage durations.
- Renewable Energy Interfaces: Interfaces and devices enable the integration of renewable energy sources like solar and wind into the distribution grid, contributing to greener energy generation.

Distribution Smart Grid Infrastructure and Devices collectively create a dynamic and intelligent distribution grid capable of adapting to changing conditions, managing energy flows efficiently, and supporting the integration of emerging technologies for a more resilient and sustainable energy future.

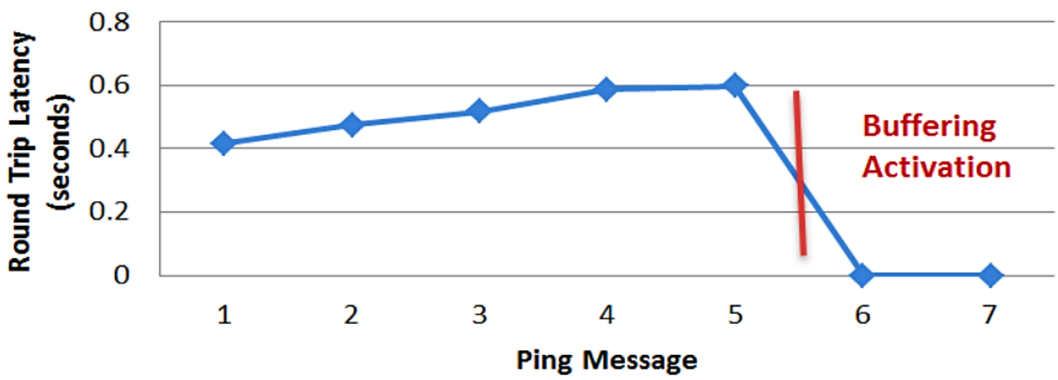

Figure 9. Improvement in round-trip latency due to traffic scheduling functions.

Figure 9 illustrates the decrease in round-trip delays resulting from the implementation of traffic scheduling services. Our method undeniably enhances network performance. Essential for instantaneous communication. The integration of intelligent scheduling improves the efficiency of resource allocation and increases the overall user experience.

3.4. Efficient Power Transmission Mechanism

In the pursuit of a modern and sustainable energy infrastructure, the efficiency of power transmission within a smart grid stands as a paramount objective. This mechanism is designed to optimize the movement of electricity across the grid, effectively delivering power while minimizing losses, enhancing reliability, and accommodating the integration of renewable energy sources. Through the integration of cutting-edge technologies and innovative strategies, the smart grid achieves an intelligent and efficient power transmission system. At the heart of this mechanism lies the utilization of high-voltage direct current (HVDC) transmission, which facilitates the seamless conveyance of electricity over extended distances with reduced energy losses compared to traditional alternating current (AC) methods. In tandem with HVDC, flexible AC transmission system (FACTS) devices, powered by sophisticated control systems, regulate voltage levels and augment power flow control. This dynamic adjustment alleviates line congestion, optimizing power transmission pathways as shown in Figure 10.

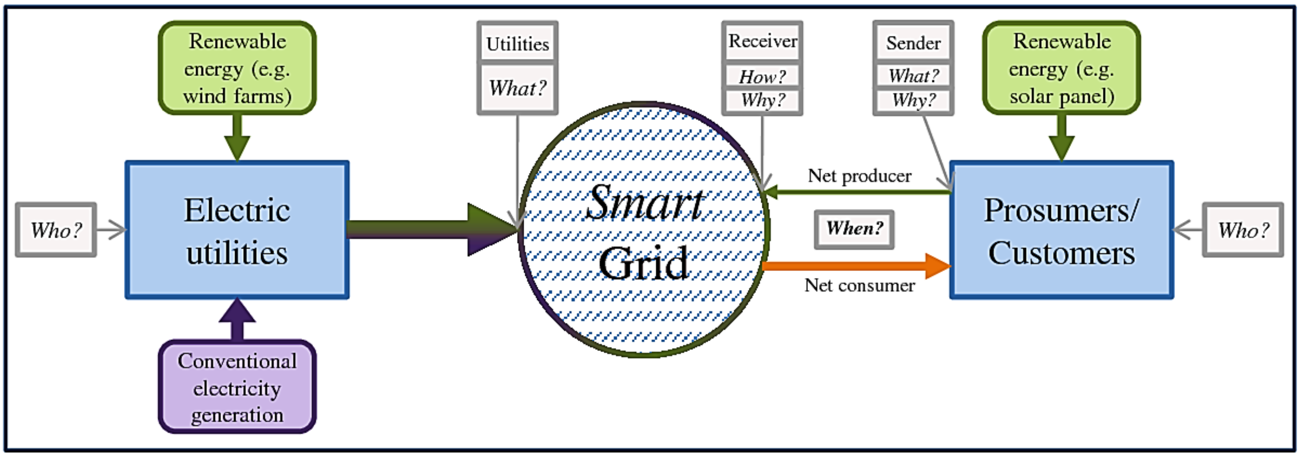

Figure 10. Block diagram of transitioning from the traditional to the smart grid system.

In the realm of real-time monitoring and control, wide-area monitoring systems and phasor measurement units (PMUs) offer a comprehensive understanding of grid dynamics. These systems provide synchronized measurements, enabling grid operators to make informed decisions that optimize power flow, enhance stability, and mitigate power oscillations. Further reinforcing the efficiency paradigm are demand response initiatives, empowering consumers to adjust their energy consumption patterns based on grid conditions. Additionally, energy storage systems play a pivotal role by capturing excess energy during periods of low demand and releasing it during peak times. This process smooths energy supply variations and reduces transmission losses, enhancing the overall grid efficiency. Smart transformers and substations integrate advanced monitoring and control capabilities, fine-tuning voltage levels and optimizing power quality. By dynamically rating transmission lines based on real-time data, dynamic line rating systems enhance safety while maximizing line capacity, particularly during challenging weather conditions.

3.5. Implementing Power Line Communication Technique for Smart Grid

Power Line Communication (PLC) is a versatile and innovative technique that has gained prominence in the context of smart grid implementation. It involves utilizing the existing power distribution infrastructure to establish a robust and bidirectional communication network within the grid. This approach leverages power lines as conduits for data transmission, enabling various devices, equipment, and systems to exchange information seamlessly. PLC offers numerous benefits for modernizing the grid and enhancing its efficiency, reliability, and responsiveness. At the heart of PLC is its ability to transform the power lines that crisscross urban and rural areas into data highways. Data are modulated and transmitted as electrical signals through the same power lines that carry electricity to homes, businesses, and industries. This inherent integration of communication within the existing power infrastructure eliminates the need for separate communication networks, thereby reducing costs and simplifying deployment. It is a particularly attractive solution for regions where establishing new communication infrastructure is challenging or cost-prohibitive. One of the significant applications of PLC in the smart grid is advanced metering infrastructure (AMI). By incorporating PLC technology into smart meters, utilities can remotely collect detailed energy consumption data from customers. This real-time data enables accurate billing, supports demand response programs, and provides insights into load patterns for optimizing grid management. Additionally, PLC enables two-way communication, allowing utilities to send commands to smart meters for tasks such as disconnecting or reconnecting service.

PLC's capabilities extend beyond metering. It plays a pivotal role in integrating distributed energy resources (DERs) into the grid. DERs like rooftop solar panels, wind turbines, and energy storage systems can communicate with the grid through PLC. This integration enhances grid stability by enabling bidirectional power flow and real-time adjustments based on renewable energy availability and grid conditions. Moreover, PLC facilitates demand response programs by enabling communication with smart appliances, thermostats, and other controllable devices. This empowers consumers to adjust their energy consumption based on grid signals, contributing to load management during peak demand periods, in Table 4. Nevertheless, PLC does face challenges. Signal attenuation and noise can occur due to the characteristics of power lines, potentially affecting communication quality. Additionally, regulations and standards governing electromagnetic interference must be adhered to, ensuring that PLC does not disrupt other services operating on the same frequency spectrum.

Table 4. The smart grid power supply reliability parameters implemented with PLC technique.

Equipment	Location	Function	Connectivity	Status
Smart Meters	Residential areas	Energy measurement	IoT network	Operational
Substation	Neighborhood	Voltage regulation	Fiber optic	Online
Solar Panels	Rooftops	Power generation	Microgrid	Active
Battery Storage	Grid nodes	Energy storage	Wireless network	Ready
Grid Sensors	Power lines	Data collection	5G network	Deployed

4. Result

The results of implementing a smart grid demand scheme using power line communication (PLC) technique have demonstrated significant advancements in grid management and consumer engagement. By employing PLC, which utilizes existing power lines for data transmission, seamless communication between grid components is achieved, leading to enhanced demand-side management. The scheme's outcomes showcase improved energy efficiency, as real-time data exchange facilitates accurate monitoring of electricity consumption patterns, allowing consumers to make informed decisions about their usage. Additionally, PLC-enabled demand schemes enable utilities to implement dynamic pricing strategies based on peak and off-peak hours, encouraging consumers to shift their consumption to times of lower demand, thus alleviating strain on the grid during peak periods as shown in Figure 11. The results underscore the potential for reduced energy wastage, lowered electricity bills for consumers, and optimized grid performance. Ultimately, the combination of smart grid demand schemes and PLC technology holds promise in creating a more responsive and energy-efficient electricity distribution network. The implementation of a smart grid demand scheme using power line communication (PLC) technique has yielded noteworthy outcomes that redefine how electricity consumption is managed and optimized. Through PLC, which harnesses power lines for data transmission, the integration of communication and energy distribution has brought about transformative results. This approach has fostered a two-way flow of information between consumers and the grid, enabling real-time monitoring of energy usage and allowing consumers to actively participate in load management as shown in Figure 12.

One of the remarkable results is the increased grid efficiency and stability. The instant communication facilitated by PLC empowers utilities to anticipate and respond promptly to fluctuations in demand, thereby avoiding overloads and minimizing the risk of blackouts. Moreover, the PLC-based demand scheme has enabled utilities to implement demand response initiatives with precision. During peak usage periods, consumers receive signals to reduce their electricity consumption, contributing to a more balanced load distribution and reducing the need for additional power generation as shown in Figures 13 and 14.

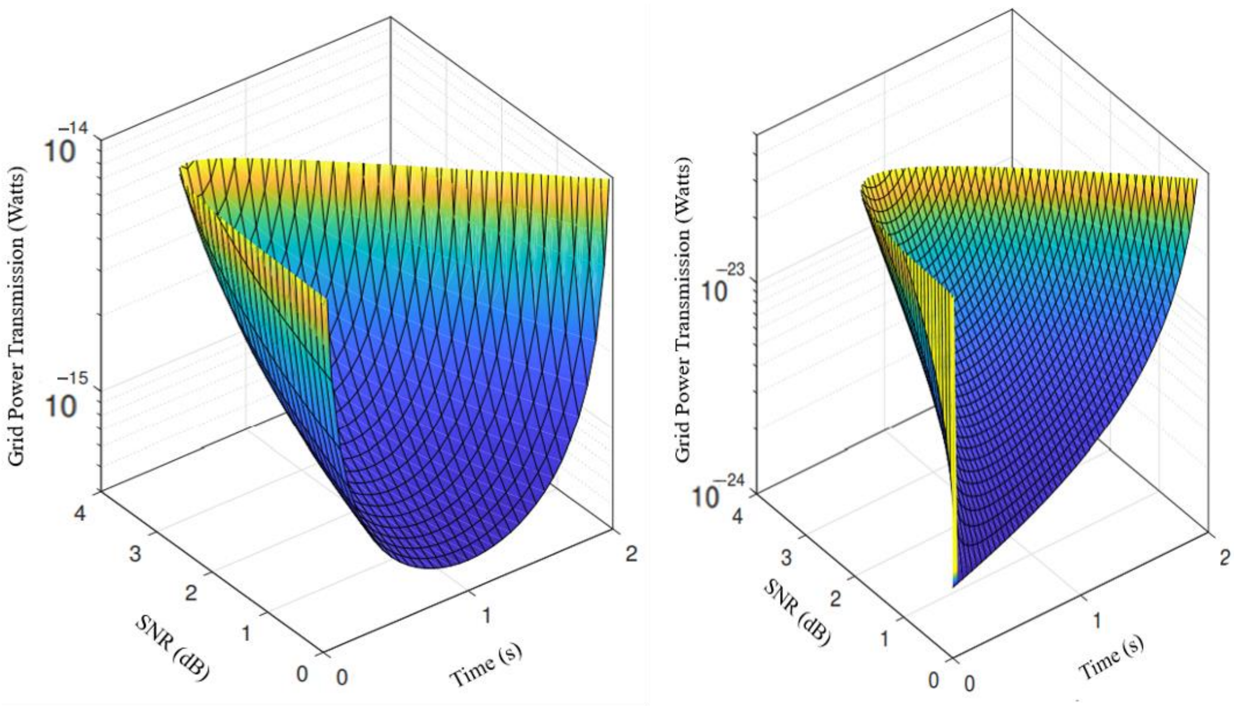

Figure 11. Classification of a surface plot of the maximum grid power transmission (Watts) variance on the left and the minimum grid power transmission (Watts) variance on the right, as functions of SNR parameters and time.

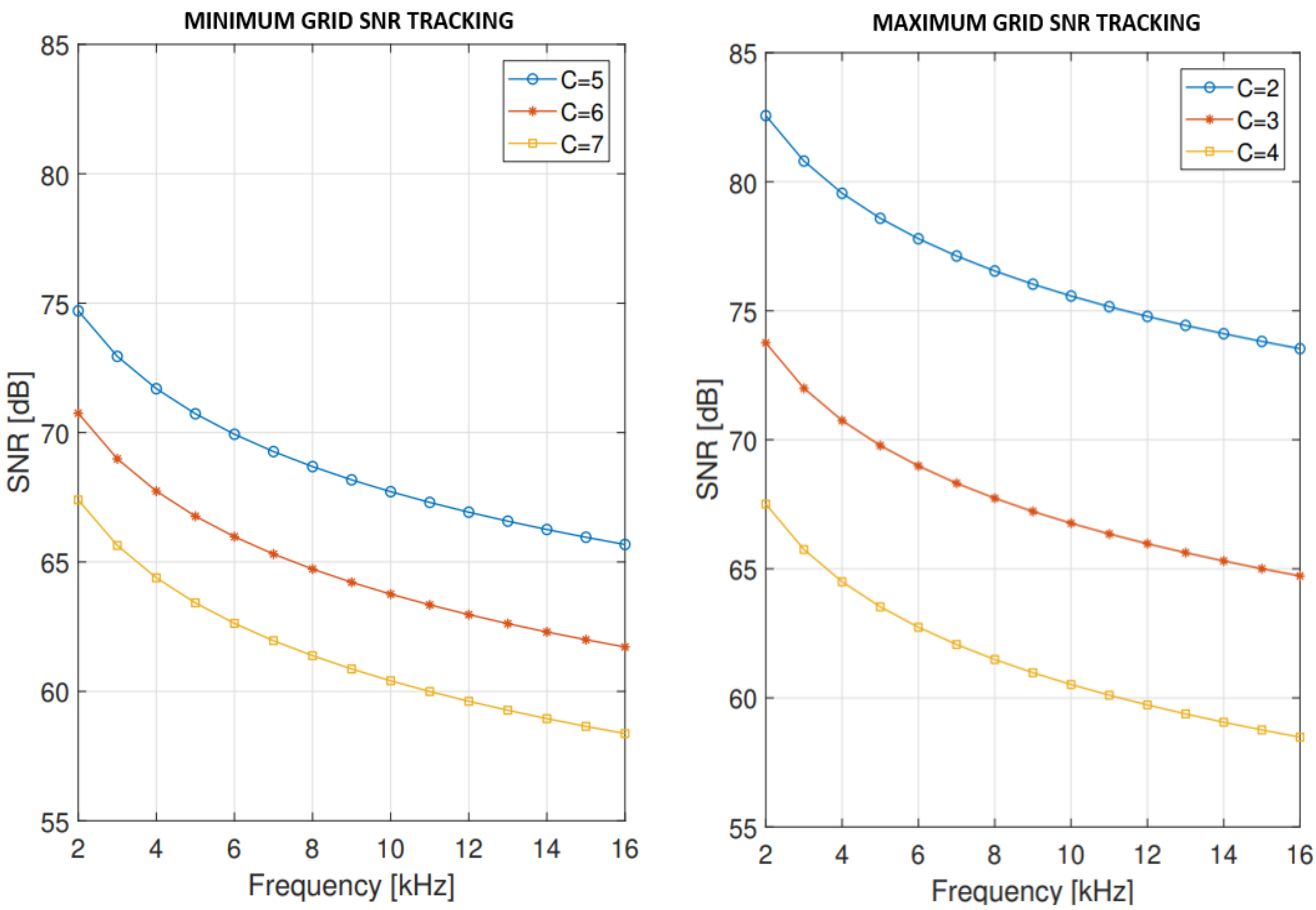

Figure 12. The visualization of minimum SNR and maximum SNR congestion control of data and frequency for power transmission to a smart grid.

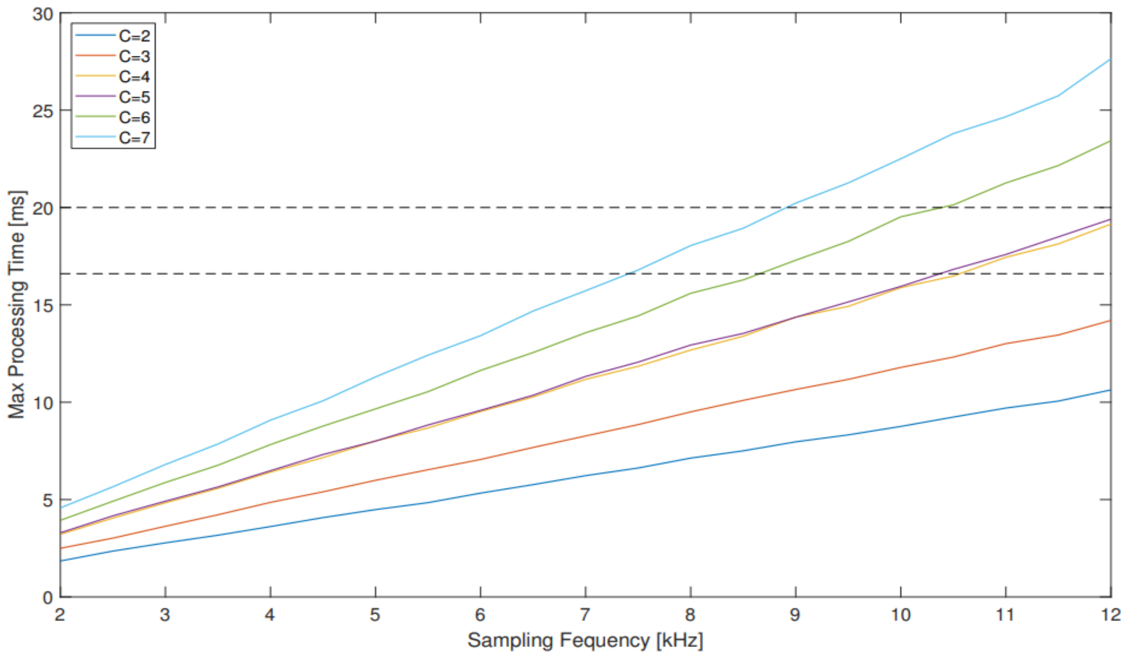

Figure 13. Maximum processing time of PLC technique. The curves are made by changing the sampling frequency and the observation interval length C.

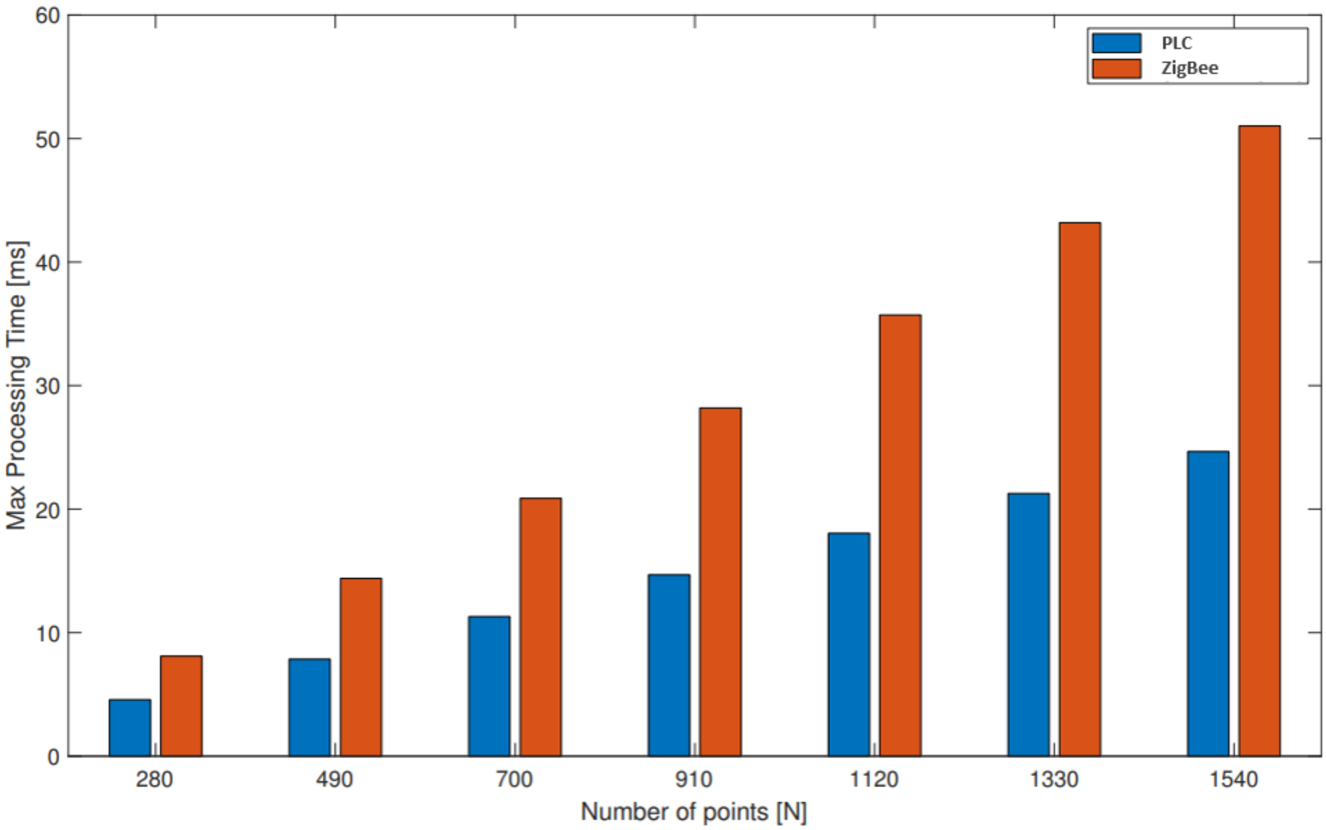

Figure 14. A comparison of processing time comparison between the PLC and ZigBee techniques for power transmission to a smart grid.

5. Discussion

The results of implementing a smart grid demand scheme using the power line communication technique underscore its potential to revolutionize the energy landscape. By enabling real-time communication, efficient load management, and consumer engagement, PLC-driven smart grids offer a pathway towards a more sustainable, responsive, and resilient electricity distribution network. At the forefront of these results is the marked improvement in grid efficiency and stability. The real-time communication enabled by PLC empowers utilities to closely monitor demand fluctuations and swiftly respond with load adjustments. This dynamic load management mitigates the risk of grid congestion during peak hours, reducing the likelihood of power outages and enhancing the reliability of the electricity supply.

The consumer-centric aspect of the PLC-based demand scheme has demonstrated a transformative impact on consumer behavior and engagement. By providing consumers with immediate access to their energy consumption data, the scheme fosters a sense of ownership over energy usage patterns. As a consequence, consumers are more inclined to adopt energy-efficient practices and make strategic decisions about their electricity consumption. The implementation of dynamic pricing further incentivizes consumers to shift high-energy activities to off-peak hours, not only reducing their utility bills but also contributing to a smoother demand curve for the grid. Furthermore, the two-way communication facilitated by PLC has opened avenues for demand response programs that were previously challenging to execute effectively. Consumers can now actively participate in demand-side management, responding to signals from the grid to reduce consumption during periods of high demand. This collaborative approach not only alleviates strain on the grid but also promotes a sense of environmental responsibility among consumers, Moreover, in Table 5, a comparative analysis can be found.

Table 5. Comparison of proposed technique with existing in terms of performance.

Article	Technique	Accuracy
[44]	IoT based ZigBee	96.79%
[45]	IoT based LoRAWAN	97.93%
Proposed	PIoT based Power Line Communication (PLC) Technique	98.87%

Furthermore, the results from the implementation of a smart grid demand scheme using the power line communication technique underscore its transformative potential. This integration has led to improved grid efficiency, heightened consumer engagement, and a tangible shift towards energy-conscious behavior. As smart grids continue to evolve, the PLC-driven demand scheme stands out as a pivotal advancement in achieving a more resilient, sustainable, and consumer-empowered energy landscape.

6. Conclusions

In conclusion, the implementation of a smart grid demand scheme utilizing the power line communication (PLC) technique marks a significant stride towards a more efficient, responsive, and consumer-driven energy landscape. The integration of PLC technology into the smart grid framework has yielded transformative outcomes that bridge the gap between energy generation, distribution, and consumption. The results underscore the potential of PLC-enabled communication to enhance grid efficiency, minimize disruptions, and empower consumers to actively manage their electricity usage. The combination of real-time communication and dynamic load management has proven instrumental in achieving grid stability and reliability. A swift response to demand fluctuations, enabled by PLC, contributes to a more balanced distribution of load across the grid, reducing the risk of blackouts during peak usage periods. Moreover, the consumer engagement aspect of the scheme has fostered a heightened awareness of energy consumption patterns among users. By providing them with access to their consumption data and incentivizing energy-efficient practices through dynamic pricing, the demand scheme promotes a culture of conscious energy consumption. Furthermore, the interactive nature of PLC-driven demand response initiatives has redefined the relationship between utilities and consumers. The ability of consumers to actively participate in load management signifies a collaborative approach towards a sustainable energy future. This not only benefits individual consumers through reduced utility bills but also contributes to the overall optimization of the grid's performance, achieving an accuracy of 98.87%. In essence, the smart grid demand scheme utilizing the power line communication technique stands as a testament to the potential of technological innovation in revolutionizing the energy sector. Its outcomes reflect an alignment with the goals of increased grid efficiency, consumer empowerment, and environmental sustainability. As the energy landscape continues to evolve, the integration of PLC technology into demand schemes is poised to play a pivotal role in shaping a resilient and consumer-centric energy ecosystem.

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