Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 10, 1297-1322
2025
Publisher: Learning Gate
DOI: 10.55214/2576-8484.v9i10.10663

Towards the development of intelligent control and monitoring schemes for smart metering systems

Olusayo Adekunle Ajeigbe[1]*, Jacobus Andries Jordaan[2]
[1,2]Department of Electrical Engineering, Faculty of Engineering and the Built Environment, Tshwane University of Technology, South Africa; sayoaje376@yahoo.com (O.A.A.).

Abstract: The increasing demand for grid stability and energy efficiency has propelled the advancement of intelligent control and monitoring technology for smart metering systems. This study examines scholarly publications, research papers, technical reports, and industry publications over a fifteen-year period (2010–2025). The evaluation emphasizes significant technological advancements, such as blockchain-enabled energy transactions, improved bidirectional communication protocols, automated demand response systems, and the integration of IoT with artificial intelligence. Despite these advancements, ongoing challenges encompass insufficient load separation, absence of intelligent load management, difficulties in energy supply-demand equilibrium, restricted bidirectional communication, and deficiencies in device classification. The results indicate the need to include edge computing, predictive load management driven by artificial intelligence, interoperability with hybrid energy systems, and improved cybersecurity. These gaps can be addressed through multidisciplinary cooperation among engineers, data scientists, legislators, and energy companies. Future smart meters should, according to the study, utilize cutting-edge technologies to offer sustainable grid management, enhance consumer satisfaction, and advance the energy economy. By incorporating sophisticated communication protocols, load management optimization, and intelligent control mechanisms, smart metering systems may significantly improve sustainable energy solutions and modernize smart grids.

Keywords: *Artificial intelligence, Energy, Intelligent control schemes, Intelligent monitoring Schemes, Smart metering system.*

1. Introduction

The energy sector globally is currently confronted with increasing consumption and variable demand and supply trends. The demand for power is escalating daily due to population growth and industrial advancement [1]. In 2019, the United Nations estimated that the global population rose from more than 2.53 billion in 1950 to over 7.79 billion in 2020, representing a rise of about 207.9%. According to additional research, the global population increased by around 55% from 2018 to 2020 [2]. The population expansion is anticipated to persist, with a forecast exceeding 10.9 billion by 2100, representing a 40% increase [3]. Due to this escalation, existing main energy resources are projected to deplete within 133 years [3]. The rising daily utilization of electrical equipment and the adoption of new cryptocurrency fees by customers are escalating concerns in the energy sector, resulting in a disparity between supply and demand. Moreover, several unlawful "grid connections" exist, resulting in a substantial quantity of energy that remains unmeasured and unpaid [4]. Generating additional electricity might enhance the circumstances, although it would not constitute a comprehensive solution. Opportunities exist to diminish the disparity between supply and demand through enhanced utilization of electricity.

The introduction of smart meters (SM) and improved metering systems has addressed numerous issues. The European Parliament, in Directive 2012/27/EU, characterizes SM or SMS as "an electronic

History: Received: 1 August 2025; Revised: 15 September 2025; Accepted: 19 September 2025; Published: 23 October 2025
* Correspondence: sayoaje376@yahoo.com

system capable of measuring energy consumption, offering more information than a conventional meter, and transmitting and receiving information via a form of electronic communication" [5]. A SM is a new kind of energy measuring device. It is usually an electrical meter recording the consumption of electrical energy. These electronic meter readings could be sent to the electrical supplier for monitoring and billing purposes. Smart metering systems provide efficient energy management for both energy consumers and providers [6]. SM enables consumers to monitor their consumption and/or generation, allowing them to manage their electricity usage more efficiently. SM facilitates demand response programs, enabling consumers to react to incentives and reduce crucial usage during peak hours. Conversely, SM serves as a tool for distribution system operators to monitor the network and obtain automatic consumption and/or generation data [7]. In addition, smart metering infrastructure in buildings becomes a necessary measure to reduce energy wastage and improve energy monitoring, control, and measurement.

SM assists effective use of electrical energy and the preservation of it. Still, smart metering systems have significant problems even with their sophisticated capabilities. Great concern arises from the large initial cost of installation, which includes obtaining SM, communication tools, and integration with current systems. Because these systems rely on IoT and cloud-based technologies and are thus prone to hacking, data breaches, and unlawful access, cybersecurity is a major concern. Technical errors or inadequate communication could make maintaining data accuracy and dependability difficult in real-time monitoring and billing. Furthermore, compatibility with current systems and different standards across areas are difficult to implement. The limited usage of smart metering may be hampered even more by consumer ignorance and resistance to embracing new technology. In the end, guaranteeing continuous functionality becomes somewhat challenging in places with little network coverage or unstable electricity supply. Optimizing the benefits of smart metering systems [8] depends on overcoming these challenges.

Smart metering system research has drawn a lot of attention recently [9]. Specifically, the communication architecture and analysis of SM data have been promoted as essential components for building efficient electricity infrastructure [10-19]. Many applications have been developed based on the SM data to meet the interests of various stakeholders [9, 20]. The authors in El Mrabet et al. [21] and Wang et al. [22] have surveyed the cybersecurity of smart metering systems and pointed out that weaknesses in communication may render the systems susceptible to hacking, data breaches, and illegal access, exposing system data to security threats. Although researchers have conducted some reviews related to control and monitoring schemes of smart metering systems [20, 22-25]. The current reviews lack the detail and comprehensiveness of this paper. The current literature does not explicitly disclose the challenges facing smart metering systems and their obligation to support high integration of renewable energy (RE) prosumers. In addition, the implementation of advanced intelligent control and monitoring technologies in smart meters (SM) is often discouraged due to limited motivation, including restricted revenue, and concerns regarding the integration of new technologies and mechanisms. The development of intelligent control and monitoring schemes in SMs faces difficulties in identifying appropriate applications and algorithms to overcome drawbacks in existing works. It is essential to identify prospective schemes that address these challenges, with the possibility of adopting changes in the integration of RE prosumers and encouraging increased operational efficiency of utilities. This will ensure access to reliable and efficient energy measurements and billing, and facilitate scalable and standardized energy metering.

This paper presents a systematic review and analysis of academic articles, research papers, technical reports, industry publications, books, and other pertinent resources concerning intelligent control and monitoring systems for SMSs. The paper entails a thorough desk evaluation of available literature covering a substantial period of fifteen years, from 2010 to 2025, encompassing a duration of one and a half decades to document the growth of knowledge, technological advancements, and new trends in the subject. This desk review facilitates the identification of significant changes, trends, and deficiencies in the current body of work, establishing a robust basis for informed findings and suggestions. The method used in this paper guarantees that the review is based on a comprehensive understanding of historical and present viewpoints, therefore augmenting the depth, relevance, and dependability of the findings. The objectives of this paper, therefore, are to review current developments in intelligent schemes for smart metering of electricity, identify research gaps, and suggest areas for future work. The research scope focuses on smart metering systems for electricity and examines technologies like AI, IoT, and machine learning. The paper's key contributions are;

1. First, it examines smart metering systems' intelligent control and monitoring schemes in detail, focusing on how they can improve energy management and grid efficiency.
2. It presents the pros and cons of SM, AI-powered control systems, machine learning applications, and methods for making decisions that are tailored to each situation.
3. The paper identifies cutting-edge technologies such as federated learning, blockchain integration, and IoT-enabled real-time data gathering, and demonstrates how these technologies influence problem identification, consumption prediction, and load forecasting.
4. The review also discusses how SMs can assist in enhancing the use of RE, the operation of microgrids, and demand-side management.
5. The way forward for creating smart metering systems that are intelligent and reliable in a world where energy is changing is outlined, looking at both long-standing problems and new trends.

The rest of this paper is systematized as outlined below: Section 2 delineates the overview of smart grid and smart metering systems, describing their features, functions, concepts, and architectural components. Section 3 illustrates in detail the control and monitoring schemes applicable to smart metering systems, explaining their types, optimizations, and system supports. It further explores various frameworks for the SM's optimization in RE usage and management. Section 4 presents results and discussion, describing the key findings, technological developments, research gaps, and future developments in smart metering systems. Section 5 presents the paper's conclusion.

2. Smart Grids (SG) and Smart Metering Systems (SMS)

This section presents an overview of SG and SMS. The smart grid comprises SM, a head-end system, and data concentrators, grouped into many communication networks. The section also describes the concepts of SMS, including their functionalities, features, and technological components. The smart metering system is an electrical power communication system that amalgamates electricity and telecommunications infrastructure to gather, monitor, and assess client energy consumption [26, 27]. As SMSs are essential for the management of SG operations, the challenges facing the SG are reflections of the smart metering systems. These challenges provide a framework for the advancement of intelligent systems, including meter control and monitoring applications that are demonstrated in Section 3.

2.1. Smart Grids (SG)

Smart grids are highly developed electrical distribution networks that make use of modern communication, sensor, and control technologies in order to optimize and manage power generation, distribution, and consumption. Additionally, they allow the utility and the customers to communicate with one another in real time, which results in an improvement in the analysis and control of power flows. This is an enhanced version of the previous electrical grid [28]. Advanced communication technologies, multi-tariff meters, and power distribution devices have been implemented to ensure the efficiency and reliability of operations in energy generation, transmission, distribution, and consumption. Figure 1 depicts a network architecture of an SG.

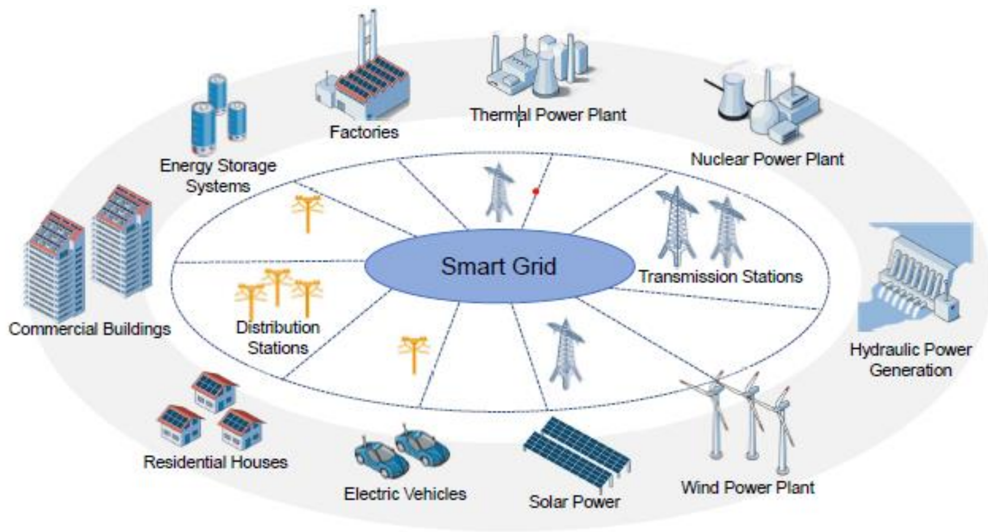

Figure 1.
Network model of a smart grid.
Source: Sahu et al. [26] and Qaddoori and Ali [27].

The smart grid (SG) has several sensors to facilitate remote testing and coordinated control, thereby enabling self-monitoring and self-healing functionalities. It also includes ancillary services such as the incorporation of renewable and distributed energy sources, along with data exchange between renewable energy sources (RES) and electric vehicles (EV) [7]. Every function of the SG encompasses many particular technologies that span the entire grid, from generation to transmission and distribution, catering to a diverse array of consumers.

2.2. Microgrids and Renewable Energy (RE) Integration

A microgrid is a compact power supply network intended to deliver electricity to a localized population. It facilitates local power generation for regional demands and comprises many small power generation sources, rendering it highly adaptable and efficient. The smart grid is interconnected with both the local generation units and the utility grid, thereby preventing power outages. Surplus energy can be sold to the utility grid or stored in a storage system. The size of the microgrid can vary from residential developments (a few kW) to municipal areas (many MW). Numerous options exist to regulate voltage and minimize power losses in the power system. Flexible AC Transmission System (FACTS) devices are recognized as a prominent method for reactive power adjustment. Utilizing renewable Distributed Generations (DGs) in proximity to loads can enhance system stability, reduce power losses, and save operational costs. Moreover, RE is more environmentally friendly compared to typical power plants [29]. Optimal distributed generation planning is crucial for improving the performance of the distribution power network to achieve anticipated outcomes and system profitability, including voltage stability, power loss reduction, and system dependability [30]. In the future, renewable energy (RE) will be the primary generation system to conserve fossil fuels and mitigate the environmental impact of conventional generation. RE sources include wind, solar cells, biomass, nuclear power, and small hydropower plants. Solar and wind power are regarded as prominent forms of RE due to the general availability of sunlight and wind [31]. In addition, advanced intelligent smart meters can be deployed to achieve a sustainable smart DC microgrid energy management system.

2.3. Smart Metering Systems

Smart metering systems are sophisticated measurement technologies that provide real-time or near-real-time monitoring, creating and managing electricity consumption data. These systems comprise a metering device that quantifies resource use, a communication module facilitating bidirectional data transfer by technologies such as RF, PLC, or Wi-Fi, and a data management system that processes and analyzes the data. Essential attributes include remote surveillance, instantaneous data accessibility, time-of-use charging, and tampering detection, which are advantageous for both consumers and utility providers by enhancing efficiency, transparency, and operational expense reductions. Despite encountering obstacles such as elevated installation expenses, interoperability complications, and cybersecurity vulnerabilities, smart metering systems offer considerable benefits, including improved resource optimization, superior demand management, and facilitation of renewable energy (RE) integration. As they develop, integration with IoT, edge computing, blockchain, and AI will further augment their capabilities, solidifying their role in promoting sustainable and efficient resource utilization. The architecture of the SMS is illustrated in Figure 2.

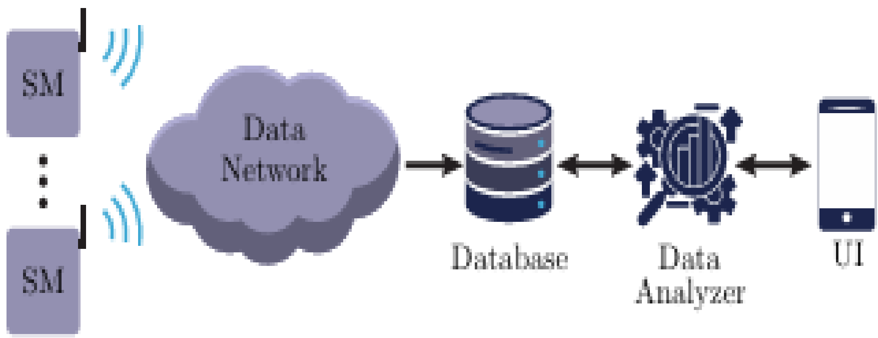

Figure 2.
Architecture of the SMS.
Source: Rahman, et al. [32].

2.3.1. Concepts and Features of Smart Metering System

The SMS is an enhanced iteration of conventional analog power meters, which are utilized in 95% of locations globally [28]. The concept of smart metering system (SMS) began to acquire prominence in 2008, although it had existed for several years prior. SMS encompasses sophisticated functionalities such as real-time power status feedback, remote billing, remote communication, energy theft detection, power data logging and storage, and cloud-based monitoring. Table 1 delineates the benefits of SMS in comparison to conventional energy meters. Figure 3 illustrates the conventional block diagram upon which the majority of smart energy metering systems (SEMS) are based. SMS designs generally comprise a microcontroller that serves as the system's central processing unit. The design will undoubtedly include sensors for measuring current and voltage. The SMS design will include either a GSM or Wi-Fi module for wireless communication to the cloud or service provider, a relay, and several additional features to improve performance and functionality [33].

DOI: 10.55214/2576-8484.v9i10.10663

Table 1.
Comparison of SEMS and conventional energy meters.

S/No	Features	SEMS	Conventional Meters
1	Energy consumption measurement technique	Current and Voltage Transducers	Magnetic Coupling
2	Supply Control	Relay	No
3	Energy Feedback/Data	Automated (Cloud and SMS)	Collection Manual
4	User Interface	Mobile App	GBD and LCD LCD, LED, OLED
5	Remote Access	Cloud (Web and Mobile app)	No
6	Real-time Communication Protocol	Wireless	No
7	Power Limit Surveillance/Disconnection	Relay Control	No
8	Bypass detection capability / Energy theft identification	Yes	No
9	Infrastructure	Advanced technology with IoT integration	Basic and outdated technology
10	Maintenance	Proactive and predictive through analytics	Reactive issues are addressed after failures occur
11	Scalability	Easily scalable for future enhancement	Difficult to expand or upgrade
12	Cost	Higher initial cost, but cost-effective in the long run	Lower initial cost but higher operational inefficiency

Source: Dahunsi, et al. [33].

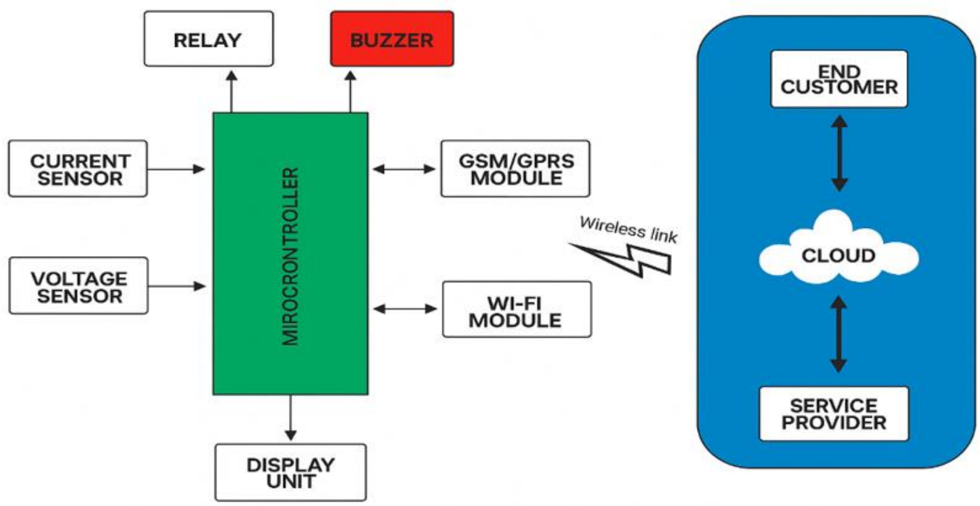

Figure 3.
Block Diagram of a Standard SMS.
Source: Dahunsi, et al. [33].

2.3.2. Smart Metering Systems Architectural Components: Sensors, Communication Protocols, And Control Units.

Electricity metering devices are typically tested for high-precision energy measurement, often requiring manual involvement from laboratory personnel. This manual process can introduce significant errors in testing data, leading to incomplete reports, subjectivity, randomness, and poor timeliness, resulting in inaccurate metering equipment with high error rates. To ensure accurate results, tests often need to be repeated multiple times, which duplicates personnel efforts and introduces safety risks. To address these challenges, the design detection process integrates automated systems that streamline tasks from receiving metering equipment to task completion. This automated process includes capabilities such as automated data acquisition, identification, feedback provision, regulation, data transmission, and real-time surveillance, which significantly reduce errors and improve efficiency.

Typical smart metering systems incorporate three core components: sensors, communication protocols, and control units.

2.3.2.1. Sensors

Sensors track basic characteristics such as energy consumption, voltage, current, and environmental factors; therefore, they offer accurate, real-time data.

2.3.2.2. Protocols of Communication

By using technologies ranging from Zigbee, LoRa, Wi-Fi, or cellular networks, communication methods guarantee reliable and safe data flow from sensors to control units.

2.3.2.3. Control Units

By processing and interpreting the data, control units help to enable automatic actions or decision-making. These elements, used together, maximize energy management, allow remote monitoring, and facilitate advanced analytics for effective use of resources [34].

2.3.3. Function, Characteristics, and Uses for Smart Meters

Different functions and capabilities of smart meters help to improve resource economy and energy management. Among the main applications are remote control of energy use, automatic billing, real-time monitoring, and consistent data collection. Advanced features include data analytics, demand-response capability, RES integration, and predictive maintenance, which help to maximize performance even further. These systems allow users to monitor and control gas, water, or electrical energy consumption, thereby supporting uses in home, business, and industrial environments. Furthermore, SMs are important in smart grid systems for load balancing, energy waste reduction, and grid dependability improvement. Smart metering systems support sustainability and cost economy by enabling clear energy consumption and arming consumers with practical knowledge [35].

Smart metering systems change resource management and improve operational efficiency by means of real-time monitoring, data transfer, and analytics. Real-time monitoring helps to find anomalies such as wastages or overuse before they become issues by allowing continuous surveillance of energy, water, or gas use and fast response to consumption trends. Safe protocols such as Wi-Fi, Zigbee, or cellular networks allow perfect connection between sensors and control units, ensuring remote access to real-time consumption data. Analytics are crucial as processing this data helps to obtain beneficial insights, including consumption trends, cost projections, and optimization plans. These shared traits enable customers and utilities to make smart decisions, improve resource economy, reduce running costs, and progress environmental goals. Advanced tracking systems that allow consumers and utility suppliers to quickly identify defects, guarantee optimal system functioning, and conduct timely maintenance as needed give real-time control and monitoring through constant evaluation of energy flow [36].

Smart meters use simple interaction with smart grids and bidirectional communication to improve grid efficiency and energy management. Two-way data interchange between utilities and consumers made possible by bidirectional communication allows real-time updates, remote meter reading, dynamic tariff modifications, and demand-response capability. While utilities can effectively distribute energy and handle problems in a timely manner, consumers may track their energy use and control their appliances by means of interactive communication. Furthermore, connection with smart grids lets one engage with distributed energy resources, including solar power systems and battery storage, thereby enabling effective load balancing, renewable energy (RE) integration, and general system stability. These features contribute to a more resilient, flexible, and sustainable energy ecosystem [37].

3. Intelligent Control and Monitoring Schemes for Smart Meters

Intelligent control and monitoring systems of SMs improve security, dependability, and power grid efficiency by integrating artificial intelligence, machine learning, and IoT for optimal energy utilization and anomaly detection. Load balancing, predictive maintenance, and real-time monitoring enable AI-driven SMs to minimize energy waste through continuous monitoring, thereby enhancing grid stability. Blockchain technology increases security and transparency in energy transactions, while bidirectional communication allows users to control usage and supports dynamic pricing. However, challenges such as cybersecurity threats and interoperability concerns require further innovation. As smart grids continue to develop, they are creating more robust and efficient energy systems [38]. These systems will become absolutely vital.

3.1. Intelligent Control Schemes

Intelligent control systems utilizing advanced algorithms, machine learning, and automation enhance system efficiency and optimize resource management in smart metering systems. These systems facilitate demand-side management, peak load reduction, and predictive maintenance by analyzing real-time data from sensors and human inputs, hence enabling dynamic decision-making. Combining user behavior patterns with such aspects as weather or energy pricing allows intelligent control systems to automatically adjust energy use, prioritize significant loads, and increase energy savings without compromising user comfort. Furthermore, these initiatives boost sustainability by helping to implement distributed energy sources (DES) and RES microgrids, hence reducing dependency on conventional energy sources [39, 40].

It is rather important since intelligent control might improve reliability, efficiency, and sustainability in resource and energy management. Using intelligent control systems allows one to maximize resource use, decrease operating expenses, and lower energy waste by means of real-time data and smart algorithms. These systems either appropriately incorporate RES or react automatically to dynamically shifting energy loads during peak demand. By empowering users more over energy use patterns, predictive maintenance also helps to minimize equipment breakdowns and boost grid stability. A society aspiring for sustainability must have intelligent control if it is to meet the growing energy demand while reducing environmental effects and constructing a wiser, more resilient infrastructure [41].

3.1.1. AI-Based Control Mechanisms

Artificial intelligence-driven control systems are revolutionizing smart meters through enhanced automation, predictive functionalities, and self-optimization. These systems analyze extensive quantities of real-time data by integrating machine learning algorithms with previous data, thereby facilitating accurate predictions of user behavior and energy use. Through the utilization of artificial intelligence, SM can autonomously detect anomalies like leaks or unauthorized usage and initiate repairs without human intervention. Furthermore, AI-driven solutions enhance energy distribution, align with consumer consumption patterns, and seamlessly integrate renewable energy sources, thereby providing tailored energy management. AI-driven control systems are essential for the advancement of intelligent and sustainable energy infrastructure, achieved through enhanced decision-making, improved efficiency, and minimized energy waste [42].

3.1.2. Employing Machine Learning (ML)

Applications of machine learning (ML) in smart metering systems improve the accuracy, efficiency, and sophistication of energy management. Using information from SM, machine learning techniques forecast future energy demand, identify use patterns, and optimize billing systems. Machine learning uses past data analysis to identify anomalies, such as equipment breakdowns, unusual consumption, or potential fraud, providing early warning signals for necessary responses. Machine learning helps utilities balance supply and demand, enabling demand forecasting by adjusting energy distribution based on anticipated usage trends. Machine learning can enable real-time dynamic pricing systems, which modify prices based on consumption levels or grid conditions. Machine learning significantly enhances the efficiency and reliability of smart metering systems through ongoing learning and adaptation, allowing for more efficient energy use and improved utility and consumer decision-making [43]. Case studies on the application of supervised, unsupervised, and reinforcement learning models in smart metering systems illustrate the diverse ways machine learning can enhance energy management.

3.1.2.1. Supervised Learning

Numerous machine learning (ML) models have been suggested for the detection of electricity theft, and experimental findings indicate that ML is a potential approach. Nevertheless, the majority of current research employs supervised learning [44]. In supervised learning, models are used for predicting energy consumption patterns based on labeled datasets, where algorithms are trained to recognize patterns from historical data to forecast future usage, optimize billing, and detect anomalies such as energy theft. Supervised power theft detectors are binary classifiers developed using datasets that include both legitimate and fraudulent electricity consumption samples. In Erhan et al. [45] Jokar et al. employed the Irish Smart Energy Trial (ISET) dataset to train a binary support vector machine (SVM) for the identification of possible electricity theft instances. Given that the ISET dataset contains solely benign samples, the authors utilized six attack functions to generate malicious samples from the benign data. The findings demonstrated the efficacy of the SVM in detecting the six categories of electricity theft cyberattacks. Yan et al. [46] and Jindal et al. [47] proposed the integration of decision trees with support vector machines to enhance electricity theft detection. Punmiya and Choe [48] proposed the use of ensembles of decision trees, including LightGBM, CATBoost, and XGBoost, rather than relying on a single decision tree. The findings indicated that utilising ensemble learning enhances detection efficacy. Buzau et al. [49] improved electricity theft detection by training an XGBoost model using electricity consumption samples from the Endesa dataset alongside auxiliary data, which included customer locations and the technical characteristics of their SM. In addition to prior research, the authors of Jokar et al. [50] and Jindal et al. [47] investigated supervised electricity theft detection utilizing deep learning (DL) methods. Deep learning enhances the detection of electricity theft by effectively capturing temporal correlations in usage data and revealing concealed patterns. Bhat et al. [51] conducted a comparison of shallow ML and DL models for the detection of electricity theft in [51]. The experimental results using a synthetic dataset demonstrated that deep learning (DL) models, such as convolutional neural networks (CNNs), long short-term memory (LSTM) networks, and autoencoders, surpass shallow machine learning models, including decision trees (DT) and random forests (RF). Zheng et al. [52] devised a mixed deep learning model to detect suspected theft situations in [52]. Their model integrates a fully connected feed-forward neural network (FCNN) with a convolutional neural network. Experimental findings utilizing the State Grid Corporation of China (SGCC) dataset demonstrated the superiority of the hybrid detector compared to independent FCNN and CNN detectors. Badr et al. [53] examined the issue of electricity theft in net metering systems in [52]. They created a multi-tiered detector utilizing a combination of a CNN and an RNN, trained on several data sources alongside power measurements. At each phase, the detector receives supplementary auxiliary data to improve its efficacy. Nonetheless, all aforementioned studies employed supervised learning, wherein detectors are engineered to identify particular attacks, and their efficacy remains uncertain when faced with novel, unobserved attacks [54].

3.1.2.2. Unsupervised Learning

Unsupervised learning has been used to identify hidden patterns and group similar consumption behaviors in large datasets without pre-labeled examples. This approach has been progressively employed in smart metering systems to discern concealed trends and group analogous consumption behaviors without necessitating pre-labeled data. Clustering methods, such as k-means and hierarchical clustering, have been utilized to categorize energy consumers according to their usage patterns, allowing utilities to formulate targeted demand-side management plans [55]. Furthermore, dimensionality reduction techniques such as principal component analysis (PCA) and autoencoders have been utilized to examine high-dimensional smart meter data, revealing latent features that distinguish consumer groups [56]. Unsupervised models for anomaly identification, such as isolation forests and self-organising maps (SOMs), have demonstrated efficacy in recognizing typical energy consumption, which may indicate potential electricity theft or defective meters [57]. Time-series clustering integrated with unsupervised learning has improved load forecasting and energy distribution, thereby enhancing grid stability and operational efficiency [58]. These approaches highlight the critical need for unsupervised learning in enhancing the intelligence and efficiency of smart metering systems. In a case study, users were categorized based on their usage habits to deliver customized energy-saving recommendations, thereby enhancing user engagement and reducing overall demand.

3.1.2.3. Reinforcement Learning

Reinforcement learning (RL) is a systematic method in which an agent acquires decision-making skills through interaction with the environment to achieve objectives based on feedback, and it has been employed to enhance real-time decision-making in demand-side management. Due to its adaptability in demanding and uncertain environments, it has proven effective across various sectors, including smart home energy management. Hao et al. [59] presented a significant instance wherein a reinforcement learning model adaptively adjusted energy use based on market prices and grid conditions, thereby optimizing consumer cost savings and minimizing energy waste.

Through demand response strategies and grid sustainability and stability enhancement, RL-driven smart meters improve energy use predictions and supply modifications [60]. Reference Kurde and Kulkarni [61] describes how reinforcement learning (RL) has evolved into a useful tool for increasing energy efficiency, enabling dynamic demand-side management, and therefore optimizing energy use in smart metering systems. Utilizing reinforcement learning algorithms, SM may discern ideal energy consumption patterns informed by real-time grid conditions, electricity pricing, and user behavior, consequently mitigating peak loads and augmenting cost savings for users. Recent research has shown the efficacy of reinforcement learning (RL) in optimizing energy distribution through the application of deep Q-networks (DQN) and policy gradient techniques to dynamically regulate power consumption, while maintaining user comfort and reducing operating expenses [62]. The amalgamation of reinforcement learning with the IoT and cloud computing significantly improves real-time decision-making, rendering smart metering systems more flexible and intelligent [63].

These case studies demonstrate how different machine learning models can be tailored to address specific challenges in smart metering systems, improving operational efficiency, reducing costs, and fostering sustainability [64]. However, they come with a series of challenges such as effective disconnection of loads resulting from inadequate energy generation, where energy has to be used sparingly; parameters for switching electronic devices and appliances on and off; load level grouping and identification; balancing energy supply and consumption; accurate and dependable energy measurements; bidirectional communication laxity; identifying schedulable and non-schedulable electrical devices; as well as identifying interruption and non-interruption appliances.

3.2. Smart Meters Optimization and System Support

Smart meter optimization and system support focus on enhancing the efficiency, accuracy, and reliability of energy consumption monitoring and management. Optimization involves advanced data analytics, machine learning algorithms, and IoT integration to improve real-time data collection, reduce losses, and ensure precise billing. System support includes maintaining network stability, cybersecurity measures, and seamless integration with RES for a more resilient and sustainable energy grid. Effective demand-side management, reduced operational expenses, and increased consumer engagement in energy conservation campaigns will rely on proficient SM optimization and support.

3.2.1. Adaptive Decision-Making for Maximizing Smart Meter Performance

Adaptive decision-making is absolutely essential for optimizing smart meter operations since it allows systems to dynamically respond to changing conditions and user requests. Using real-time data and advanced algorithms, these systems may investigate consumption patterns, environmental variables, and network restrictions, making informed adjustments. This addresses maximizing energy distribution, demand-response action automation, overload prediction, and prevention to balance supply and demand. As the system learns from prior data and adapts to new conditions, energy forecasting becomes more accurate; resource allocation is improved, and running expenses are reduced. Adaptive decision-making primarily ensures reliability, efficiency, and uniformity in smart meter operations, aligning with environmental goals and user comfort. Powered by artificial intelligence and predictive analytics, smart operations are transforming sectors such as financial services by streamlining procedures, reducing operating costs, and enhancing overall performance. AI-powered solutions provide expedited and precise operations by automating straightforward tasks such as data entry, customer service, and transaction processing. AI-driven chatbots and virtual assistants may manage client contacts, respond to inquiries, and process requests autonomously, thereby significantly enhancing operational efficiency and enabling organizations to rapidly adapt to evolving circumstances [65].

3.2.2. Utilization of Artificial Intelligence (AI) For System Optimization and Decision-Making

Artificial intelligence enhances the performance of smart metering systems and facilitates robust decision-making. Real-time data from smart meters enables artificial intelligence systems to forecast patterns in energy consumption, facilitating dynamic pricing, precise invoicing, and customized energy conservation initiatives. By analyzing consumption patterns and dynamically redistributing energy loads to avert grid overloads, particularly during peak demand, AI enhances demand-side management. Moreover, artificial intelligence is becoming an indispensable instrument for energy systems to maximize demand projection, grid resilience, and energy distribution. Large datasets are extracted [66] by means of machine learning techniques, including regression analysis, classification, and clustering, thereby enhancing forecasting accuracy and supporting proactive energy use. Smart metering systems enhance energy consumption, demand forecasting, and the integration of renewable energy sources through the application of machine learning techniques on historical data. Furthermore, artificial intelligence-driven anomaly detection systems can recognize typical usage patterns, including potential fraud, leakage, or malfunctions, and trigger prompt repair alerts.

3.2.3. Anomaly Detection, Consumption Prediction, and Load Forecasting.

Essential components of smart metering systems that enhance system reliability and efficiency include anomaly detection, consumption forecasting, and load prediction. Advanced algorithms facilitate the detection of anomalies in energy use, such as sudden surges, theft, or equipment malfunctions, allowing for timely intervention and thereby diminishing the likelihood of system failure. Prediction forecasts future energy use by utilizing machine learning models and historical data, thereby assisting utilities and consumers in more efficiently managing consumption patterns. This predictive capability also facilitates customized pricing and distinct energy conservation measures. Load forecasting employs historical data and external variables, such as weather conditions, to predict future energy demand, so enabling utilities to optimize energy production, distribution, and grid management, ensuring a balanced supply that prevents overloads and minimizes waste. These characteristics, taken together, increase the general affordability, sustainability, and efficiency of smart metering systems [67].

3.3. Intelligent Monitoring Systems

Smart meter monitoring systems provide a scientific approach for acquiring, assessing, and managing energy usage data in order to provide efficient power distribution. IoT, cloud computing, and artificial intelligence together offer predictive maintenance, real-time monitoring, and anomaly detection. Important components include data analytics, visualization tools, data collection, and communication systems. They support demand-side management, grid dependability, and renewable energy (RE) integration. For consumers and utilities, a well-designed monitoring system guarantees proper invoicing, reduces energy losses, and improves overall energy efficiency.

3.3.1. Real-Time Data Acquisition

In order to improve energy distribution, utilities can use real-time data to track consumption patterns, identify anomalies, and quickly implement fixes. Through increased awareness, real-time consumption monitoring empowers consumers to make well-informed decisions about energy efficiency and cost management. Through secure communication protocols, smart metering systems provide effective data transmission, frequent information updates, quick responses to changing conditions, error prevention, and overall system efficiency. Moreover, real-time data collection allows sophisticated analytics, which guide well-informed judgments, improving the dependability and sustainability of energy management systems [68].

3.3.2. Continuous Data Collecting via IoT-Enabled Gadgets.

Using IoT-enabled devices for continuous data collection in smart metering systems changes energy management by providing a real-time understanding of energy usage trends. Continuous data collection about ambient conditions, voltage, current, and energy consumption is made possible by these sensors and communication devices, which then send the data to central systems for analysis. By using IoT technology, SM can deliver real-time data through secure communication networks, allowing utilities to improve energy distribution management and monitoring. This constant flow of data makes it easier to identify irregularities like energy theft, malfunctions, or inefficiencies early on, enabling quick fixes. Real-time energy consumption monitoring is made possible by IoT-enabled devices, which encourage energy saving and improved usage control [69].

3.3.3. Smart Grid Cloud Platform

The primary objective of the SG is to provide a comprehensive real-time system that encompasses the entire power system process, from generation to consumption, including generation, transformation, transmission, distribution, and scheduling. Power generation necessitates the equilibrium of supply and demand to the greatest extent feasible. The smart grid must acquire user power consumption data, employ contemporary networking, communication, and information technologies to facilitate interaction and enable information exchange among grid equipment, thereby optimizing power generation, distribution, and utilization, while autonomously executing monitoring, measurement, information control, system protection, and other fundamental functions. The many links in the digital collection apparatus differ, corresponding to the user interface of the smart meter, which is a microprocessor-based, intelligent, compact system. The smart meter not only collects and measures local power consumption and electricity data during various periods but also disseminates extensive information regarding peak power pricing and electricity rates from power companies, enabling users to manage their internal power usage effectively. The electric utility's system gathers, retains, analyzes, and processes this data for application in other operations. In an integrated distributed protection system, the wide-area monitoring system will amalgamate monitoring and control, digital protection, and modern communication technologies to systematically oversee the power network [70].

3.3.4. Big Data Analytics Module

A primary aspect of Big Data is the processing of data in real-time or near-real-time. Data generally expands swiftly at an annual growth rate of 50%, especially unstructured data. Grid big data necessitates high-performance, high-throughput, and substantial capacity storage systems for smart grids, which are equipped with a rising number of sensors and SM. The attributes of smart grid big data can be encapsulated as follows: a substantial volume of data, characterized by multiple dimensions and types; data from decentralized and distributed energy sources; significant economic worth; the data link is intricate and necessitates comprehensive analysis. The existing power data warehouse is limited to fulfilling static statistical requirements, operating on a T+1 model. The extensive data retained within the power network is static, and its statistics may only be extrapolated from the statistical data of the preceding time unit. The interconnections among diverse large datasets are intricate [71].

3.4. Cutting-Edge Developments and Trends Evaluation of Smart Metering Systems

The necessity to resolve metering concerns coincides with the advancement of distribution electrical systems. A significant progression is evident from the inaugural electricity meter, patented by Gardiner [72] and [73], which solely conveyed data regarding the duration of the electric current flow, to contemporary systems capable of offering a diverse array of uses beyond mere metering. The initial automatic and commercial remote meter is credited to Paraskevakos [74] and Borges de Oliveira [75]. Nevertheless, the remote metering notion was not actualized in the anticipated power framework for several years. Climate change, heightened awareness of energy efficiency, emerging trends in electricity markets, and the gradual transformation of consumers into more active participants are promoting the adoption of RES, Distributed Generation (DG), and Distributed Storage (DS), thereby requiring a substantial evolution of the existing electricity model. The transition to an electricity grid model that can effectively manage multiple generation and storage devices in a decentralized fashion is the core of the Smart Grid (SG) concept, making the deployment of advanced metering systems, or smart metering, an essential strategy to realize this goal.

The European Parliament, in the 2012/27/EC Directive, defined an SMS as "an electronic system capable of detecting energy use, providing enhanced energy consumption data that is more comprehensive than that of a standard meter, and capable of transmitting and receiving information through electronic communication" [76]. Machine-to-Machine (M2M) communications occur between technologies that possess the ability to interact autonomously, without human involvement. The acquired event-driven data is transmitted over a communication channel (either wired or wireless) to the servers responsible for data extraction, processing, and response generation [77]. M2M capabilities are essential for SM efficacy, since they facilitate the necessary bidirectional connection between consumption locations and monitoring and control centers [78]. In addition to the control and management functionalities afforded by SM implementation, the acquired metering data, along with supplementary information, can be utilized by automated systems to provide new applications, including predictive and load management systems.

Recent infrastructure investments have mostly concentrated on the metering aspect of electricity. The first attempt at metering automation, or Automated Meter Reading (AMR), enabled metering systems to remotely access consumption data and fundamental status information from customers' premises [79]. AMR's unidirectional communication technology restricts it to remote reading and precludes the execution of supplementary applications, leading utilities to transition to Smart Metering or Advanced Metering Infrastructure (AMI). Smart Metering enables utilities to establish bidirectional communication with the meter and assess the condition of the grid. Contemporary smart metering systems, featuring an enhanced architecture and collaborating with advanced sensors and sophisticated distributed control technologies, enable utilities to execute grid control and management [80].

Advanced Artificial Intelligence (AI) is significantly enhancing the functionality of smart metering systems, with deep learning, edge AI, and federated learning driving improvements in energy management and operational efficiency. Particularly in the analysis of energy consumption patterns and anomaly detection, many research studies have used data-driven machine learning models to improve the efficiency and intelligence of smart metering systems. Load profiling and consumer behavior analysis have benefited greatly from commonly used techniques, including support vector machines (SVM) [61, 62], hidden Markov models (HMM) [81] and k-nearest neighbors (kNN). Combining a CNN with a bidirectional long short-term memory (BiLSTM) network combines deep learning in a more sophisticated manner. In smart grid data, this method efficiently captures spatial and temporal dependencies, thus enhancing demand forecasting accuracy, anomaly detection, and occupancy-based energy management. CNN and BiLSTM's sequential fusion outperforms conventional models, making this approach highly promising for real-time decision-making in smart metering systems [82].

Mishra et al. [65] used EAI to maximize power generation, distribution, and consumption. Edge artificial intelligence in smart meters improves real-time data processing, hence lowering latency and dependency on cloud computing. By integrating artificial intelligence directly into edge devices, such as

SM, it enables efficient energy consumption monitoring, anomaly detection, and predictive analytics. This approach improves grid reliability, enhances demand-side management, and ensures data privacy by processing information locally [83]. Edge AI-driven SM can detect irregular energy usage patterns, optimize load distribution, and support RE integration, making power systems more sustainable and resilient [84]. The technology is particularly beneficial in regions with limited internet connectivity, ensuring uninterrupted and intelligent energy management [85]. Edge AI processes data locally, reducing latency and enabling quick, real-time decision-making for better grid management.

Recently, federated learning (FL) has been examined to tackle the data-sharing issue in load forecasting [86]. The local load forecasting model is developed at SMs utilizing local metering data before transmission to the global server for processing in subsequent rounds. This method safeguards user privacy by maintaining raw data locally and preventing the transfer of sensitive information across networks. Nevertheless, such approaches have faced difficulties in addressing data heterogeneity, as they assume that each SM possesses a dataset with a similar data distribution. However, this is not feasible in practical metering networks, as each Smart Meter generally has a distinct metering data distribution owing to the individual energy consumption habits of households. Federated learning further enhances privacy by allowing data from distributed devices to be used for system improvement without sharing sensitive user information [20, 43, 87, 88]. Numerous studies have sought to improve the latency of federated learning (FL) and its application in multi-hop networks. For instance, Khan et al. [89] enhanced model aggregation, routing, and spectrum allocation to augment efficiency, whereas Liu et al. [90] introduced FedAir to alleviate communication-related effects on FL performance. Moreover, Mohasen and Baroudi [91] presented hierarchical federated learning with adaptive grouping to improve scalability, [92] aimed at mitigating congestion through the prediction of future network topologies, and Pinyoanuntapong et al. [93], Nguyen et al. [94], and Cash et al. [95] examined the impact of jamming attacks on decentralized federated learning. Figure 4 illustrates the architecture for federated load forecasting in the Multihop metering network.

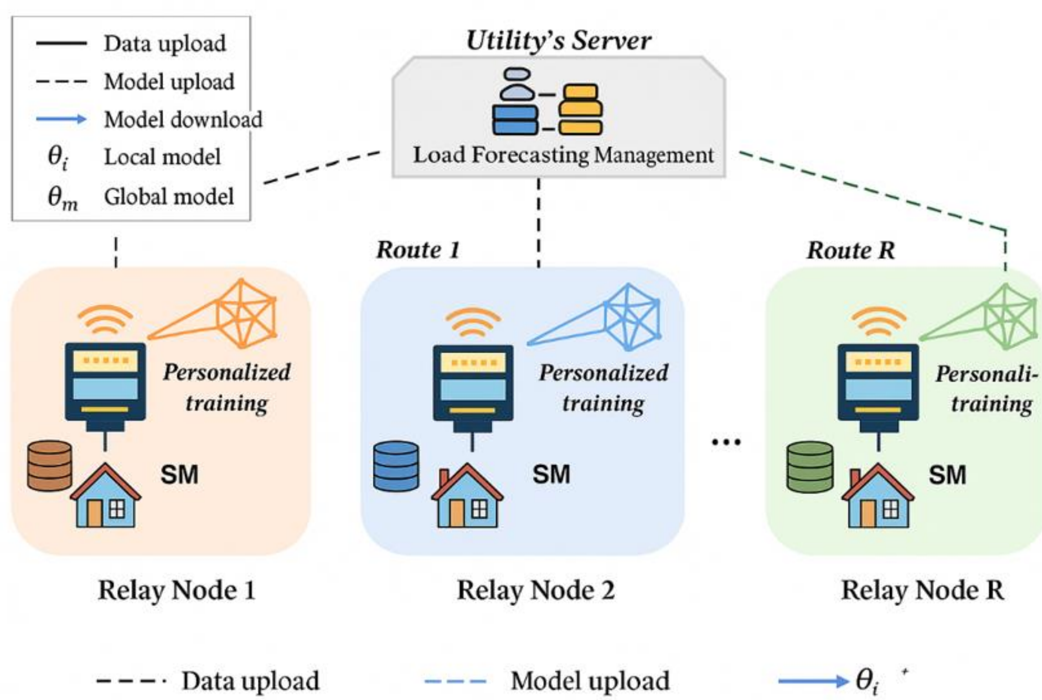

Figure 4.
Architecture for Federated Load Forecasting in the Multihop Metering Network.
Source: Pasqualon et al. [96].

Blockchain integration provides a secure and transparent framework for managing energy consumption data, ensuring the integrity of records and preventing tampering or unauthorized access. Blockchain technology is essential for protecting smart metering systems. Jiang et al. [97], inspired by BlocHIE, suggested a framework for smart metering systems that uses blockchain technology for effective and safe energy data management. Consumption-Chain for real-time energy use records and User-Chain for tailored consumption patterns and preferences helped this architecture to arrange metering data into two separate blockchains. It guarantees data integrity, immutability, and user anonymity by using on-chain verification, therefore overcoming the limits of conventional metering storage systems. Further adaptable to maximize energy data distribution, improve system capacity, and guarantee fair energy management, justice-oriented approaches such as FAIR-FIRST and TP&FAIR are implemented. In smart metering, this blockchain-powered technique enhances dependability, security, and openness, thereby strengthening the user-centric energy management system.

To improve security, efficiency, and justice in energy data management, Jiang et al. [98] present a framework combining blockchain technology with an equitable transaction packing technique. Also inspired by BlocHIE, this system arranges metering of data into two blockchains: User-Chain for individual consumption patterns and Consumption-Chain for real-time energy use. The FAIR-PACK technique is used, employing heuristic and min-heap approaches to divide energy transactions depending on response time, thereby optimizing transaction processing inside permissioned blockchains in IoT-enabled smart grids. Through a thorough investigation of system parameters such as transaction arrival rate, block generating time, block size, and block validity ratio, FAIR-PACK enhances fairness and reduces average reaction time compared to traditional approaches. Furthermore, searchable blockchain technologies help maintain user privacy by enabling exact searches within secured energy storage systems. However, there are challenges since the system currently supports only single-keyword searches, and multi-keyword implementations could compromise database speed and confidentiality. Smart metering systems become more robust and user-centric when this blockchain-powered solution improves transparency, security, and fair energy management.

For information systems able to run dynamic updates and multi-keyword searches while preserving anonymity, Khan et al. [99] presented a sophisticated blockchain-based framework. The bloom filter identifies a low-frequency keyword from the database to execute search instructions, hence minimizing computational costs and search space. It performs the process in a single iteration, ensuring comprehensive privacy protection. The results indicate that the multi-keyword search protocol surpasses the current method by 14.67 percent in time delay and 59.96 percent in financial costs. Adjusting the parameters of the filter system can yield additional enhancements and create a more resilient system. Together, these advancements optimize energy distribution, improve grid stability, and contribute to a more secure, efficient, and reliable smart metering ecosystem, supporting both consumers and utility providers in achieving smarter, more sustainable energy usage [100]. However, there are numerous challenges, such as data quality deficiencies, computational restrictions, and network limitations that impede real-time learning and decision-making. Concerns regarding privacy and security emerge from the sensitivity of energy consumption data, necessitating stringent protective measures.

3.5. Applications of Smart Metering Systems

Smart metering systems have several uses in energy management, enhancing efficiency, precision, and sustainability. They provide real-time surveillance of electricity consumption, enabling consumers to monitor and optimize usage. Utilities employ SM for automated invoicing, load forecasting, and demand-side management. Smart meters encourage the integration of renewable energy (RE) by facilitating net metering for solar and wind energy. Additionally, they enhance grid reliability by enabling remote disconnections or reconnections, minimizing energy losses, and identifying defects. Energy conservation and cost reduction are facilitated by their applications, which include industrial automation, environmental monitoring, and smart cities.

3.5.1. Deployment of SM

As the smart grid evolves in complexity, it necessitates extensive SMs for data collection, monitoring, and regulation of utility energy consumption. Traditional methods necessitate extensive energy meter networks, which frequently incur substantial expenses for deployment, maintenance, and data collection [99]. Consequently, the optimization of smart meter deployment has garnered significant attention. The deployment necessitates the utilization of a minimal number of SMs to monitor extensive utility states promptly [100-102]. Research endeavors frequently employ optimization methodologies in the communication networks of SM, taking into account practical limitations. One method involves decomposing the power distribution network into a forest of multiple trees, optimizing the deployment locations and the requisite number of SM accordingly [103]. Furthermore, the operation of SM necessitates electricity, resulting in considerable energy consumption for large-scale installations. It poses challenges in determining the optimal deployment and data transmission rate for SM to reduce overall energy consumption [50]. Moreover, the physical constraints of communication networks may affect the overall efficacy of smart metering [104]. Constraints such as communication bandwidth and data transmission rate frequently lead to communication delays, thereby compromising power system stability [90]. Such constraints must be taken into account during the optimization of smart meter deployment to achieve viable outcomes.

3.5.2. Smart Meters for Grid Management and Renewable Energy Usage Optimisations

Smart meters significantly optimize renewable energy utilization and improve grid management by delivering real-time data on energy consumption and generation. By precisely monitoring renewable energy production, including solar and wind, SM assists utilities in optimizing the equilibrium between supply and demand. They enhance the integration of renewable energy into the grid by supplying information on energy availability, facilitating dynamic load balancing, and thereby diminishing dependence on traditional energy sources. SM aids in regulating changes caused by weather conditions or time of day by enhancing the prediction of energy generation from renewable sources. In addition, they support demand-side management by encouraging consumers to adjust their usage during peak times or when RE is abundant, ultimately reducing strain on the grid. This optimization not only improves the sustainability and resilience of the energy grid but also contributes to more cost-effective and environmentally friendly energy usage [105].

Edge computing's prominence in IoT is defined by processing occurring at the data source. It promotes the processing of data at the sensory nodes to utilize the cloud for broader applications while enabling the SMs to operate more efficiently and decrease latency through localized data processing on edge devices [106]. Given that artificial intelligence methods are implemented in anomaly detection for smart grids, it is theoretically possible to achieve positive results with edge AI by utilizing lightweight, computationally efficient AI and machine learning techniques on resource-limited processors. Fuentes-Velazquez et al. [107] present an enhancement of SM with edge computing capabilities and artificial intelligence for anomaly detection in Advanced Metering Infrastructures [107].

The state of the art in smart metering systems is rapidly advancing, incorporating cutting-edge technologies such as Advanced AI, blockchain, edge computing, and renewable energy integration.

Deep learning, edge AI, and federated learning are utilized to enhance energy consumption forecasting, facilitate real-time decision-making, and augment system intelligence, allowing smart meters to adjust to fluctuating consumption patterns and optimize energy distribution. The integration of blockchain technologies promotes data security and transparency, thereby ensuring the integrity of information regarding energy usage and facilitating secure, decentralized transactions. Moreover, intelligent management systems are employed to optimize the utilization of renewable energy sources such as solar and wind, hence enhancing grid management and facilitating the integration of these variable resources. Since edge computing handles data locally at the source, it reduces latency and enables faster response times in real-time energy management. With ongoing efforts aimed at establishing global standards and cooperative frameworks that enable seamless integration and communication among various systems and devices, promoting the adoption and efficiency of smart metering technologies [108], advancements in standardizing and interoperability remain a main emphasis.

3.6. Impacts of Intelligent Smart Metering Systems

The impact of intelligent smart meters spans social, environmental, and economic domains. These systems optimize resource utilization by providing precise data on energy consumption, hence reducing overall consumption and waste, resulting in a diminished environmental impact. By enhancing operational efficiency, reducing energy losses, and facilitating dynamic pricing that promotes energy conservation, smart meters generate cost savings for consumers and utilities. This results in diminished utility expenses for consumers and enhanced regulation of energy usage. Smart metering systems provide social access through real-time usage statistics, thereby enabling informed decision-making and fair resource distribution, particularly in areas with varying energy sources. The major initial outlay of funds for implementation, including social media, tools for communication, and interface with present systems, causes enormous concern. They also help utilities identify poor areas and apply more concentrated solutions to ensure fair energy distribution, thereby fostering greater social equality in energy access [109].

3.7. Challenges in Intelligent Smart Metering Systems

Despite their advanced features, intelligent smart metering systems face many challenges. Because these systems depend on IoT and cloud-based technology, they are vulnerable to hacking, data breaches, and illegal access, making cybersecurity a major concern. In real-time monitoring and billing, technical failures or communication breakdowns could compromise data accuracy and dependability. Furthermore, applying these systems compatibly with the current infrastructure and meeting diverse criteria across various sectors is difficult. Consumer ignorance and resistance to adopting new technologies could further limit the use of smart metering. The significant upfront costs of implementation, including acquiring smart meters, communication tools, and connectivity with existing systems, are also a major concern. Given that these systems rely on IoT and cloud-based technologies, cybersecurity remains a critical issue. Technical faults or communication failures could hinder the maintenance of data accuracy and dependability in real-time monitoring and billing. Compatibility with current systems and adherence to different standards across regions are additional challenges. Moreover, consumer ignorance and resistance to adopting new technology further impede the widespread application of smart metering.

Ensuring constant operation becomes very difficult in areas with limited network coverage or unreliable energy supplies in the end. Overcoming these issues will help to maximize the advantages of intelligent smart metering systems [8, 110-112]. Especially in times of insufficient energy generation when cautious use of energy is required, intelligent smart metering systems struggle greatly in controlling energy use. Among the main challenges are figuring out the appropriate turning on and off values for arranging and recognizing appliance load levels, and matching energy supply with consumption. For these devices, accurate and consistent energy measurements are absolutely necessary; nonetheless, bidirectional communication laxity or communication delays can cause differences. Further essential for effective load control is differentiating between schedulable and non-schedulable devices as well as interruptible and non-interruptible systems. High implementation costs and restricted funding, among other economic restrictions, further impede the general acceptance of these systems. With possible risks including hacking, data breaches, and illegal access, cybersecurity and data privacy also present major concerns. Implementing strong encryption, blockchain, and safe communication protocols helps to reduce these hazards and safeguard user data, thereby guaranteeing the integrity of the smart metering system [113, 114].

4. Results of the Findings

The review outcomes show that although smart metering systems have grown significantly over the past one and a half decades, there are still research gaps in intelligent control and monitoring strategies. Addressing these research gaps requires collaboration among researchers across different fields. Future research on smart metering solutions should involve advanced AI-driven analytics, improved bidirectional communication, and robust security mechanisms to ensure efficient and sustainable energy management.

The review conducted over a fifteen-year period (2010–2025) provides a comprehensive assessment of scholarly and industrial progress in the field of intelligent control and monitoring schemes for smart metering systems. The key findings are categorized based on technological evolution, integration trends, challenges, and future directions.

4.1. Technological Advancements in Smart Metering Systems

Smart metering systems have undergone significant advancements, including blockchain for secure and decentralized energy trading, advanced bidirectional communication for real-time data exchange, automated demand response (ADR) for peak load management, and the integration of IoT with AI for intelligent monitoring and predictive control. These innovations collectively enhance energy efficiency, grid reliability, and consumer engagement in modern energy systems.

i. Blockchain-Enabled Energy Transactions: There is a growing incorporation of blockchain for secure, decentralized, and transparent energy trading. Smart contracts have been leveraged to automate peer-to-peer (P2P) energy exchanges, enhancing trust and efficiency in distributed energy systems.
ii. Enhanced Bidirectional Communication Protocols: Advancements in communication technologies such as ZigBee, LoRaWAN, LTE, and 5G have significantly improved real-time data exchange between utilities and consumers. These protocols enable better energy forecasting, remote monitoring, and fault detection.
iii. Automated Demand Response (ADR) systems: ADR frameworks using intelligent algorithms allow utilities to automatically shift or reduce consumer load during peak hours, contributing to grid stability and optimized energy usage. Integration with AI enhances response precision and consumer participation.
iv. IoT and AI Integration: Smart meters have evolved from simple data collectors to intelligent nodes that utilize AI for load forecasting, anomaly detection, and dynamic pricing. IoT sensors provide granular data, which AI models process for predictive analytics and control optimization.

4.2. Identified Challenges and Limitations

Despite technological advancements, smart metering systems continue to face key limitations, including inadequate load separation, limited intelligent load management, and ongoing challenges in balancing energy supply and demand due to the variability of renewable sources. Many systems still operate with restricted bidirectional communication, reducing their responsiveness and control capabilities. Additionally, the lack of accurate device classification hinders effective appliance-level monitoring and personalized energy optimization. These issues collectively impact the efficiency, adaptability, and overall performance of modern energy management systems.

i. Insufficient load separation: Many current smart metering systems lack the ability to distinguish between different appliances or load types, hindering fine-grained energy analysis and control.
ii. Lack of intelligent load management: There is limited implementation of adaptive and autonomous load control mechanisms, resulting in suboptimal energy usage and reduced consumer engagement in demand-side management.

iii. Energy Supply-Demand Imbalance: Variability in renewable energy sources and unpredictable consumption patterns continue to pose challenges in achieving real-time supply-demand equilibrium.
iv. Restricted Bidirectional Communication: Despite progress, many systems still operate on limited or one-way communication protocols, restricting the scope of interaction, feedback, and remote actuation.
v. Device Classification Deficiencies: A lack of accurate device identification and classification algorithms hampers the ability of smart meters to optimize individual appliance performance and consumption.

4.3. Emerging Trends and Solutions

Emerging trends in smart metering systems emphasize the use of advanced technologies to boost efficiency, responsiveness, and security. Key developments include the integration of edge computing for real-time data processing and reduced system latency, as well as AI-driven predictive load management to anticipate energy demand and optimize grid performance. The increasing use of hybrid energy systems demands smart meters capable of seamless interoperability and intelligent coordination. Additionally, strengthened cybersecurity measures such as advanced encryption, authentication, and anomaly detection are being implemented to ensure data protection and system reliability.

i. Edge Computing: Deployment of edge computing resources at the meter or substation level reduces latency, supports real-time analytics, and alleviates bandwidth demands on central systems.
ii. Predictive Load Management with AI: Machine learning models are being adopted to anticipate future energy demand and implement preemptive control strategies, improving grid efficiency and user experience.
iii. Hybrid Energy Systems Integration: Smart meters are increasingly being designed to interface with hybrid systems involving solar, wind, and storage units. This necessitates interoperability standards and intelligent coordination mechanisms.
iv. Cybersecurity Enhancement: New encryption algorithms, authentication protocols, and anomaly detection systems are being introduced to safeguard data privacy and infrastructure security.

4.4. Strategic Recommendations

Strategic recommendations for advancing smart metering systems emphasize the need for multidisciplinary collaboration among engineers, data scientists, policymakers, and utility providers to align technological innovations with regulatory and market requirements. Establishing regulatory support and standardized protocols is crucial for ensuring interoperability, facilitating widespread adoption, and building consumer trust. Additionally, a consumer-centric approach should guide the design of future smart meters, focusing on user-friendly interfaces, customizable energy options, and transparent billing to enhance user engagement and satisfaction.

i. Multidisciplinary Collaboration: The development of next-generation smart metering systems requires coordinated efforts among electrical engineers, data scientists, policymakers, and utility companies to align technical innovation with regulatory frameworks and market demands.
ii. Regulatory Support and Standardization: The lack of uniform standards across regions hinders large-scale adoption. Harmonized protocols and compliance policies can enhance system compatibility and consumer trust.
iii. Consumer-Centric Design: Future smart meters should prioritize user-friendly interfaces, customizable energy plans, and transparent billing to increase consumer engagement and satisfaction.

4.5. Key Summary of Findings

The key findings in Table 2 highlight a transformative shift in smart metering systems from passive metering to intelligent, interactive components of a sustainable smart grid ecosystem. The integration of cutting-edge technologies and multidisciplinary strategies will be critical to overcoming current limitations and unlocking the full potential of smart energy management.

Table 2.
Key Summary Finding.

S.NO	Focus Area	Key Findings
1	Communication Protocols	Shift towards 5G and LPWANs for robust, scalable, low-latency data transfer
2	Control Mechanisms	AI-enhanced ADR and self-healing grid strategies are gaining traction
3	Data Analytics	Edge AI enables real-time decisions with reduced central processing burden
4	Security	Blockchain and advanced encryption improve data integrity and transaction trust
5	Interoperability	Integration with DERs and hybrid grids remains a major development goal
6	Policy and Collaboration	Need for unified frameworks and multi-stakeholder engagement

5. Discussions

The relevant significant developments, new trends, and enduring problems in the industry have been revealed by a thorough analysis of the literature on intelligent control and monitoring systems for smart metering over the previous one and a half decades. This section discusses the main conclusions, as well as technical developments, shortcomings, and the need for improved SMSs.

5.1. Important Advances in Technology

The review cites a number of noteworthy advancements in smart metering systems, chiefly:

i. Predictive load management and real-time monitoring are facilitated by the improved data analytics enabled through the integration of IoT and AI with SM.
ii. Bidirectional communication technologies like Zigbee, LoRa, and 4G have made it easier for customers, utilities, and grid operators to send data in the most effective way.
iii. Smart meters are being integrated with automated demand response systems to improve grid stability and optimize energy use patterns.
iv. Consumers and prosumers can now safely and remotely transfer energy thanks to the development of blockchain technology.

5.2. Constant Issues Using Smart Meters

Notwithstanding these developments, many issues still exist, including the efficient disconnection of loads resulting from inadequate energy generation, which requires sophisticated load prioritizing strategies.

i. Current SM mostly tracks energy use instead of arranging loads depending on priority or providing control options for turning appliances on or off.
ii. Many current SM lack strong bidirectional connections, therefore restricting their capacity to enable demand-side management and real-time energy changes.
iii. Finding schedulable and non-schedulable electrical equipment, as well as distinguishing interruptible from non-interruptible appliances, continues to be a challenge for device categorization.

5.3. Emerging Trends and Future Directions

This work offers a comprehensive evaluation of intelligent control and monitoring systems for SMS in view of energy management in buildings. Emerging trends and future directions cover a lot over an interesting fifteen years. The research reveals some fresh trends and possible improvements for smart metering systems: future SM should incorporate load distribution optimization and patterns of energy consumption forecasts driven by artificial intelligence. By improving data processing at the meter level and hence reducing latency, edge computing can help to increase system responsiveness.

Intelligent smart meters should be developed to successfully combine traditional and renewable energy sources, thereby facilitating hybrid energy systems. Emphasizing data security methods in smart metering systems can help protect consumer information and prevent intrusions. Future research should focus on developing intelligent smart metering systems that provide users with customized energy management and control information, thereby enhancing energy efficiency and cost savings.

6. Conclusions

This paper presents a state-of-the-art review of intelligent control and monitoring schemes for smart metering systems (SMS), considering building energy management. Covering a significant period of fifteen years, from 2010 to 2025, a comprehensive desk review of the existing literature entails a systematic analysis of scholarly publications, research papers, technical reports, industry publications, books, and other relevant resources concerning intelligent control and monitoring systems for SMS. Future smart metering systems must incorporate advanced technologies, including AI-driven predictive load management, IoT-enabled remote monitoring, and blockchain for secure energy transactions, to improve energy efficiency, grid stability, and consumer satisfaction. Modern bidirectional communication systems are essential to provide real-time interactions among customers, utilities, and businesses. Further development should enhance load management systems to maximize energy efficiency, rank important loads, and enable independent demand response systems. Smart meters must be compatible with hybrid energy systems to ensure seamless integration of renewable energy sources and to enhance cybersecurity standards, primarily for data protection and preventing unauthorized access. Regulatory frameworks and support must advance the adoption, standardization, and data privacy compliance in smart metering systems. Additionally, aggressive consumer awareness, marketing, and educational programs aimed at motivating active participation in demand-side management and energy-saving initiatives should be promoted. Adhering to these recommendations will optimize smart meters to meet increasing energy demands and ensure their sustainability, reliability, and efficiency.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Acknowledgments:

The authors would like to thank the Faculty of Engineering and the Built Environment, Tshwane University of Technology (TUT), South Africa, for the research support and facilities.

References

[1] O. Munoz, A. Ruelas, P. Rosales, A. Acuña, A. Suastegui, and F. Lara, "Design and development of an IoT smart meter with load control for home energy management systems," *Sensors*, vol. 22, no. 19, p. 7536, 2022. https://doi.org/10.3390/s22197536

[2] A. Balali, A. Yunusa-Kaltungo, and R. Edwards, "A systematic review of passive energy consumption optimisation strategy selection for buildings through multiple criteria decision-making techniques," *Renewable and Sustainable Energy Reviews*, vol. 171, p. 113013, 2023.

[3] European Union, "Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC," *Official Journal of the European Union*, vol. 315, pp. 1–56, 2012.

[4] Z. Jastaneyah, H. Kamar, and H. Al Garalleh, "A review paper on thermal comfort and ventilation systems in educational buildings: Nano-mechanical and mathematical aspects," *Journal of Nanofluids*, vol. 12, no. 1, pp. 1-17, 2023. https://doi.org/10.1166/jon.2023.1902

[5] A. Menati, K. Lee, and L. Xie, "Modeling and analysis of utilizing cryptocurrency mining for demand flexibility in electric energy systems: A synthetic texas grid case study," *IEEE Transactions on Energy Markets, Policy and Regulation*, vol. 1, no. 1, pp. 1-10, 2023.

[6] M. S. I. Sadek, M. A. H. Joy, M. K. Islam, M. A. Ananna, M. H. Bhuyan, and M. S. Aktar, "Design and analysis of a rooftop hybrid solar pv system using homer pro and MATLAB Simulink," *Southeast University Journal of Electrical and Electronic Engineering (SEUJEEE)*, vol. 2, no. 1, pp. 35-45, 2022.

[7] S. Vitiello, N. Andreadou, M. Ardelean, and G. Fulli, "Smart metering roll-out in europe: Where do we stand? cost benefit analyses in the clean energy package and research trends in the green deal," *Energies*, vol. 15, no. 7, p. 2340, 2022. https://doi.org/10.3390/en15072340

[8] M. Pau *et al.*, "A cloud-based smart metering infrastructure for distribution grid services and automation," *Sustainable Energy, Grids and Networks*, vol. 15, pp. 14-25, 2018.

[9] Z. Chen, A. M. Amani, X. Yu, and M. Jalili, "Control and optimisation of power grids using smart meter data: A review," *Sensors*, vol. 23, no. 4, p. 2118, 2023.

[10] H. Komatsu and O. Kimura, "Peak demand alert system based on electricity demand forecasting for smart meter data," *Energy and Buildings*, vol. 225, p. 110307, 2020. https://doi.org/10.1016/j.enbuild.2020.110307

[11] S. Sahoo, D. Nikovski, T. Muso, and K. Tsuru, "Electricity theft detection using smart meter data," in *2015 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT) (pp. 1-5). IEEE*, 2015.

[12] M. Papadimitrakis, N. Giamarelos, M. Stogiannos, E. Zois, N.-I. Livanos, and A. Alexandridis, "Metaheuristic search in smart grid: A review with emphasis on planning, scheduling and power flow optimization applications," *Renewable and Sustainable Energy Reviews*, vol. 145, p. 111072, 2021. https://doi.org/10.1016/j.rser.2021.111072

[13] E. Sarker *et al.*, "Progress on the demand side management in smart grid and optimization approaches," *International Journal of Energy Research*, vol. 45, no. 1, pp. 36-64, 2021.

[14] J. Batalla-Bejerano, E. Trujillo-Baute, and M. Villa-Arrieta, "Smart meters and consumer behaviour: Insights from the empirical literature," *Energy Policy*, vol. 144, p. 111610, 2020. https://doi.org/10.1016/j.enpol.2020.111610

[15] M. R. Asghar, G. Dán, D. Miorandi, and I. Chlamtac, "Smart meter data privacy: A survey," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 4, pp. 2820-2835, 2017.

[16] P. Moutis *et al.*, "A survey of recent developments and requirements for modern power system control," *Pathways to a Smarter Power System*, pp. 289-316, 2019. https://doi.org/10.1016/B978-0-08-102592-5.00010-7

[17] N. Saputro and K. Akkaya, "Investigation of smart meter data reporting strategies for optimized performance in smart grid AMI networks," *IEEE Internet of Things Journal*, vol. 4, no. 4, pp. 894-904, 2017.

[18] Z. A. Obaid, L. M. Cipcigan, L. Abrahim, and M. T. Muhssin, "Frequency control of future power systems: Reviewing and evaluating challenges and new control methods," *Journal of Modern Power Systems and Clean Energy*, vol. 7, no. 1, pp. 9-25, 2019.

[19] E. B. Alzate, M. Bueno-López, J. Xie, and K. Strunz, "Distribution system state estimation to support coordinated voltage-control strategies by using smart meters," *IEEE Transactions on Power Systems*, vol. 34, no. 6, pp. 5198-5207, 2019. https://doi.org/10.1109/TPWRS.2019.2902184

[20] D. Alahakoon and X. Yu, "Smart electricity meter data intelligence for future energy systems: A survey," *IEEE Transactions on Industrial Informatics*, vol. 12, no. 1, pp. 425-436, 2015. https://doi.org/10.1109/TII.2015.2414355

[21] Z. El Mrabet, N. Kaabouch, H. El Ghazi, and H. El Ghazi, "Cyber-security in smart grid: Survey and challenges," *Computers & Electrical Engineering*, vol. 67, pp. 469-482, 2018. https://doi.org/10.1016/j.compeleceng.2018.01.015

[22] Y. Wang, Q. Chen, T. Hong, and C. Kang, "Review of smart meter data analytics: Applications, methodologies, and challenges," *IEEE Transactions on smart Grid*, vol. 10, no. 3, pp. 3125-3148, 2018. https://doi.org/10.1109/TSG.2018.2818167

[23] A. Chaudhari and P. Mulay, "A bibliometric survey on incremental clustering algorithm for electricity smart meter data analysis," *Iran Journal of Computer Science*, vol. 2, no. 4, pp. 197-206, 2019.

[24] G. Shamim and M. Rihan, "Exploratory data analytics and PCA-Based dimensionality reduction for improvement in smart meter data clustering," *IETE Journal of Research*, vol. 70, no. 4, pp. 4159-4168, 2024.

[25] Y. Chen, P. Tan, M. Li, H. Yin, and R. Tang, "K-means clustering method based on nearest-neighbor density matrix for customer electricity behavior analysis," *International Journal of Electrical Power & Energy Systems*, vol. 161, p. 110165, 2024. https://doi.org/10.1016/j.ijepes.2024.110165

[26] A. Sahu, H. K. Tippanaboyana, L. Hefton, and A. Goulart, "Detection of rogue nodes in AMI networks," in *2017 19th International Conference on Intelligent System Application to Power Systems (ISAP) (pp. 1-6). IEEE*, 2017.

[27] S. L. Qaddoori and Q. I. Ali, "An embedded intrusion detection and prevention system for home area networks in advanced metering infrastructure," *IET Information Security*, vol. 17, no. 3, pp. 315-334, 2023. https://doi.org/10.1049/ise2.12097

[28] N. D. Noviati, S. D. Maulina, and S. Smith, "Smart grids: Integrating ai for efficient renewable energy utilization," *International Transactions on Artificial Intelligence*, vol. 3, no. 1, pp. 1-10, 2024.

[29] A. M. Eltamaly and A. N. A. Elghaffar, "Techno-economical study of using nuclear power plants for supporting electrical grid in Arabian Gulf," *Technology and Economics of Smart Grids and Sustainable Energy*, vol. 2, pp. 1-8, 2017.

[30] A. M. Eltamaly, Y. S. Mohamed, A.-H. M. El-Sayed, and A. N. Abd Elghaffar, "Analyzing of wind distributed generation configuration in active distribution network," in *2019 8th International Conference on Modeling Simulation and Applied Optimization (ICMSAO) (pp. 1-5). IEEE*, 2019.

[31] A. M. Eltamaly, Y. S. Mohamed, A. H. M. El-Sayed, and A. N. A. Elghaffar, "AC microgrid protection coordination," *Microgrid Technologies*, pp. 197-226, 2021. https://doi.org/10.1002/9781119710905.ch8

[32] R. Rahman, P. Moriano, S. U. Khan, and D. C. Nguyen, "Electrical load forecasting over multihop smart metering networks with federated learning," *arXiv preprint arXiv:2502.17226*, 2025.

[33] F. M. Dahunsi, S. O. Eniola, A. A. Ponnle, O. A. Agbolade, C. N. Udekwe, and A. O. Melodi, "A review of smart energy metering system projects," *Jurnal Elektronika dan Telekomunikasi*, vol. 21, no. 1, pp. 70-78, 2021.

[34] H. Song, X. Xia, M. Zhang, H. Yuan, and S. Wang, "Research of communication protocols for energy metering devices," in *Proceedings of CECNet 2022, pp. 24-31. IOS Press*, 2022.

[35] X. Luo *et al.*, "Design of test system for micro-power communication module of smart meter," in *2018 13th World Congress on Intelligent Control and Automation (WCICA) (pp. 1042-1046). IEEE*, 2018.

[36] S. Chowdhury, "Guidelines for net energy metering in Bangladesh integrating distributed renewable energy systems into the grid," *The Sustainable and Renewable Energy Development Authority (SREDA)*, 2017.

[37] I. Rahman, "Smart net energy metering system," *Journal of Electrical and Electronic Systems*, vol. 7, no. 4, pp. 285-289, 2018.

[38] S. A. Khan, J. Deepika, S. K. Singh, and N. Patel, "Design and optimization of intelligent control systems for renewable energy integration in smart grids," *Nanotechnology Perceptions*, vol. 20, no. S8, pp. 1522–1534, 2024. https://doi.org/10.62441/nano-ntp.vi.2462

[39] H. M. Bijoy, M. M. Hasan, M. A. Jaman, and M. H. Bhuyan, "Design, simulation, and implementation of a smart net-metering system for the distributed PV and grid-connected customers," in *2024 3rd International Conference on Advancement in Electrical and Electronic Engineering (ICAEEE) (pp. 1-6). IEEE*, 2024.

[40] A. A. Pathare, R. P. Singh, and D. Sethi, "An IoT-Enabled smart net-metering system for real-time analysis of renewable energy generation in MATLAB/Simulink," *Journal of The Institution of Engineers (India): Series B*, vol. 105, pp. 1583-1598, 2024. https://doi.org/10.1007/s40031-024-01052-9

[41] N. Nikolov, "Intelligent urban systems and industry 5.0: Creating adaptive ecosystems for sustainable energy and resource management," *International Journal of Current Science Research and Review*, vol. 8, no. 1, pp. 103-115, 2025.

[42] D. Sudharson, A. Bhuvaneshwaran, T. Kalaiarasan, V. Sushmita, and N. Jyothi Lakshmi, "A multimodal AI framework for hyper automation in industry 5.0," in *2023 International Conference on Innovative Data Communication Technologies and Application (ICIDCA) (pp. 282-286). IEEE*, 2023.

[43] R. Pujari, J. R. Ganapa, K. Makanyadevi, P. V. H. Prasad, S. Rusia, and S. Nagaraju, "Artificial intelligence in smart grids enhancing energy management and optimization through machine learning," *Nanotechnology Perceptions*, vol. 20, p. S13, 2024.

[44] Y. Liu *et al.*, "Evaluating smart grid renewable energy accommodation capability with uncertain generation using deep reinforcement learning," *Future Generation Computer Systems*, vol. 110, pp. 647-657, 2020. https://doi.org/10.1016/j.future.2019.09.036

[45] L. Erhan *et al.*, "Smart anomaly detection in sensor systems: A multi-perspective review," *Information Fusion*, vol. 67, pp. 64-79, 2021. https://doi.org/10.1016/j.inffus.2020.10.001

[46] Y. Yan, Y. Qian, H. Sharif, and D. Tipper, "A survey on smart grid communication infrastructures: Motivations, requirements and challenges," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 5-20, 2012. https://doi.org/10.1109/SURV.2012.021312.00034

[47] A. Jindal, A. Dua, K. Kaur, M. Singh, N. Kumar, and S. Mishra, "Decision tree and SVM-based data analytics for theft detection in smart grid," *IEEE Transactions on Industrial Informatics*, vol. 12, no. 3, pp. 1005-1016, 2016. https://doi.org/10.1109/TII.2016.2543145

[48] R. Punmiya and S. Choe, "Energy theft detection using gradient boosting theft detector with feature engineering-based preprocessing," *IEEE Transactions on Smart Grid*, vol. 10, no. 2, pp. 2326-2329, 2019. https://doi.org/10.1109/TSG.2019.2892595

[49] M. M. Buzau, J. Tejedor-Aguilera, P. Cruz-Romero, and A. Gómez-Expósito, "Detection of non-technical losses using smart meter data and supervised learning," *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 2661-2670, 2019. https://doi.org/10.1109/TSG.2018.2807925

[50] P. Jokar, N. Arianpoo, and V. C. Leung, "Electricity theft detection in AMI using customers' consumption patterns," *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 216-226, 2015. https://doi.org/10.1109/TSG.2015.2425222

[51] R. R. Bhat, R. D. Trevizan, R. Sengupta, X. Li, and A. Bretas, "Identifying nontechnical power loss via spatial and temporal deep learning," in *2016 15th IEEE International Conference on Machine Learning and Applications (ICMLA) (pp. 272-279). IEEE*, 2016.
[52] Z. Zheng, Y. Yang, X. Niu, H.-N. Dai, and Y. Zhou, "Wide and deep convolutional neural networks for electricity-theft detection to secure smart grids," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 4, pp. 1606-1615, 2017.
[53] M. M. Badr, M. I. Ibrahem, M. Mahmoud, M. M. Fouda, F. Alsolami, and W. Alasmary, "Detection of false-reading attacks in smart grid net-metering system," *IEEE Internet of Things Journal*, vol. 9, no. 2, pp. 1386-1401, 2021.
[54] A. Alshehri, M. M. Badr, M. Baza, and H. Alshahrani, "Deep anomaly detection framework utilizing federated learning for electricity theft zero-day cyberattacks," *Sensors*, vol. 24, no. 10, p. 3236, 2024. https://doi.org/10.3390/s24103236
[55] J. Wu *et al.*, "Self-supervised graph learning for recommendation," in *Proceedings of the 44th International ACM SIGIR Conference on Research and Development in Information Retrieval*, 2021.
[56] C. Wei, J. Liang, D. Liu, and F. Wang, "Contrastive graph structure learning via information bottleneck for recommendation," *Advances in neural information processing systems*, vol. 35, pp. 20407-20420, 2022.
[57] Y. Wu *et al.*, "Multi-view multi-behavior contrastive learning in recommendation," in *International Conference on Database Systems for Advanced Applications (pp. 166-182). Cham: Springer International Publishing*, 2022.
[58] J. Chen, Z. Zhu, H. Li, W. Jiang, G. Jeon, and Y. Qian, "A data augmentation model integrating supervised and unsupervised learning for recommendation," *Scientific Reports*, vol. 15, no. 1, p. 4862, 2025. https://doi.org/10.1038/s41598-025-88858-9
[59] X. Hao *et al.*, "Smart meter deployment optimization for efficient electrical appliance state monitoring," in *2012 IEEE Third International Conference on Smart Grid Communications (SmartGridComm) (pp. 25-30). IEEE*, 2012.
[60] P. Karuppusamy, "A sensor based IoT monitoring system for electrical devices using Blynk framework," *Journal of Electronics and Informatics*, vol. 2, no. 3, pp. 182-187, 2020.
[61] A. Kurde and V. Kulkarni, "IOT based smart power metering," *International Journal of Scientific and Research Publications*, vol. 6, no. 9, pp. 411-415, 2016.
[62] V. Namboodiri, V. Aravinthan, S. N. Mohapatra, B. Karimi, and W. Jewell, "Toward a secure wireless-based home area network for metering in smart grids," *IEEE Systems Journal*, vol. 8, no. 2, pp. 509-520, 2013. https://doi.org/10.1109/JSYST.2013.2260700
[63] W. Xu, M. Dong, P. Meira, and W. Freitas, "An event window based load monitoring technique for smart meters," in *2014 IEEE PES General Meeting| Conference & Exposition (pp. 1-1). IEEE*, 2014.
[64] M. Esmaeili *et al.*, "Generative adversarial networks for anomaly detection in biomedical imaging: A study on seven medical image datasets," *IEEE Access*, vol. 11, pp. 17906-17921, 2023. https://doi.org/10.1109/ACCESS.2023.3244741
[65] A. K. Mishra, A. K. Tyagi, Richa, and S. R. Patra, *Introduction to machine learning and artificial intelligence in banking and finance. In Applications of Block Chain technology and Artificial Intelligence: Lead-ins in Banking, Finance, and Capital Market*. Cham: Springer International Publishing, 2024.
[66] M. M. Alam, M. Hossain, M. A. Habib, M. Arafat, and M. Hannan, "Artificial intelligence integrated grid systems: Technologies, potential frameworks, challenges, and research directions," *Renewable and Sustainable Energy Reviews*, vol. 211, p. 115251, 2025. https://doi.org/10.1016/j.rser.2024.115251
[67] R. E. Ogu, C. I. Ikerionwu, and I. I. Ayogu, "Leveraging artificial intelligence of things for anomaly detection in advanced metering infrastructures," in *2020 IEEE 2nd International Conference on Cyberspac (CYBER NIGERIA) (pp. 16-20). IEEE*, 2021.
[68] X. Liu, F. Liu, X. Liu, and Z. Xu, "Real-time access and processing of massive measurement data in smart power grids," *Applied Mathematics and Nonlinear Sciences*, vol. 9, no. 1, pp. 1–16, 2024. https://doi.org/10.2478/amns-2024-1479
[69] S. Tan, W.-Z. Song, M. Stewart, J. Yang, and L. Tong, "Online data integrity attacks against real-time electrical market in smart grid," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 313-322, 2016. https://doi.org/10.1109/TSG.2016.2550801
[70] P. Pal, N. Narayanasamy, and A. S. Babu, "Design and implementation of smart meter for bilateral transaction of solar energy," in *International Conference on Advanced Network Technologies and Intelligent Computing (pp. 44-64). Cham: Springer Nature Switzerland*, 2023.
[71] J. Qian, Z. Cao, X. Dong, J. Shen, Z. Liu, and Y. Ye, "Two secure and efficient lightweight data aggregation schemes for smart grid," *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 2625-2637, 2020.
[72] S. Gardiner, "Improvement in apparatus for measuring the electric current used for electroplating," U.S. Patent No. 133,188. United States Patent and Trademark Office, 1872.
[73] N. Uribe-Pérez, L. Hernández, D. De la Vega, and I. Angulo, "State of the art and trends review of smart metering in electricity grids," *Applied Sciences*, vol. 6, no. 3, p. 68, 2016. https://doi.org/10.3390/app6030068
[74] T. Paraskevakos, "Sensor monitoring device," U.S. Patent No. 3,812,296. United States Patent and Trademark Office, 1977.

[75] F. Borges de Oliveira, *Background and models. In On Privacy-Preserving Protocols for Smart Metering Systems: Security and Privacy in Smart Grids*. Cham: Springer, 2017.

[76] E.-A. Maria, G.-P. Limniou, and S. Kokkaliaris, "The energy efficiency directive and the challenges for the Hellenic legislative process in times of crisis," *Advances in Building Energy Research*, vol. 7, no. 1, pp. 128-154, 2013. https://doi.org/10.1080/17512549.2013.809273

[77] J. Kim, J. Lee, J. Kim, and J. Yun, "M2M service platforms: Survey, issues, and enabling technologies," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 1, pp. 61-76, 2013.

[78] G. López, J. Moreno, H. Amarís, and F. Salazar, "Paving the road toward Smart Grids through large-scale advanced metering infrastructures," *Electric Power Systems Research*, vol. 120, pp. 194-205, 2015. https://doi.org/10.1016/j.epsr.2014.05.006

[79] M. R. Hossain, A. M. T. Oo, and A. S. Ali, "Evolution of smart grid and some pertinent issues," in *2010 20th Australasian Universities Power Engineering Conference (pp. 1-6). IEEE*, 2010.

[80] H. Farhangi, "The path of the smart grid," *IEEE Power and Energy Magazine*, vol. 8, no. 1, pp. 18-28, 2009.

[81] V. Marinakis *et al.*, "From big data to smart energy services: An application for intelligent energy management," *Future Generation Computer Systems*, vol. 110, pp. 572-586, 2020. https://doi.org/10.1016/j.future.2018.04.062

[82] R. Manjulalayam, B. Vyas, R. Patel, A. Goswami, H. Mistry, and C. Mavani, "A comparative study of deep learning architectures for activity Recognition," presented at the 2024 3rd International Conference on Computational Modelling, Simulation and Optimization (ICCMSO) (pp. 95-101). IEEE, 2024.

[83] L. Zhang, E. C. Kerrigan, and B. C. Pal, "Optimal communication scheduling in the smart grid," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 9, pp. 5257-5265, 2019. https://doi.org/10.1109/TII.2019.2915051

[84] R. W. R. de Souza, L. R. Moreira, J. J. Rodrigues, R. R. Moreira, and V. H. C. de Albuquerque, "Deploying wireless sensor networks–based smart grid for smart meters monitoring and control," *International Journal of Communication Systems*, vol. 31, no. 10, p. e3557, 2018. https://doi.org/10.1002/dac.3557

[85] S. H. Mir, S. Ashruf, Y. Bhat, and N. Beigh, "Review on smart electric metering system based on GSM/IOT," *Asian Journal of Electrical Sciences*, vol. 8, no. 1, pp. 1-6, 2019. https://doi.org/10.51983/ajes-2019.8.1.2340

[86] B. Chun, B. Oh, C. Cho, and D. Lee, "Design and implementation of lightweight messaging middleware for edge computing," in *Proceedings of the 6th International Conference on Control, Mechatronics and Automation*, 2018.

[87] T. Adegbija, R. Lysecky, and V. V. Kumar, "Right-provisioned IoT edge computing: An overview," in *Proceedings of the 2019 Great Lakes Symposium on VLSI*, 2019.

[88] T. Bian and Z.-P. Jiang, "Reinforcement learning for linear continuous-time systems: An incremental learning approach," *IEEE/CAA Journal of Automatica Sinica*, vol. 6, no. 2, pp. 433-440, 2019. https://doi.org/10.1109/JAS.2019.1911390

[89] M. F. Khan, A. Jain, V. Arunachalam, and A. Paventhan, "Roadmap for smart metering deployment for Indian smart grid," in *2014 IEEE PES General Meeting| Conference & Exposition (pp. 1-5). IEEE*, 2014.

[90] J. Liu, M. Yang, Y. Yu, H. Xu, K. Li, and X. Zhou, "Large language models in bioinformatics: Applications and perspectives," *arXiv preprint arXiv:2401.04155*, 2024.

[91] O. F. Mohasen and U. Baroudi, "Federated learning: The effect of device clustering for multi-hop networks," presented at the International Wireless Communications and Mobile Computing (IWCMC), 2022.

[92] X. Chen, G. Zhu, Y. Deng, and Y. Fang, "Federated learning over multihop wireless networks with in-network aggregation," *IEEE Transactions on Wireless Communications*, vol. 21, no. 6, pp. 4622-4634, 2022.

[93] P. Pinyoanuntapong, P. Janakaraj, P. Wang, M. Lee, and C. Chen, "Fedair: Towards multi-hop federated learning over-the-air," in *IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, 2020: IEEE, pp. 1-5.

[94] T. V. Nguyen, N. D. Ho, H. T. Hoang, C. D. Do, and K.-S. Wong, "Toward efficient hierarchical federated learning design over multi-hop wireless communications networks," *IEEE Access*, vol. 10, pp. 111910-111922, 2022.

[95] M. Cash, J. Murphy, and A. Wyglinski, "WIP: Federated learning for routing in swarm based distributed multi-hop networks," in *IEEE 24th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2023, pp. 316-319.

[96] C. Pasqualon, Y. F. Coutinho, T. F. Moreira, and M. V. Ribeiro, "Improving user interaction in smart metering systems through ai-powered conversational interfaces," in *Proceedings of Brazilian Congress of Automation (CBA 2024). Universidade Federal de Juiz de Fora, MG, Brazil*, 2024.

[97] S. Jiang *et al.*, "Privacy-preserving and efficient multi-keyword search over encrypted data on blockchain," in *2019 IEEE International Conference on Blockchain (Blockchain) (pp. 405-410). IEEE*, 2019.

[98] S. Jiang, J. Cao, H. Wu, Y. Yang, M. Ma, and J. He, "Blochie: a blockchain-based platform for healthcare information exchange," in *2018 IEEE International Conference on Smart Computing (smartcomp) (pp. 49-56). IEEE*, 2018.

[99] M. A. Khan *et al.*, "A deep learning-based intrusion detection system for MQTT enabled IoT," *Sensors*, vol. 21, no. 21, p. 7016, 2021. https://doi.org/10.3390/s21217016

[100] M. P. Maharani, P. T. Daely, J. M. Lee, and D.-S. Kim, "Attack detection in fog layer for iiot based on machine learning approach," in *2020 International Conference on Information and Communication Technology Convergence (ICTC) (pp. 1880-1882). IEEE*, 2020.

[101] A. Lahouar and J. Ben Hadj Slama, "Day-ahead load forecast using random forest and expert input selection," *Energy Conversion and Management*, vol. 103, pp. 1040-1051, 2015. https://doi.org/10.1016/j.enconman.2015.07.041

[102] R. Yao, N. Wang, Z. Liu, P. Chen, and X. Sheng, "Intrusion detection system in the advanced metering infrastructure: A cross-layer feature-fusion cnn-lstm-based approach," *Sensors*, vol. 21, no. 2, p. 626, 2021. https://doi.org/10.3390/s21020626

[103] A. M. Mezher, C. L. Dueñas Santos, J. P. Astudillo Leon, J. Cárdenas-Barrera, J. Meng, and E. Castillo Guerra, "Are ML models scenario-independent in enhancing routing efficiency for smart grid networks?," in *Proceedings of the Int'l ACM Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks*, 2023, pp. 83-90.

[104] M. Shateri, F. Messina, P. Piantanida, and F. Labeau, "Privacy-cost management in smart meters using deep reinforcement learning," presented at the IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 2020.

[105] B. K. Barman, S. N. Yadav, S. Kumar, and S. Gope, "IOT based smart energy meter for efficient energy utilization in smart grid," in *International Conference on Power, Energy and Environment: Towards Smart Technology (ICEPE)*, 2018, pp. 1-5.

[106] K. Okafor, G. Ononiwu, U. Precious, and A. Godis, "Development of arduino based iot metering system for on-demand energy monitoring," *International Journal of Mechatronics, Electrical and Computer Technology*, vol. 7, no. 23, pp. 3208-3224, 2017.

[107] J. Fuentes-Velazquez, E. Beltran, E. Barocio, and C. Angeles-Camacho, "A fast automatic detection and classification of voltage magnitude anomalies in distribution network systems using PMU data," *Measurement*, vol. 192, p. 110816, 2022.

[108] Y. Wang, "Research on error and correction system of electric energy experimental metering device based on configuration design," *Third International Conference on Electronics and Communication; Network and Computer Technology*, vol. 12167, pp. 55-59, 2022.

[109] K. T. Islam, A. J. Islam, S. R. Pidim, A. Haque, M. T. H. Khan, and S. Morsalin, "A smart metering system for wireless power measurement with mobile application," presented at the International Conference on Electrical and Computer Engineering (ICECE), 2016.

[110] U. Assad *et al.*, "Smart grid, demand response and optimization: A critical review of computational methods," *Energies*, vol. 15, no. 6, p. 2003, 2022. https://doi.org/10.3390/en15062003

[111] W. Han and Y. Xiao, "FNFD: A fast scheme to detect and verify non-technical loss fraud in smart grid," in *Proceedings of the 2016 ACM International on Workshop on Traffic Measurements for Cybersecurity*, 2016, pp. 24-34.

[112] Z. A. Khan, M. Adil, N. Javaid, M. N. Saqib, M. Shafiq, and J.-G. Choi, "Electricity theft detection using supervised learning techniques on smart meter data," *Sustainability*, vol. 12, no. 19, p. 8023, 2020. https://doi.org/10.3390/su12198023

[113] A. Maamar and K. Benahmed, "Machine learning techniques for energy theft detection in AMI," in *Proceedings of the 2018 International Conference on Software Engineering and Information Management*, 2018.

[114] T. Balikhina, A. Al Maqousi, A. AlBanna, and F. Shhadeh, "System architecture for smart home meter," in *International Conference on the Applications of Information Technology in Developing Renewable Energy Processes & Systems (IT-DREPS)*, 2017.