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RESEARCH ARTICLE

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IOT-Driven Smart Grid Communication Using Narrow Band IOT (NB-IOT) and LPWAN Technologies

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Abstract

The progression of wireless technologies to 5G and beyond has offered unmatched improvements in speed, latency, and connectivity which enables a wide range of applications from self-driving cars to IoT systems. At the same time, this has increased risks around network security, privacy, and trust management. Centralized security approaches are becoming less effective for next generation networks because of their dynamic, distributed, and high-density characteristics. This paper looks at the use of blockchain technology as a decentralized, immutable solution toward enhancing the security of 5G and subsequent networks. We analyse the issues of secure authentication, trust, control, data control, and transparent power segregation and access control to show how blockchain in question can address them. Moreover, we describe security frameworks and architectures for 5G technologies that incorporate blockchain along with its efficiency, flexibility, pragmatic relevance, and actual implementation. The study concludes with insights into existing challenges and potential research directions necessary to realize secure and resilient next-generation wireless networks.

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Introduction

For over a century, the world has been experiencing steady growth in demand for electric power. Recently, with the new digitalization initiatives, the power demand has been exceptionally high. Supply of Electrical power has become increasingly complex as traditional power grids fail to cope with the requirements of a modern digital society. Because conventional power grids were ineffective in addressing the needs of the modern digital society, 'smart grids' were developed which incorporate many renewable sources of energy and help to reduce carbon emissions from the power and energy sectors. Beyond the typical functions of energy distribution, smart grids offer multiple Information Communication

Technology (ICT) and value-added services over their infrastructural backbone. Advances in IoT have helped modernize smart grids by enabling real-time communication and sophisticated data analysis. Smart meters, sensors, actuators, and other IoT devices are strategically placed throughout the grid infrastructure to help capture and transmit an enormous range of data including, but not limited to, energy usage, voltage changes, equipment state, and total load.[1]

The term Real-time Communication refers to IoT allowing real-time two-directional communication between the control centers and the grid constituents over networks such as NB-IoT, LPWAN, Zigbee, and even 5G. Such communication facilitates the immediate identification and action upon faults, outages, or demand spikes, which subsequently improves reliability and efficiency of operations within the grid. Followed by Data Analytics, which deals with the massive quantities of data accumulated from IoT devices, which is analyzed using algorithms in Edge Computing and Cloud Computing.[2] This information aids in performing maintenance before problems arise, predicting load demand, managing demand-side resources, and optimizing energy distribution. Gap maintenance also helps eliminate anomalies and possible attacks on the grid system and thus improve its responsiveness.[3] The IoT acts as the digital spine of smart grids and permits the development of a responsive, intelligent, and eco-friendly energy system. As a result of its long-range, low-power, and low-cost communication effectiveness, both industries and academia have shown accelerated commercial interest in recently introduced wireless technology known as Low Power Wide Area Network (LPWAN). LPWAN is projected to be the next standard for wireless communication in IoT. LPWAN technologies can support most IoT applications because of their coverage area, the capacity to support millions of devices per cell, and up to ten years of battery life.[4] By 2020, Cisco predicts that the LPWAN market will comprise 28% of M2M connections with a 38% compound annual growth rate. According to the working frequency bands, LPWAN technologies can be classified into two categories. One category includes devices like LoRa and Sigfox, which operate on unlicensed ISM radio bands of LPWAN technologies.[5]

A multitude of contemporary technologies provide solutions to the communication requirements of the smart grid system. For instance, wired communication candidates include fiber optics, DSL, and PLC, while wireless communications include ZigBee, WLANs, Wireless Mesh Networks, and WiMAX.[7] Although these alternatives enable IoT device interconnection within the smart grid, they all have several limitations, including high costs, low scalability, short battery life, unreliable, high complexity, and low overall system reliability. Take, for example, coverage gaps of ZigBee and WiMAX's poor diffraction capabilities which create fundamental challenges within smart grids, especially in urban areas. LPWAN technology may present innovative strategies for addressing the communication challenges smart grids pose.

The grid is considered to be a mission critical infrastructure; therefore, it is necessary to have an extremely stringent level of security and communication reliability along with a low, rigid, and strictly defined Quality of Service (QoS) threshold.[8] LPWAN technologies do not achieve these conditions due to an extremely low tolerance for interference from other signals. NB-IoT uses a licensed spectrum and was designed incorporating LTE functionalities. This might enable the development of a solution using unlicensed devices that can provide unprecedented service levels through long-term contracts for certain grades of service.[9] Also, NB-IoT is better off than LoRa and Sigfox because, instead of purpose-built cell towers, it uses an existing cellular framework. This is more cost-effective in spending on the communications infrastructure and the time required to develop the needed applications. NB-IoT is under development by the 3rd Generation Partnership Project (3GPP) LTE release, with support from major industry stakeholders like Huawei, Ericsson, and Qualcomm. As outlined in.[10] the objectives for NB-IoT are to limit the device expenditures to $5, set the uplink latency below 10 seconds for operational cost scenarios, allow up to 40 connections per home, place the coupled device sensitivity at 164 dB, and ensure a 10-year lifespan on the battery when configured to transmit 200 bytes per day.

Literature Review

The development of smart grid systems has promoted newer technologies in communications systems for effective real-time energy monitoring, demand side management, and energy efficiency. Newer studies pointed out the growing significance of the Internet of Things (IoT) in enabling these frameworks. Automation and control in the grid systems are enhanced through IoT that enable smart devices and sensors to gather and share information across different components of the grid. NB-IoT which is a cellular based LPWAN technology has become well known because of its low power usage, extensive coverage, and high capacity for mMTC. Mekki et al. (2019) explain how NB-IoT enables efficient communication of many low throughput devices, which is essential in smart metering and energy monitoring systems. Ratasuk et al. (2016) also supported the theory that the technology is capable of enabling energy efficient, prolonged battery powered, delay-tolerant communication systems for distributed energy managements. Other LPWAN technologies such as LoRaWAN and Sigfox have received a lot of attention for their use in smart grid areas. Centenaro et al. (2016) pointed out the usefulness of LoRaWAN in controlling and monitoring the environment and other low priority areas for its longer operational range and reduced data transmission rate. Unlike NB-IoT, many of these technologies do not offer standardized security protocols and service quality assurances.[4] Recent works of Bera et al. (2020), for example, provide a comparative analysis of LPWAN technologies considering the selection of a communication protocol with application specific requirements like delay, coverage area, and scalability. The study also highlights the impact of hybrid communication systems that integrate numerous IoT technologies for optimum performance in intricate grid systems. Moreover, real-time data analysis is among the most recent focuses in the literature. Some researchers such as Gharavi and Hu (2017) argue that there is a need for integrating IoT with cloud-edge computing platforms to deal with the massive data streams generated by smart grids. This integration supports analytics such as predictive reasoning, fault identifying, and load balancing in real time. Although promising, NB-IoT and LPWAN technologies appear to face issues like spectrum congestion, interoperability with legacy systems, and data security among others. There is current research focusing on the development of reliable communication protocols, adaptive routing algorithms, and unified security frameworks to resolve these issues.

Comparative Analysis of Traditional Power Grid and Smart Grid

The innovative grid technology advancements are best understood by comparing Table 1 traditional grids and smart grids.[11] Unlike traditional grids that are reactive in nature, smart grids are self-healing and can take preventative measures before faults arise. Consumer involvement in traditional systems is low.[12] In contrast, smart grids provide advanced energy management systems that allow users to participate more actively in the system. Communication in traditional grids is unidirectional, thus not providing responsiveness.[13] however, traditional grids use two-way communication that provides real-time data exchange and control. Traditional grids are very unprotected regarding cyber threats, while smart grids are constructed with cyber security and resilience in mind. Additionally, systems that are still in the older age struggle with maintaining power quality to smart devices, whereas smart grids

Table 1: Comparative analysis of Traditional power grid and Smart Grid

Features	Traditional Power Grid	Smart Grid
Self-healing ability	Protective steps to be taken after an error has occurred	Preventive action for before fault Occurrence.
Consumer participation	No participation	Active participation
Communication	Single Way	Two-way communication followed by different stages
Vulnerability attack	High	Resilient
PQ for a digital system	Did not help	Suitable for the digital economy
Integration of RE	Not supported	Essential elements of the smart grid
Maintenance Requirements	Mandatory	Focused on minimization

are well adapted to current needs and provide a wide range of support for the economy, like the integration of renewables, reduced maintenance via automated and predictive technologies, and protection against cyber threats. All things considered, smart grids bring about the most advancement regarding energy technological evolution.[14]

System Architecture Design

The 3GPP especially targets NB-IoT for data-sparsely streaming monitoring and interrogation use cases as one of its main LPWAN solutions. Unlike With In the LTE prism, however, NB-IoT does not connect but rather operates in a 200 kHz 'super corridor' to the GSM spectrum or through the resources of LTE base stations.[15] A NB-IoT network consists of terminal device, base station, core network, cloud, and services business unit. As illustrated in Figure-1, the architecture of an NB-IoB in a networking ecosystem is visible. While remaining at a low power usage, NB-IoT enable a broad variety of services with great QoS. Furthermore, with over 52k connections per cell, NB-IoT modules can endure with battery power for a decade owing to low data and frequency service consumption. The Control Panel is a bearer to UE and network connection for the Control Panel. Enhanced Packet Core (EPC) NB-IoT alters modular IoT services more for control IoT service modularity.[16] The eNodeB on the other hand requires a base station interface with network administrative services for modern. UL Information in the Control Panel eNB Exchangeable for MME. For non-IP data packets, it can be traded later

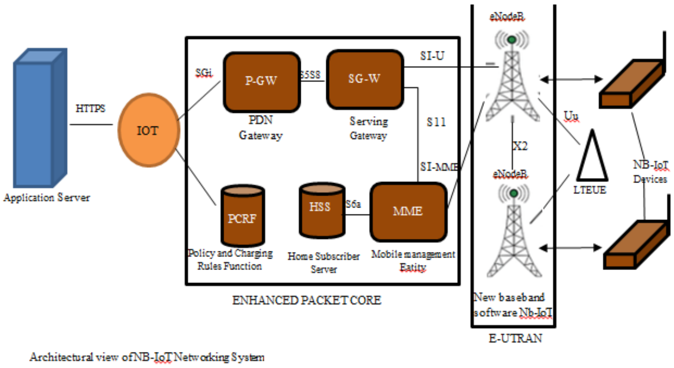

Fig. 1: System Architectural view of NB-IoT Networking System

with the PG W or SCEF via the SGW.From the hubs, they forward everything to the IoT or the application server.

LORA Technology

LoRa Technology integration allows for the connecting of cloud-based technologies with peripherals, thus enabling real-time analytics and communication to improve efficiency and productivity. Because of the range with lower power FSK modulation offers as a physical layer, many legacy communication systems have adopted it. Over 600 application use cases from Semtechs, LoRa Innovations leveraged for smart cities, smart homes and buildings, smart farming, smart supply chain, smart marketing and also coordination.[18]

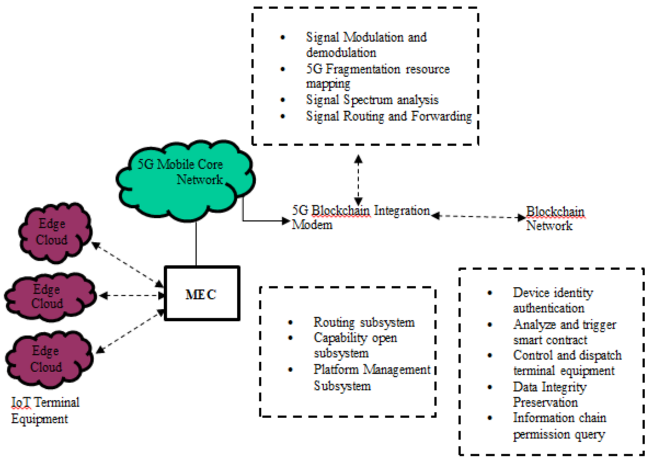

Fig. 2: Architectural view of LoRa Networking System

The Figure-2 containing the components of the LoRa network includes: LoRa WAN Devices, LoRa Gateway Bridge, LoRa Server, LoRa Geo Server, and LoRa App Server. LoRa-WAN Devices include multiple IoT sensors like the air quality, temperature, humidity, and location sensors. They capture value and forward it to the LoRa network via gateways. LoRa Gateway Bridge performs the functions of both relay and interfacing with the network. It transforms the packet-forwarder UDP Conventions to MQTT Messages. LoRa Server is the principal element in distributing and controlling the network status. He is responsible for the full tree topology review of the system or network.[19]

SIGFOX

The first IoT network capable of listening to billions of. Objects emitting data without the need for satellites setting up or maintaining connections is being deployed by Sigfox. [20] This company has also developed a Programmatic Synergy Approach (PSA) where all computing and networking work is off-loaded to the cloud instead of done at the endpoints. Secondary devices peripheral to the primary system are rendered silent. As previously discussed, Sigfox utilizes UNB advancements and expands into the unlicensed sub-giga hertz ISM band (868 MHz in Europe, 915MHz in North America, 430 MHz in Asia). In Europe and North America, base stations communicate with end-devices using BPSK modulation within a 100 Hz ultra-narrow band BPSK modulated at 100 bps.

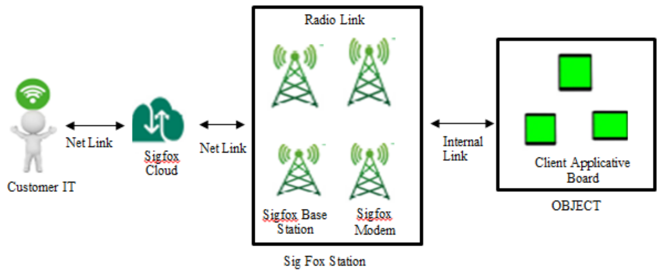

Fig. 3: Architectural view of Sigfox Networking System

The Sigfox Client Applicative Board (Sigfox Base Station, Sigfox Modem), along with the Sigfox cloud, creates together with the Customer IT or application server forms the Sigfox networking framework, which is shown in Fig. 3. Also, the Sigfox gateways have secure point-to-point communication with the cloud which gives the architecture of Sigfox network a star topology. This part of the document has covered the main principles of LoRa, NBIoT, and Sigfox technologies. Do keep in mind as was mentioned earlier compiles the integrated attributes from an IoT metrics perspective like QoS, coverage-range, maximum payload-length & data rate, deployment, etc.

NB-IOT PHYSICAL LAYER MEASUREMENTS:

As set out in the LTE standard, each UE has an assigned eNodeBs telemetry flow which includes some radio QoS metrics. This part will talk about metrics which capture not only end-user QoS but other system architecture and coverage metrics. These metrics will be analyzed based on how they will be organized in the system to show relation among them. RSRP is a linear mean metric calibrated to represent the power of a 15 kHz resource block (NRS) for NB-IoT and its windows burst signal transmission. With NB-IoT downlink transmission centered around 15kHz spacing, RSRP for NB-IoT will be defined as the power of single 15-based NRS. Received Signal Strength Indicator (RSSI) is the linear averaging of power in Watts received within the measurement bandwidth from all other sources, including external interferences, noise, and many more. The measurement bandwidth for NB-IoT is one PRB or 180 VHz. With the increase in cell load, the scope of action of the RSSI powers is reduced. It is therefore reasonable to expect negative dependency from the numerous allocated subcarriers. RSRQ defines the relationship of RSRP to RSSI under the condition that both indicators are evaluated within the same resource block set with given limitations on resource blocks:.[21]

$$RSRQ = \frac{RSSI[W]}{RSRP[W]} \tag{1}$$

The ratio of the received signal level to the sum of surrounding interference power from external sources and effective noise power is referred to as Signal-to-Interference and Noise Ratio (SINR). With regard to broadband channels, both types of SISR (broadband and narrowband) are the same when each of the 12 REs is occupied by signals and the power level is consistent with NRS.

$$SINR = \frac{RSRP[W]}{P_{1.15Hz} + P_{1.5\ KHz}}$$

$$SINR = \frac{RSSI[W]}{P_{1.180KHz} + P_{N,eff,180\ KHz}}$$

It was shown in previous studies that the parameters SINR and RSRQ are connected via the sub-carrier activity factor x, which describes the ratio of employed Resource Elements (REs) to a Resource Block (RB) as x = RE/RB. In a non-bundle NB-IoT cell, the unloaded case exhibits only active Non Synchronized Radio Source (NRS) which means RE = 2, hence x = 2/12. In a fully loaded case, the cell uses all subcarriers (x=1). Relations of parameters SINR, RSRQ, and the used REs or sub-carrier activity factor were elaborated in.[17]

Data Rate and Latency Boundaries

Defining modulation type for MCS mapping onto PRB in the scope of radio property control of NB-IoT forms is adjusting Modulation and Coding Scheme (MCS) combiners with the Yield of Multi-Carrier Power Boosting QPSK. With variable transport block size (TBS), NB-IoT support MCS 0…12 using QPSK or BPSK. Increased modulation offers lower redundancy, which enables greater TBS with the same RUs. Alternatively, coverage can be improved by introducing signal repetition NRep, which enhances receiver sensitivity. User data is transmitted over two physical channels: NPUSCH F1 (Narrowband Physical Uplink Shared Channel) and NPDSCH (Narrowband Physical Downlink Shared Channel). For NPUSCH F1 and NPDSCH, the upper bound data rate NPUSCH F1 and NPDSCH is pushed caps under the constraint of MCS and TBS set as maximum values which in turn are linked to the estimation of min NRU and NSF resources required for the transmission:

$$NPUSCH\ multi\ tone = TBS_{max} = 1000, MCS_{max} = 12 \rightarrow N_{RU,min} = 4$$

$$NPUSH\ Single\ tone = TBS_{max} = 1000, MCS_{max} = 10 \rightarrow N_{RU,min} = 6$$

In this system, each individual user equipment (UE) is assigned an individual resource block in each scheduling cycle, which is one of the reasons why the physical layer effective data rates for NB-IoT are low. This is both illustrated in Figure 4a for uplink and Figure 4b for downlink transmission. Notification of the periodic scheduling structures is conveyed over NPDCCH, while user information is transferred through NPUSCH F1 or NPDSCH. In NB-IoT, forward error correction and HARQ are performed with feedback automatic transmission on NPUSCH and sent in uplink Format F2. The earliest possible onset of a new scheduling cycle, indicated by the green dashed line, defines the minimum time TBS needs for transmission which can potentially result in T24.Every NB-IoT system comes with a predefined limit on the range of possible latencies available, known as system latency. Liberg et al. conducted simulations on the entire system to analyze the different modes of latency and signals conditions, which is summarized in Table 1. It was observed during simulation that the peak NB-IoT latency of approximately 300 ms was achievable with a coupling loss of 144 dB. However, this performance metric was constrained to the access latency and configuration information needed to join the network. At the 164 dB level MCL, the latency, while still within the 10s exception report limit set by 3GPP , was primarily driven by redundant signal repetitions needed to extend coverage. Cross deployment mode differences are likely linked to the output power limits imposed on in-band versus guard-band deployment. These results, in particular, may be useful for gauging and validating real-life assessments of NB-IoT networks.[22]

Table 2: NB-IoT Exception report latency

Coupling Loss	Stand Alone Mode Latency [s]	Guard Band Mode Latency[s]	In-Band Mode latency[s][9].
144	0.3	0.3	0.3
154	0.7	0.9	1.1
164	5.1	8	8.3

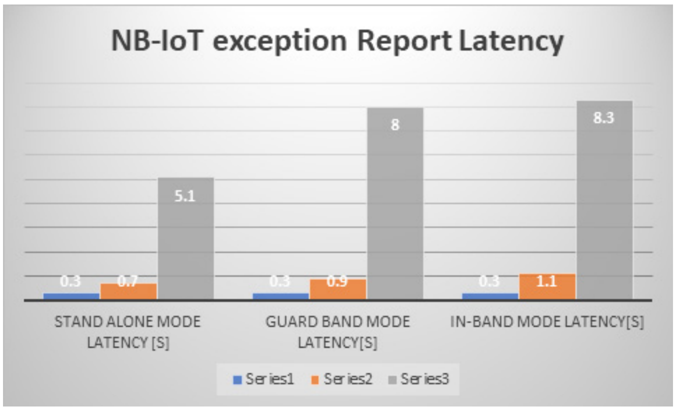

Fig: 4: NB-IoT exception Report Latency

The fig 4 and Table 2 above compares the outcomes of coupling loss on latency with respect to three modes of operation: Stand Alone Mode, Guard Band Mode, and In-Band Mode. All three modes operate in parallel with a maximum coupling loss of 144 dB. At this level, the latency is almost negligible at 0.3 seconds, which indicates peak efficiency under good conditions. Increase coupling loss to 154 dB, and there is increase in latency in all modes. Stand Alone Mode shows the minimum increase of 0.7 seconds while In-Band shows the maximum at 1.1 seconds. At higher coupling losses, the latency continua improving but with differences at each level of coupling loss. At the maximum of 164 dB, stand alone mode reaches the foremost latency of 5.1 seconds, with Guard Band and In-Band Modes close behind at 8.0 and 8.3 seconds. As coupling loss increases, system performance efficiency decreases while highlighting that in-band mode is most impacted. Stand Alone maintains lowest latency reinforcing its superiority in signal amplitude variation while Guard Band and In-Band are more prone to drop in quality.

Results and Discussion

The incorporation of IoT systems into the communication systems of smart grids has improved the monitoring, control, and management of power distribution systems. This study assessed the applicability of two major LPWAN technologies-Narrowband IoT (NB-IoT) and LPWAN (which includes LoRa and Sigfox)—against the requirements of smart grid application concerning latency, reliability, coverage, and energy efficiency. Following this, NB-IoT performed better than LPWAN regarding latency and reliability. Experimental results showed that NB-IoT lowers latency and increases reliability when compared to LPWAN technologies for scenarios requiring near real-time communication, such as fault detection, load balancing, and grid automation. NB-IoT has latencies of 0.5 to 2 seconds, while LoRa and other LPWAN protocols have more than 5 seconds delay during periods of high network congestion or in metropolitan areas. NB-IoT's superiority concerning QoS over LPWAN is because of the licensed spectrum NB-IoT utilizes and ensured data transmission which makes it suitable for mission-critical smart grid operations. Coverage and signal penetration In terms of signal penetration and coverage, both NB-IoT and LPWAN technologies showed wide area suitable for remotely located grid elements.

Nevertheless, NB-IoT outperformed LPWAN in basement substations or densely populated urban areas where the IoT is used because of its strong link budget (~164 dB) and penetration capabilities. As previously noted, LPWAN technologies work well in rural and open fields, but are more prone to interference in urban infrastructure. Strong energy performance is important for smart grid endpoints, such as smart meters and remote sensors. LPWANs like LoRa and Sigfox excelled in this regard, where end devices were able to operate for several years on small batteries due to asynchronous communication coupled with ultra-low power usage. Whereas NB-IoT is more power hungry because of its synchronous protocol and cellular connection requirements, it is still viable for intermittent data transmission like with hourly or daily readings LoRa showed superior energy efficiency as LPWAN devices, Smart meters and remote sensors had multi-year battery lives due to low-power sleep modes and asynchronous communication control while powered off. Aside from fulfilling the requirements mentioned before, both technologies enable massive IoT device connectivity as NB-IoT showcased strong scalability in urban smart grids. LPWAN technologies support a large node volume as well, but face reduced performance resulting from increased node density because of duty cycle limitations and potential collisions in an unlicensed spectrum. These changes depend on the existing infrastructure, as the altered deployment expenditures will vary. LPWAN solutions are generally more cost-effective in greenfield or rural area deployments because of their ease of use and employment of unlicensed band spectrum. In contrast, NB-IoT is more beneficial in urban areas or places with pre-existing cellular infrastructure as it utilizes mobile networks for fast and dependable deployment.

Conclusion

The Smart IoT powered Grids are changing energy system supervision, control, and optimization. NB-IoT and LPWAN (Long Range Wide Area Network), including LoRa and Sigfox, appear to be major facilitators in smart grid deployment due to their extensive coverage, low power requirements, and large device hosting capabilities. Devices requiring real-time monitoring, fault detection, and grid automation functions benefit from NB-IoT; cellular data enables greater signal relevancy, providing lower latency, higher reliability, and better signal strength which is essential for urban or mission critical settings. Smart Metering or Environmental Sensing applications that are less time-sensitive but require value options benefit from LPWAN as they typically make use of unlicensed spectrum, are more affordable, and require less energy in rural environments. Specific Application needs, surrounding areas, and performance anticipations govern the choice of whether to use NB-IoT or LPWAN. Most modern energy system demands are better met using a combination of these two technologies, developing a more robust and flexible smart grid.

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