Cloud and NB-IoT Integration for Automatic Meter Reading in Smart Grids: A Conceptual Implementation Framework and Requirements

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***Abstract*— Modernizing the energy sector relies heavily on the integration of smart metering systems and advanced measuring equipment to enhance the efficiency of power grid operations. Low-power, wide-area network capabilities of the Narrowband Internet of Things (NB-IoT) and Cloud platforms' computational efficiency make them ideal for integrating to transform the smart grid, especially Automatic Meter Reading (AMR). This paper examines NB-IoT's capacity, scalability, and cost-effectiveness to manage extensive deployments of smart metering devices, as well as the feasibility of combining Cloud and NB-IoT technologies to support energy monitoring and management. The integration of NB-IoT with Cloud platforms helps improve data storage, processing, and analytics capabilities, thereby addressing the requirements of existing AMR systems. The research conducted in this paper, along with the presented real-world smart metering scenarios, aims to offer better insights and recommendations for the effective implementation of integrated Cloud-NB-IoT smart metering systems.**

***Keywords*— 4G, AMR, Cloud, NB-IoT, smart grid, smart metering**

I. Introduction

Smart Grid (SG) is a conceptual model that will enhance the operation, control, and utilization of the electrical grid network and its related services. It is formed by a combination of power grid infrastructure and an accompanying information and communication technology (ICT) network [1]. Applying ICTs in power grid management results in the enhancement of efficiency, sustainability, and reliability, enabling bi-directional data flows for automated and intelligent energy systems [2, 3]. In the context of the SG, smart metering is an essential tool that enables consumers, as well as suppliers of energy, to have easy and convenient ways of measuring energy use by an individual consumer and exchanging data between the two parties in real-time for the benefit of both. Instead of using ad-hoc solutions, widespread communication solutions based on the existent telecommunication infrastructures can be leveraged for this purpose [2].

SG utilizes various ICT-based services, including the popular Internet of Things (IoT), to enhance its functions. IoT is a vital technology for SG applications, through which data gathering, processing, and sharing are established among physical entities. Customer-side measurement and management of energy can be done through IoT. It can be utilized to monitor power generation, energy storage, consumption, transmission lines, and substations. IoT advances the SG capability of warning, disaster recovery, and reliability [4, 5].

The rapid expansion of SG technologies has led to massive amounts of data being collected daily by smart meters, sensors, and other connected devices. Efficient management, processing, and analysis of this data are critical for the success of SG operations, which rely on continuous information exchange and near real-time decision-making [6]. Cloud computing solutions have emerged as the ideal approach to handle such demands due to their ability to efficiently manage large-scale data, providing the scalability, computational power, and flexibility required for SG systems [7]. In parallel, Narrowband IoT (NB-IoT) technology offers a low-power and resource-efficient version of IoT, making it particularly well-suited for large-scale SG initiatives. Its ability to manage the substantial connectivity requirements of these projects while operating on a narrow bandwidth enables reliable communication for a vast number of devices transmitting low data rates [1, 8]. Integrating NB-IoT and Cloud computing provides a promising solution for addressing the challenges of Automatic Meter Reading (AMR) in SGs. This paper investigates the integration of Cloud computing and NB-IoT technologies within AMR, aiming to discuss implementation options, technical and operational specifications, and potential advantages and challenges, to provide valuable insights and practical guidance for the development and adoption of next-generation AMR system - the Cloud-NB-IoT AMR system.

As a result, this paper is structured as follows. In the second section, which follows the Introduction, the key concepts, definitions, and performance of NB-IoT technology are presented. The third section explains how NB-IoT can support smart metering applications. The requirements and available solutions for AMR, specifically focusing on Cloud platforms and NB-IoT integration are given in the fourth section. Section five presents several case studies showcasing the practical applications of NB-IoT in smart electricity metering. The research concludes with a last section that presents concluding remarks and future research directions.

II. NB-IoT Technology

The primary objective of SGs is to incorporate cutting-edge communication technologies into power grids to collect and analyze data, identify valuable information, and optimize grid performance. The effectiveness of a successful smart metering system hinges on the communication technology used, which must be cost-efficient, guarantee a suitable transmission distance and capacity, offer security measures, and consume minimal power. No single communication solution can be considered the best option. The best option could be influenced by several considerations, such as existing infrastructure, regional geography, and the service functionalities the Distribution System Operator (DSO) wishes to introduce [2].

NB-IoT is a leading cellular, Low Power Wide Area (LPWA) technology that is part of the 3rd Generation Partnership Project (3GPP) cellular WAN technology family and its purpose is to offer low-cost, energy-efficient, wide-area cellular connectivity for IoT [9, 10]. The name implies the need for a narrow bandwidth for its functioning. NB-IoT is compatible with various cellular communication infrastructures and can be deployed standalone in areas where cellular networks are unavailable [11].

This technology is built upon 3GPP open specifications which date back several decades to the Global System for Mobile Communications (GSM) networks. Back then IoT devices were called machine-to-machine (M2M). For several years IoT devices simply ran on 2G/3G networks as the capabilities then did not far exceed the needs of narrowband devices. However, as 4G LTE progressed, the speed and bandwidth capabilities far exceeded the narrowband IoT needs. In 3GPP Rel-12, LTE Category 0 satisfied certain lower throughput requirements. Further technologies in Rel-13 and Rel-14 introduced LTE CatM, NB-IoT, and EC-GSM-IoT technologies to utilize existing LTE and GSM channel assignments. The comparison between the main cellular IoT device capabilities is shown in Table I. They have differing requirements in terms of bandwidth, data rate, modulation, antennas, latency, and battery life.

TABLE I. Comparison of 4G IoT device capabilities [12]

IoT technology capabilities	**LTE-M/(eMTC)**	**NB-IoT**
Standard	3GPP (Rel-13/14):	3GPP (Rel-13/14)
Spectrum bandwidth	Cat1: 1.4 MHz Cat2: 1.4/3/5 MHz	Licensed 700 – 900 MHz Channel bandwidth: 200 kHz in LTE channel, and in LTE guard bands
Duplex mode	FD/HD-FDD & TDD	HD-FDD & TDD
Antennas MIMO	1Tx1Rx	1Tx1Rx
Modulation	16QAM	BPSK & QPSK
Max data rate (DL/UL)	CatM1: 0.60 – 1.119 Mbps CatM2: 4 – 7 Mbps	CatNB1: 20-66 kbps CatNB2: 120-166 kbps
Latency	10 ms to 15 ms	1.6 s to 10 s
Energy consumption	Low	Low
Battery	up to 10 years	up to 10 years
Cost	Low	Low
Network size	<50000	<50000
UE transmit power	20 dBm or 23 dBm	20 dBm or 23 dBm

NB-IoT and LTE-M are 3GPP standards that will coexist with other 5G technologies, fulfilling long-term 5G LPWA requirements. In other words, they both are crucial for future 5G networks to meet the density and latency demands of massive machine-type communication (mMTC) [13].

Technical specifications for NB-IoT are defined in 3GPP Rel-13 [14]. NB-IoT provides extensive coverage area, low power usage, a cost-efficient deployment method, and enhanced data transmission capabilities [15] (Fig. 1). NB-IoT's capability to facilitate large-scale device connectivity while using minimal energy makes it highly suitable for SG functions, enabling measurement, control, protection, and monitoring of SG and its components [1]. It is particularly well-suited for smart metering thanks to its ability to support a large number of connections, low data transmission rate requirements, cost efficiency, reliability, security features, ease of integration with existing infrastructure, and real-time monitoring and control capabilities [16]. On the other side, the challenges NB-IoT is encountering include limited bandwidth, difficulties in network compatibility, regulatory obstacles, market competition, and the need for device ecosystem development (Fig. 1).

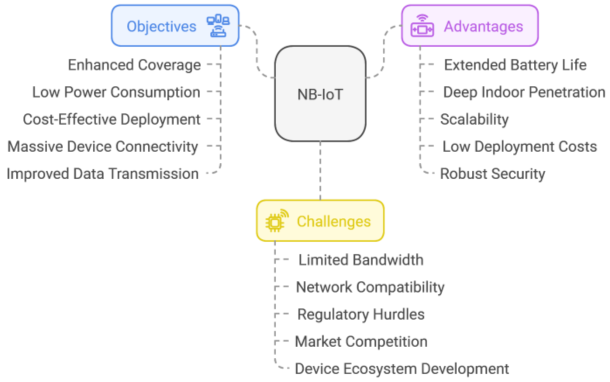

Fig. 1. NB-IoT: Objectives, advantages, and challenges

III. NB-IoT Network Performance to Support Smart-Metering Applications

The key factors that have to be considered when a communication system is chosen within SG applications are its availability, scalability, reliability, Quality of Service (QoS), data volume, network throughput, and latency. The system should be operational and user-friendly, particularly for individuals residing in rural and distant regions. The system should be reliable, guaranteeing secure and uninterrupted data transmission from end to end, along with backup systems. To maintain optimal communication performance, the system needs to guarantee accurate data to prevent congestion when user density and device connections continue to rise. Communication technologies and protocols must take into account the maximum amount of information transmitted over specific time intervals [2]. In addition to NB-IoT performance indicators given in Table I, it is important to mention associated data rates (uplink:< 250 kbps, downlink: < 230 kbps), and coverage range (<35 km) [16].

The Advanced Metering Infrastructure (AMI) is a two-way communication network that combines smart meters, sensors, monitoring systems, computer equipment, software, and data management systems, to collect and distribute information between consumers and energy providers. This system provides utilities with access to remote meter management and outage detection capabilities, offering data and insights into energy consumption, power quality, voltage levels, and load profiles. NB-IoT's performance metrics enable it to meet the majority of AMI applications. The following are the major characteristics of NB-IoT that make it suitable for SG applications, including AMI [16]:

- Latency: The smart meter sends small amounts of data, primarily in uplink, with delay tolerance due to the wide transmission period [17]. NB-IoT is designed for latency-insensitive applications. In Rel-15, early data transmissions (EDT) for the smart metering scenarios are proposed to significantly reduce latency, achieving over 50% reductions for smaller message sizes, making it crucial for real-time applications and demand response strategies [18].
- Frequency range: To address line-of-sight problems and offer high-quality and cost-efficient communication services over utility service areas, SG applications may need to operate on the lower end of the frequency spectrum (below 2 GHz). NB-IoT meets this requirement because it utilizes a shared licensed frequency band with 3GPP cellular systems.
- Reliability: NB-IoT can provide greater reliability than unlicensed solutions by operating over cellular networks on licensed frequencies owned by operators. It offers robust and reliable communication in challenging environments like basements and rural areas, ensuring smart meters maintain connectivity for continuous monitoring and demand response. Rel-13 of the 3GPP proposes the repetition of data or control signals as a potential method to improve the transmission reliability of NB-IoT systems.
- Data rate: Data transmission rates for AMI and distribution automation are minimal, necessitating 200 kbps for each meter reading. NB-IoT technology, boasting a peak downlink data rate of 230 kbps and 250 kbps for the uplink, is particularly well-suited for low-data-rate applications such as AMI.
- Security: Effective security measures are essential for SGs. NB-IoT operates on standardized frequency bands - relies on cellular networks, which have inbuilt security features based on physical subscriber identification modules (SIM). NB-IoT can leverage the security and privacy capabilities of cellular networks, which include user identity confidentiality, entity authentication, confidentiality, data integrity, and mobile equipment identification.
- Scalability: Since the first 3GPP release of NB-IoT and LTE-M specifications in 2016, the growth in the number of connections and networks across the world has accelerated [15]. In densely urban environments, the number of smart meters is likely to rise substantially [17]. NB-IoT possesses the capability to support numerous low-throughput devices. NB-IoT technology has a maximum coupling loss (MCL) of 164 dB, offering extended coverage of 20 dB relative to legacy GPRS devices, and allowing for a range of up to 35 km. According to 3GPP Rel-13; NB1, an NB-IoT network can support up to 1,000 smart meters per single base station communicating within a 15-minute window [6]. Managing large-scale urban deployments effectively requires this capacity, which enables utilities to collect and process data from numerous devices in a timely and efficient manner [18].
- Flexibility: NB-IoT provides deployment flexibility with three alternatives: in-band, stand-alone, and guard-band [19]. It supports multiple data rates through tones or subcarriers, enabling higher data rates by expanding available bandwidth. Assigning devices with multiple tones or subcarriers has the potential to boost data rates by 12 times.
- Cost efficiency: Because a massive number of smart meters are needed, they must be cost-effective. NB-IoT technology is cost-effective, mainly due to reduced operational costs associated with its deployment and maintenance in comparison to conventional metering systems. This technology's low power usage also prolongs the lifespan of batteries in linked devices, resulting in a lower overall cost of ownership.
- Availability: The system's high availability enables its widespread deployment, making it a suitable choice for numerous smart metering applications.

A. *Demand Response Management and NB-IoT*

Demand Response (DR) general communication requirements, as identified in [16], are presented in Table II.

TABLE II. DEMAND RESPONSE GENERAL COMMUNICATION REQUIREMENTS

	Data rate	Latency	Reliability	Security	Coverage
Demand Response	14 - 100 kbps (per node/device)	500 ms - 1 min	>99%	High	5-10 km

However, the general communication requirements should be reassessed based on the specific needs of each DR program. DR programs are typically categorized into: incentive-based demand response (IBDR) and price-based demand response (PBDR). PBDR programs like Time-of-Use (TOU) or Real-Time Pricing (RTP) are less time-critical. IBDR programs, especially those involving ancillary services, such as frequency regulation, are designed for real-time or near-real-time execution.

Considering NB-IoT network performance, it is straightforward to conclude that most DR programs can be easily accommodated with this communication technology. However, frequency regulation, which requires lower latency and faster response times (typically within seconds or less), is generally unsuitable for NB-IoT due to its inherent communication delay. However, some simulation studies on NB-IoT smart metering applications, such as [18], indicate that transmission delays can be reduced to under 500 ms by utilizing the EDT feature.

IV. CLOUD PLATFORMS AND NB-IOT INTEGRATION: REQUIREMENTS AND AVAILABLE SOLUTIONS FOR AMR

By integrating NB-IoT and Cloud computing, the reliability of SG operation is significantly improved. NB-IoT's efficient, wide-area network ensures proper real-time monitoring and controlling of energy consumption in the whole grid. It accommodates numerous smart meters and sensors to guarantee data acquisition and precision [20]. On the other hand, Cloud computing offers reliable data storage and processing capabilities to the utilities for big data to be analyzed in real-time. Big data and the use of machine learning (ML) techniques can help forecast changes in demand and select the most efficient strategies for energy distribution, as well as for immediate identification of failures or faults. Fig. 2 illustrates an example of NB-IoT device integration with a Cloud platform via a narrowband data transmission link.

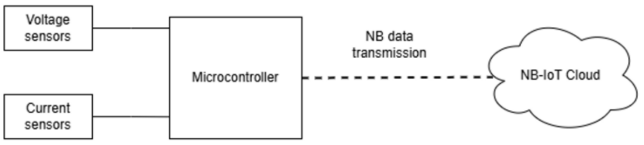

Fig. 2. The architecture of smart metering NB-IoT system

A. *Building NB-IoT-based smart metering systems*

The issues to consider in realizing smart metering infrastructure include the ability to meet increasing demand, connectivity, optimal use of power with minimal wastage, storage, protection and confidentiality of data, compatibility, and affordability (Fig. 3). It includes the ability to have thousands to millions of smart meters reporting data simultaneously, the secure transfer of data using encryption and meeting current and forthcoming regulation compliance, interconnectivity with many different smart meters, IoT protocols, and other legacy systems while keeping the requirements for deployment and operationalization costs low.

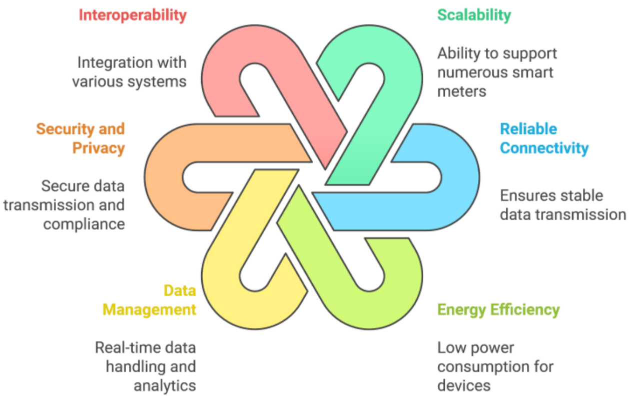

Fig. 3. Requirements for NB-IoT and Cloud platforms integration within a smart metering infrastructure

A smart metering system typically incorporates metering and communication infrastructures [21]:

- The metering part comprises time-of-use pricing control, a data management system, and an AMR framework.
- The communication part includes network connection and control infrastructure, which allows the meter to communicate with distant centers and execute control commands. Wired or wireless technologies can be used for two-way data exchange, enabling smart meters to timely obtain customer and utility grid information.

In addition to the two primary infrastructures, the smart metering modules comprise power supply, control, metering, timing, communication, indicating, encoding, and timing modules [21]. Software, as one of the crucial components of a smart metering system, must be modular, easy to expand, and simple to maintain through updates. It is also important to highlight that smart meters must meet different regulatory requirements based on the country in which they are installed. In the European Union (EU), the key standards comprise the EN 62056 series for data exchange and the IEC 62052, and IEC 62053 which specify general requirements, tests, and test conditions for electricity metering equipment.

Addressing all the challenges illustrated in Fig. 3 can be very costly and technically complex resulting in the adoption of standardized pre-built solutions.

1) *Standardized pre-built solutions*

There are several products currently available on the IoT market regarding NB-IoT Cloud integration with prominent commercial solutions including Amazon AWS IoT Core, Microsoft Azure IoT Hub, and Google Cloud IoT Core. All of these platforms offer similar core functionalities, including support for standard IoT communication protocols, robust scalability, advanced analytics as well as secure communication mechanisms [22]. These features make them particularly suitable for managing NB-IoT deployments of any size including large-scale deployments which involve a vast number of devices spread across wide geographical areas. NB-IoT devices in smart meters utilize lightweight protocols like HTTP or Message Queuing Telemetry Transport (MQTT) which enable communication with servers. These Cloud platforms provide the capability to manage thousands of smart meters at scale, supporting remote monitoring, telemetry, and over-the-air (OTA) [23] updates which minimize the need for physical intervention and reduce operational costs. When metering data is transmitted to the Cloud, services such as AWS Analytics, Azure Stream Analytics, and Google Cloud BigQuery can process the data and provide valuable insights, such as optimized energy distribution, anomaly detection, and demand forecasting. Since enterprise-level solutions are not always needed, platforms like Thinger and ThingSpeak are valuable NB-IoT Cloud alternatives [24]. These platforms offer fast, real-time data processing as well as storage capacities and reliability but lack computing power, robust scalability, and advanced security features making them less suited for large, complex deployments.

However, the downside of pre-made solutions is relying on third-party services, which can be problematic when attempting to develop an independent product with distinct intellectual property (IP) and more specific functions.

2) *A Custom-Built Solution*

An alternative to standardized pre-built solutions is to create an in-house, custom-built solution. This approach involves designing a database with all necessary entities, developing the accompanying backend service, and creating endpoints for HTTP-based communication or topics when implementing an MQTT broker. One of the examples employs Mosquitto MQTT broker along with MySQL database and backend written in Node-RED programming language [25].

Developing a custom NB-IoT Cloud solution offers several advantages and the most important one is full control over the architecture of the system. This ensures that the solution is in accordance with specific requirements while also complying with the constraints of the project. Additionally, it provides the flexibility to incorporate unique features and functionalities that may not be available on general-purpose IoT Cloud platforms. However, this approach requires significant investment in resources, expertise, and time. One of the main problems with custom solutions is robust scaling where a large number of NB-IoT devices can flood the Cloud with requests making it unstable or even unresponsive.

V. Real-world applications of NB-IoT in smart electricity metering

The following case studies highlight the real-world applications of NB-IoT in smart electricity metering, showcasing its potential to deliver scalable, reliable, and cost-effective solutions for modern utilities.

A. NB-IoT-based Smart Meter IoT Trial in Portugal [26-28]

One notable initiative for the integration of NB-IoT technology into smart electricity metering is the NB-IoT pilot project conducted by EDP Distribuição (now E-REDES) in Lisbon, Portugal.

The pilot project brought together several key players [26, 28]:

- **EDP Distribuição**: Portugal's primary electricity distribution company, responsible for leading the pilot.
- **NOS**: A Portuguese telecommunications and media company that deployed the NB-IoT network infrastructure.
- **Huawei**: Provided the underlying technology for the 4.5G NB-IoT network.
- **Janz CE**: Designed and manufactured the new smart meters.
- **u-blox**: Supplied the NB-IoT modules integrated into the meters.

The pilot project was conducted in the Parque das Nações area of Lisbon, selected for its existing infrastructure and suitability for early adoption. The area is served by two NOS base stations providing 3GPP-standardized NB-IoT coverage. The project involved approximately 100 customers and aimed to test the feasibility and reliability of NB-IoT technology in smart metering. The initiative was part of the UPGRID project, funded under the European Commission's Horizon 2020 Program [16]. The infrastructure network for the pilot was installed by NOS, utilizing Huawei's NB-IoT technology, making NOS the first operator in Portugal and one of the first globally to deploy this standardized technology.

Despite this pilot project's promising aspects, there is a notable lack of publicly available technical data regarding its performance and outcomes. This limitation poses challenges for stakeholders seeking to evaluate the feasibility and scalability of similar projects.

B. China Mobile Electric Smart Metering [29]

China Mobile is using NB-IoT technology to transform AMR for improved electricity management in utilities and urban areas. The system combines NB-IoT smart meters with OneNET, a Cloud-based platform, to facilitate deployment in industrial parks, buildings, and residential areas. This integration enhances data accuracy, simplifies processes, and ensures real-time monitoring. In collaboration with the State Grid Electric Power Research Institute and Provincial Metrology Institute, China Mobile has deployed 200 NB-IoT smart meters in cities like Yingtan, Wuxi, Zhuhai, Chengdu, Chongqing, and Beijing. The AMR service, which runs over 2G or 4G networks, captures real-time data including voltage, current, and power consumption, and helps utilities optimize electricity supply and billing.

Pilot tests demonstrated benefits such as reliable meter reading, device management, report generation, and installation tracking. Smart NB-IoT meters simplify installation and maintenance and reduce costs by eliminating manual readings and enabling real-time data transmission, which swiftly detects issues like power outages. Enhanced network coverage ensures that these meters function in hard-to-reach locations, such as buildings and cabinets, by utilizing existing mobile networks for seamless connectivity. Deployment is straightforward, with pre-established network coverage allowing for flexible installation without additional planning. Moreover, NB-IoT provides secure communication through licensed spectrum and 4G-based encryption to protect data and ensure reliable service, making it an efficient solution for modern utility management. NB-IoT's standardized approach enables China Mobile to reduce costs, simplify operations, and efficiently manage large-scale smart metering networks, making it an ideal solution for scaling systems with cost savings and operational efficiency. The success of the pilot program has encouraged China Mobile to expand its NB-IoT smart metering system improving electricity network efficiency and coverage across the country.

C. NB-IoT Pilot Project for Munich Airport [30]

Munich Airport faced challenges with insufficient signal strength in buildings and underground areas, limiting sensor applications. The adoption of NB-IoT resolved these issues, enabling innovative sensor deployment and supporting digitalization efforts. To automate energy data logging from analog electricity meters and centralize data access for its IT department, the airport collaborated with Huawei, Telefónica Germany, and Q-loud to implement a smart retrofit solution. The solution integrates Q-loud's EnergyCam, which digitizes analog meter readings by capturing images of rolling counters, analyzing and identifying the readings through embedded software, and transmitting them via Telefónica Germany's NB-IoT network to Huawei's OceanConnect IoT platform. This innovative approach eliminates the need for manual readings, significantly reducing the time and effort required to coordinate with tenants and visit properties while supporting hundreds of meters both on-site and across a 10 km radius. By utilizing a pre-integrated, ready-to-deploy solution like EnergyCam, the airport has modernized its legacy systems and created a more efficient, reliable process for energy data collection, paving the way for broader IoT applications.

By transforming traditional energy meters into smart devices, the airport's IT department gains seamless access to real-time consumption data, enabling prompt responses to unplanned usage changes. The solution avoids infrastructure replacement costs, ensures error-free automated data processing, and supports compliance with ISO DIN ISO 50004, and 50015 standards, fostering efficient energy management.

VI. Conclusion

The NB-IoT technology and the feasibility of combining it with the Cloud platforms to transform smart metering applications have been examined in this paper. The integration brings together low-power, wide-area aspects of NB-IoT with scalable, data-intensive processing features of Cloud platforms, allowing for efficient, reliable, and cost-effective energy monitoring and management. Despite numerous advantages, enhancing device energy efficiency, ensuring extensive network coverage, and addressing data security issues remain challenging tasks. This paper also presents several case studies concerning the practical uses of NB-IoT in smart electricity metering.

Conducted research provides a foundation for developing custom-built smart metering system and demonstrates the importance of Cloud and NB-IoT technologies integration in promoting innovation and efficiency within energy management systems. Future research will be based on the practical implementation of smart metering system, and the application of advanced analytics.

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