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An Internet of Energy Things Based on Wireless LPWAN

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ABSTRACT

Under intense environmental pressure, the global energy sector is promoting the integration of renewable energy into interconnected energy systems. The demand-side management (DSM) of energy systems has drawn considerable industrial and academic attention in attempts to form new flexibilities to respond to variations in renewable energy inputs to the system. However, many DSM concepts are still in the experimental demonstration phase. One of the obstacles to DSM usage is that the current information infrastructure was mainly designed for centralized systems, and does not meet DSM requirements. To overcome this barrier, this paper proposes a novel information infrastructure named the Internet of Energy Things (IoET) in order to make DSM practicable by basing it on the latest wireless communication technology: the low-power wide-area network (LPWAN). The primary advantage of LPWAN over general packet radio service (GPRS) and area Internet of Things (IoT) is its wide-area coverage, which comes with minimum power consumption and maintenance costs. Against this background, this paper briefly reviews the representative LPWAN technologies of narrow-band Internet of Things (NB-IoT) and Long Range (LoRa) technology, and compares them with GPRS and area IoT technology. Next, a wireless-to-cloud architecture is proposed for the IoET, based on the main technical features of LPWAN. Finally, this paper looks forward to the potential of IoET in various DSM application scenarios.

1. Introduction

Under intense environmental pressure, the global energy sector is transitioning toward clean and sustainable development. The concept of the smart grid has been widely accepted in the last decade as a means of integrating higher percentages of renewables [1,2]. In 2016, China's government announced new policies on combining the Internet with smart energy in order to demonstrate new clean energy technologies [3,4]. The government and the energy industry have recognized that the construction of an energy-Internet backbone via smart grid is the core strategy to promote a clean energy revolution for a new era.

A clean energy system requests a robust communication infrastructure that can accept greater variation from renewable energy inputs [5]. From the perspective of control theory, maximizing system observabilities enhances the system controllability. To balance a complex energy system, it is therefore necessary to obtain abundant information from both the supply and demand side. The information Internet is a reliable tool that can collect information at zero marginal cost. Nevertheless, energy systems are still restricted by closed-information environments due to management and technical issues.

Particularly on the demand side, for example, communication infrastructure is incomplete at the power distribution level [6], and even less communication infrastructure is available for utilization systems at lower voltage levels. Despite developments in the smart grid over the last decade, periphery energy networks are still out of the scope of system operators [7].

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Management is not the only problem, as technology also plays a critical role in the issue of demand-side management (DSM). The current power automation architecture was developed based on standards to satisfy the particular requirements of centralized generation and transmission systems [8]. With the rapid integration of distributed energy resources, the current design cannot meet the requirements of the fast changes that are happening on the demand side. Meanwhile, the end users do not have the expertise required to operate and maintain such complicated systems. Under these circumstances, technical complexity has become a major bottleneck restricting the acceptance of DSM applications such as demand response in the real world [9,10].

To overcome this barrier, low-power wide-area network (LPWAN) is a new solution in the context of a wireless breakthrough in the communication sector. Unlike WiFi and ZigBee, LPWAN enables massive wireless connections covering long distances with minimum power consumption and maintenance [11]. Two representative technologies of LPWAN are the narrow-band Internet of Things (NB-IoT) [12] and Long Range (LoRa) technology [13]. The NB-IoT is inherited from cellular communication, and seamlessly works on the existing global system for mobile (GSM) and long term evolution (LTE) networks in licensed frequency bands [14]. Many telecom operators have been ambitiously working on weaving together city-scale Internet of Things (IoT) networks based on NB-IoT. In contrast, LoRa technology operates in the unlicensed frequency band, so that end users are free to build up LoRa gateways that are similar to house-owned WiFi routers. Therefore, LoRa technology is perfect for outlying regions without cellular network coverage, or for establishing private networks with specific requirements for quality and security [15].

LPWAN provides a practical and economical way of establishing IoT networks. This paper presents the potential of an Internet of Energy Things (IoET) based on LPWAN as a future communication infrastructure for DSM applications. First, we briefly review the technologies of NB-IoT and LoRa as the representatives of LPWAN. Next, a new architecture is proposed for the IoET to establish wireless-to-cloud connections between end devices and the cloud computing center. Finally, this paper looks forward to the potential of the IoET in various DSM application scenarios.

2. LPWAN technologies

LPWAN represents a new trend in the evolution of IoT technologies. Unlike 3G/4G or WiFi, these systems do not focus on enabling high data rates per device or on minimizing latency. Rather, the key performance metrics defined for LPWAN are energy efficiency, scalability, and coverage. Many LPWAN players have come to the market, with the two most widely accepted players being the LoRa and NB-IoT technologies. This section briefly reviews the main features of both technologies and compares them with existing telecom and IoT technologies.

2.1. LoRa technology

LoRa technology, developed by Semtech, is the most widely used technology for LPWAN in the sub-GHz unlicensed band [16]. Due to the utilization of unlicensed bands, the LoRa network is open to customers who lack authorization from radio frequency regulators. As a result, the LoRa network is easy to deploy over a range of more than several kilometers, and serves customers with minimum investment and maintenance costs.

LoRa technology has made tremendous improvements to existing technology in order to achieve its target [17,18]. The first of these is LoRa modulation based on the chirp spread spectrum (CSS) scheme, which uses broadband linear frequency-modulated pulses whose frequency increases or decreases based on the encoded information. The Shannon-Hartley theorem indicates that an increase in transmission channel bandwidth is a way to overcome a poor signal-to-noise ratio (SNR). CSS, which has been used for radar applications since the 1940s, was chosen for its inherent robustness to channel degradation mechanisms such as multipath fading, the Doppler effect, and in-band jamming interference. As a result, the maximum coupling loss (MCL) for the LoRa modulation reaches as high as 148 dB—20 dB greater than that of existing sub-GHz communications—in order to extend the coverage distance to kilometers and increase the capacity of the network. LoRa modulation features six spreading factors that result in adaptive data rates. This feature enables multiple differently spread signals to be transmitted at the same time on the same frequency channel.

The other improvement is the optimization of the LoRa network protocol for energy-limited sensors because the uplink traffic usually exceeds the amount of downlink for IoT networks. Under this environment, the LoRa technology specification has defined three modes of different data-receiving windows for different application scenarios. In addition, data encryption is supported by LoRa technology to ensure channel security by means of AES-128 encrypted key pairs.

Thus far, LoRa technology has been tested in 56 countries in demonstrations on smart meters, traffic tracking, smart appliances, and smart healthcare [19]. In the Netherlands, the telecom operator KPN has deployed a LoRa network that covers the entire country, as has SK Telecom in Korea [20]. In addition, a LoRa Alliance with more than 300 members is collaborating to define an open global standard for secure and carrier-grade LPWAN connectivity representing the different layers of an ecosystem, from chipsets, modules, devices, and gateways to network and application servers.

2.2. NB-IoT technology

NB-IoT is a new narrow-band IoT system built from existing LTE functionalities. The technology standard was announced by the 3rd generation partnership project (3GPP) in 2016, which promises to provide improved coverage for a massive number of low-throughput low-cost devices with low device power consumption in delay-tolerant applications.

NB-IoT technology makes use of narrow-band channels to provide higher sensitivity and long range at the expense of limited data rates—typically below a few hundred bits per second (bps) [21,22]. The demodulated spectrum is much wider than individual transmissions so that multiple uplinks can occur simultaneously. The base station carries the complexity to decode multiple narrow-band channels simultaneously without knowing the exact frequency of these channels. The advantages of NB-IoT technology include its enhanced indoor coverage, which is targeted at an MCL of 164 dB, and its ability to connect a massive number of low-throughput devices with an adapted data rate. As indicated by the 3GPP guideline, the design objectives of NB-IoT technology include low-cost devices, high coverage (a 20 dB improvement over the general packet radio service (GPRS)), long device battery life (more than 10 years), and massive capacity (more than 52 000 devices per channel per cell). Latency is relaxed, although a delay budget of 10 s is the target for exception reports.

In addition, NB-IoT network supports three deployment operation modes to provide flexibility based on existing cellular infrastructure [23]:

(1) Acting as a standalone and dedicated carrier. In standalone operation, NB-IoT network can be used as a replacement for one or more GSM carriers. This allows the efficient re-farming of GSM infrastructure for IoT.

(2) Acting in-band within the reserved physical resource block (PRB) of a wideband LTE carrier. Here, all communication channels are shared between LTE and NB-IoT network, with the possibility of using power spectral density boosting on the NB-IoT PRB.

(3) Acting as the guard-band of an existing LTE carrier. In the guard-band mode of operation, NB-IoT network utilizes new resource blocks within the guard-band of an LTE carrier.

Compared with LoRa network, NB-IoT network is designed to work seamlessly on existing GSM and LTE networks within the licensed frequency bands, without enormous updates on the existing base stations. Due to its efficient utilization of existing cellular networks, many telecom manufacturers, including Huawei, Ericsson, and Nokia, support the standardization of NB-IoT network.

Thus far, the commercialization of NB-IoT networks has been initiated, with a particular focus on applications for smart transportation, logistic management, smart grids, and smart manufacturers [24–26]. Telecom giants such as AT&T and China Telecom have announced ambitious plans for using NB-IoT networks to implement coverage in major cities in 2017 [27].

2.3. Comparisons with GPRS technology

Before LPWAN, many IoT business applications were run on GPRS networks [28–32]. GPRS technology is commonly referred to as "2.5G" mobile communication; the subsequent 3G and 4G technologies are targeted to high data rates per device or to minimum latency in order to support the high-quality transmittal of voice, image, and video [33–35].

Table 1 compares the main features of GPRS and LPWAN technologies regarding the aspects of power consumption, latency, coverage, and data rate. End devices in LPWAN are expected to have one tenth of the energy consumption and a 20 dB improvement over GPRS networks. In addition, the capacity of GPRS networks is limited by communication channels, whereas both NB-IoT and LoRa networks have optimized utilization of channel composition in order to extend connection capabilities under lower data rates.

2.4. Comparisons with area IoT technology

For connections among personal devices, ZigBee [36] and WiFi [37] have dominated the current IoT market. These technologies possess different features and performances. WiFi benefits from a high data rate and low latency, but its power consumption is much higher than that of ZigBee. ZigBee is designed for small-scale projects that need wireless connections, and is used to create personal area networks with small, low-power consumption, such as for home automation, medical device data collection, and other low-power low-data-rate scenarios. Although ZigBee has been optimized for IoT networks, its prominent problem is its low coverage distance and device scalability. Therefore, WiFi and ZigBee are referred to as "area IoT" in that they can be used to support connections between devices within a limited area [38–40].

Table 2 compares the communication distance, maximum connection, and data rate among WiFi, ZigBee, and LPWAN. LPWAN provides a much greater coverage distance and a higher connection capability for IoT networks.

3. IoET architecture based on LPWAN

3.1. Wireless-to-cloud architecture

Section 2 presented the key features of LPWAN and compared LPWAN with the technologies of cellular telecom (GPRS) and area IoT (ZigBee/WiFi). The primary advantages of LPWAN lie in its wide communication coverage and low-power consumption; its disadvantages are its relatively low data rate and the limited computation capability of its end devices. A wireless-to-cloud architecture is therefore proposed for the IoET, in order to integrate cloud computing into end devices via LPWAN, as shown in Fig. 1(a).

As shown in Fig. 1, an IoET enables communication between end devices and the cloud platform via wireless connections. Compared with area IoT architecture, shown in Fig. 1(b), the primary distinction is the savings on the area IoT gateway associated with the gateway network layer. As a result, the LPWAN-based IoET architecture becomes manageable for both network operators and end users. This simplified network topology conveniently extends the integration of sensing and control devices in actual energy systems. In addition, the functions of end devices become extendable by the computing capacity provided by the cloud center.

The three functional layers of the wireless-to-cloud architecture, as shown in Fig. 1(a), are discussed in the following subsections.

3.2. Remote-sensing and control layer

Actual energy-related devices are connected through the remote-sensing and control layer, which is associated with a huge amount of energy sensors, controllers, and embedded computer and wireless communication modules. Energy sensors monitor device statuses and send them to the cloud center, while controllers deliver the instructions provided by the cloud center.

Embedded systems compactly incorporate embedded central processing units (CPUs), memory, periphery devices, and wireless communication modules as the carrier of energy sensors and controllers for machine-to-machine (M2M) communication conversion. They also control actions with quality of service (QoS) requirements. Therefore, in addition to sensing and control functions, real-time services are provided via embedded systems in order to enhance the sensitivity of communication QoS to wireless transmitting and cloud computing. This concept, which is named "fog computing," fills in the technical gaps of cloud computing [41].

Table 1
Comparisons between GPRS and LPWAN technologies.

Technology	Power consumption	Latency	Coverage	Data rate
GPRS	High	Low	MCL 130 dB	Maximum 171.2 kbps
LPWAN	Low	Not guaranteed	MCL 150 dB	Adaptive from 0.1 kbps to 250 kbps

Table 2
Comparison of ZigBee, WiFi, and LPWAN technologies.

Technology	Communication distance	Maximum connection	Data rate
ZigBee	10–75 m	≤ 255	Maximum 171.2 kbps
WiFi	100 m	≤ 255	> 10 Mbps
LPWAN	3 km to city scale	≤ 50 000 (NB-IoT), ≤ 200 000 (LoRa)	Adaptive from 0.1 kbps to 250 kbps

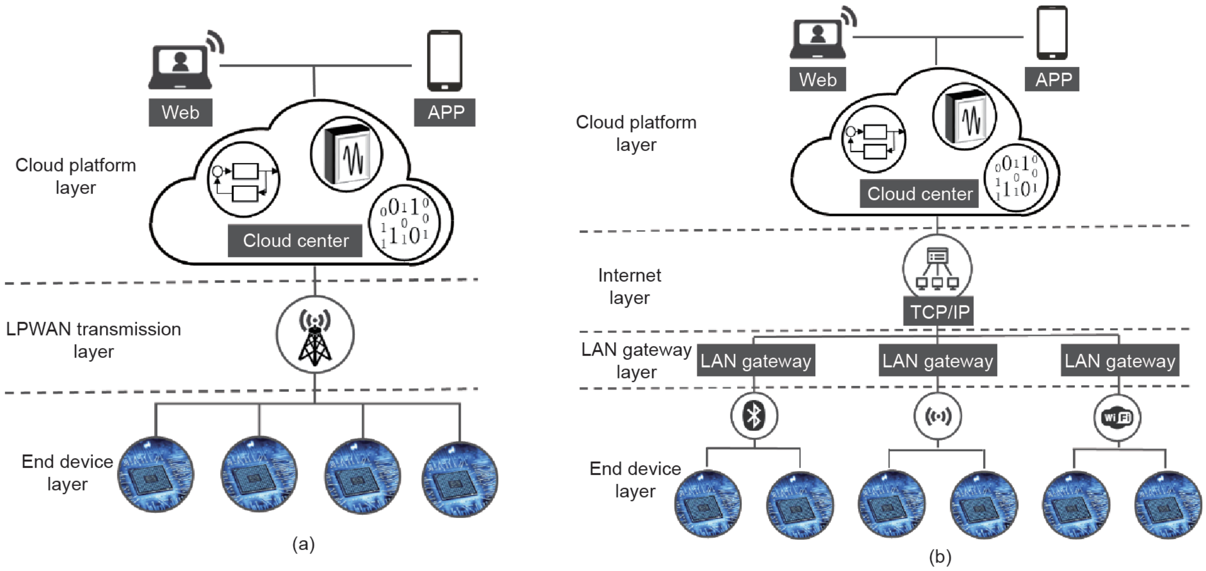

Fig. 1. (a) LPWAN-based IoET architecture; (b) area IoT architecture. LAN: local area network.

3.3. LPWAN transmission layer

Distributed energy devices are usually geographically dispersed, making IoT technologies such as ZigBee and WiFi difficult to use. Under such scenarios, LPWAN becomes the alternative.

The LPWAN transmission layer establishes wireless channels between end devices and the cloud platform. As representative technologies, NB-IoT and LoRa technologies are suitable for different application scenarios. In outlying districts without cellular coverage, LoRa network is the practical choice, as it forms a star-shaped topology around end devices that are served by a single base station (BS). In the example illustrated in Fig. 2, a LoRa BS that is set up in a substation in a rural area communicates with distributed photovoltaic (PV) panels. In a city with cellular networks, end devices simply connect with the cloud center via NB-IoT cellular network by paying a data fee to telecom companies. Fig. 3 shows a scenario in which the cloud center coordinates home appliances and electric vehicles (EVs) dispersed throughout the city via the NB-IoT cellular network. For systems with particular security requirements, one solution is to establish a virtual private network with secured channels in an NB-IoT cellular network; another choice is to construct a private LoRa network to physically secure the connections.

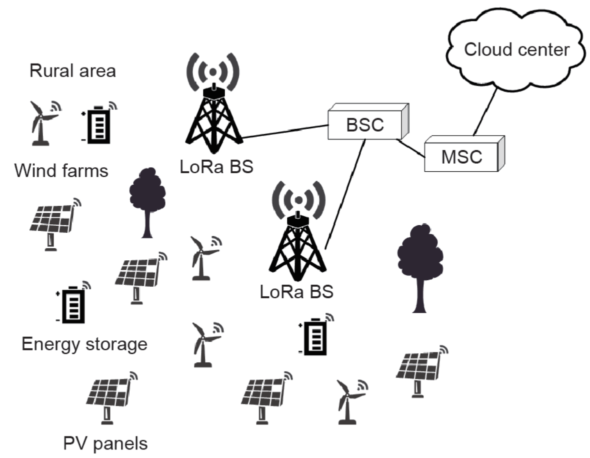

Fig. 2. Application scenarios of LoRa network in rural areas. BSC: base station control; MSC: multi-service control.

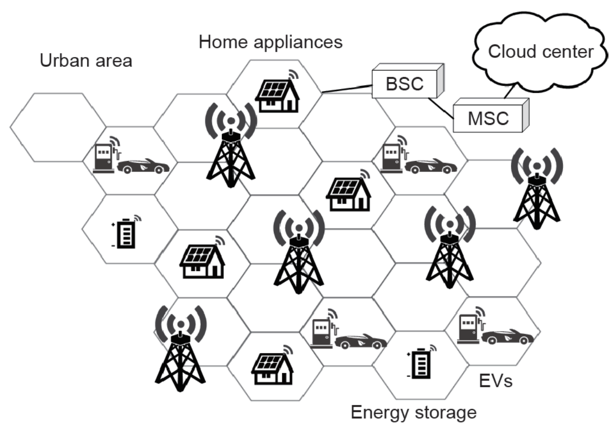

Fig. 3. Application scenarios of NB-IoT cellular network in a city.

3.4. Cloud platform layer

The cloud platform layer serves as the cloud platform that hosts energy applications via data exchange and communication between devices. More specifically, the platform corporates the functions of information conversion, integration, and interoperation, as shown in Fig. 4. The corresponding functions are described below.

(1) Protocol parsing. An IoET must deal with communications between various end devices that have different protocols. It is not realistic to assume that every device understands all the protocols in the network. Instead, the protocols are parsed by the cloud platform, other than the field devices. Therefore, it is convenient to decouple actual devices and communication protocols under centralized management and maintenance. To achieve higher flexibility, the cloud platform also provides a programming interface to enable user-defined protocols for connections with unknown devices.

(2) M2M communications. M2M communication among energy devices is the main feature of an IoET, in order to extend the interoperability of networks between devices. Limited by wireless bandwidth, a "subscribe/publish" pattern is suitable for M2M communications. Many event-driven middleware technologies have implemented this pattern, which enables almost unlimited device

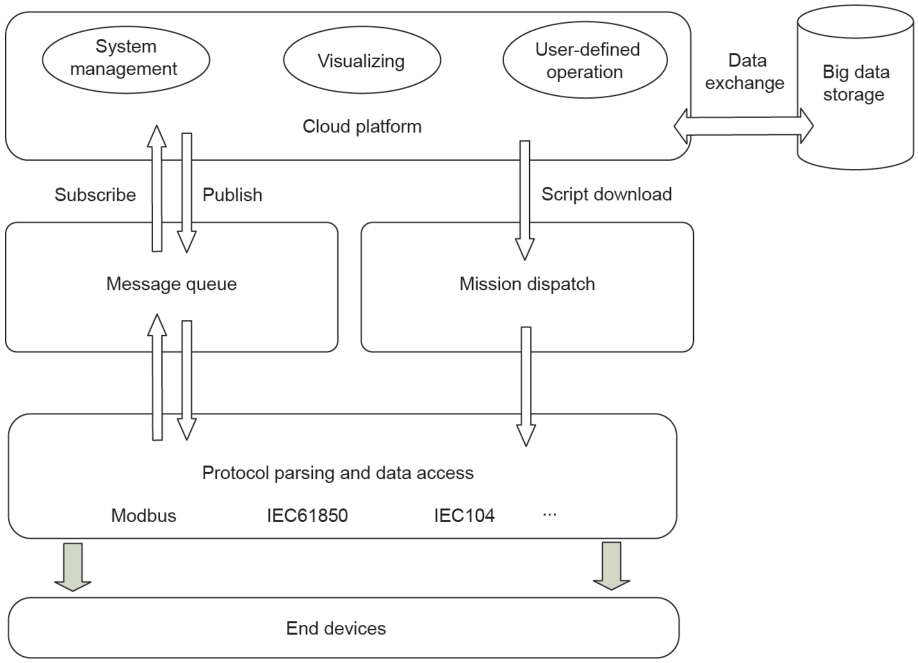

Fig. 4. The structure of the cloud platform layer.

addressing and efficient bandwidth utilization. Data encryption is also supported by middleware to enhance communication security.

(3) Big data storage and analysis. Access to a huge number of sensors inevitably results in massive data storage and analysis requirements. The cloud platform supports both real-time and historical data access for specific energy system applications. Real-time data is accessed by memory database in order to meet the requirements of low latency and high concurrency. The historical data is accessed by distributed file systems in order to meet the needs of massive data storage and big data analysis.

(4) End user interoperations. At present, energy systems are restricted to closed-information environments in order to secure management operations. However, inflexible information exchanges will make it difficult to address diverse interoperations among various end user roles in the clean energy era. The cloud platform extends user interoperations by visualizing the energy devices in the cloud-based pool to permit platform-independent accessing. A cloud-based tool is also set up to program the working flow for user-defined operations by editing the graphics, model, and data of visualized energy devices in the platform.

4. IoET-based DSM applications

Based on LPWAN, an IoET enables extensive connections between energy devices at very low cost and without expert knowledge. An IoET extends the reach of the energy information system to match the requirements of DSM. Many DSM concepts being reported in the literature now become practical once they are supported by IoET infrastructure.

4.1. Smart appliances and smart home systems

One of the primary objectives of smart appliances is to reduce energy consumption and energy bills. The smart appliance market has attracted considerable attention, from manufacturing to industry; however, an obstacle remains in the form of a lack of appropriate communication channels. The current solution is to use ZigBee or WiFi to establish connections between appliances and the cloud platform [42]. The drawback to this solution is that diverse communication environments usually result in unexpected failures that may challenge end users who lack patience and specific knowledge. Another alternative is to set up an independent gateway for appliances. However, this solution often results in fragmented applications for different brands and in poor user feedback.

The NB-IoT-based IoET provides city-scale networks of devices to satisfy the requirements of smart appliances and smart home systems. Wireless channels established by NB-IoT networks give smart appliances access to the cloud platform without any particular configurations on the gateway. As long as appliances are connected, the cloud platform automatically recognizes them and provides feedback to smart home applications [12]. Adding an appliance to the cloud platform thus becomes a simple task, and the entire process is completed without the need for expert knowledge. Moreover, smart home systems are prompted to carry out management based on the statuses of appliances and on historical data stored in the cloud platform.

4.2. Microgrids and distributed energy systems

Microgrids and distributed energy systems aim at the high-percentage integration of clean energy and at highly reliable power supply. These energy systems are suitable for outlying districts such as islands, highlands, and river valleys, where large-scale power systems are too expensive to construct [43].

The operation of a distributed energy system usually requires flexible and reliable communication systems. However, cable-based communications are impractical in most cases due to their complicated maintenance. Furthermore, the communication distances of ZigBee and WiFi are too short to be practical for an energy site [44]. Therefore, LPWAN-based IoET becomes another option for microgrids and distributed energy systems.

Unlike LoRa network, an NB-IoT network must be set up within an existing cellular network. Therefore, LoRa technology is a more flexible tool to meet the requirements of outlying districts. Since LoRa network works in the unlicensed band, the site owner is allowed to set up a wireless BS to connect energy devices that are dispersed over distances of several kilometers, without authorized permission. A star topology is simpler than a more complex network, and is more convenient to maintain without expert skills.

4.3. Active distribution networks and aggregated demand response

An active distribution network manages a high percentage of distributed energy resources that are integrated at the distribution and utilization systems. With the emergence of distributed generators and storage at the low voltage level, various smart energy devices now request the level of information-sharing that is associated with distribution system operations. Nevertheless, it is difficult to extend current information systems to end consumers due to complex field environments and security concerns. In particular, utilization networks at the lowest voltage level lack the space and communication channels required to add additional remote devices to enable interoperations with power distribution systems [45,46].

The current solution is to use GPRS networks operated by telecom companies [47]. The substantial data bill makes it necessary to use smart meters in order to save measurements at the gateway and send them back to the operation center when inquired for. To address this issue, the LPWAN-based IoET provides an economical way to reach consumers at the low voltage level. On the one hand, by investing in enterprise-own LoRa networks, the cloud platform receives data generated by energy consumers with no charge from telecom companies. On the other hand, bi-directional communication enables the aggregation of energy consumers to participate in demand response. Considering the reachability of LPWAN, demand-response capacities are anticipated to be comparable to peak-valley differences and renewable variations.

4.4. Electric vehicles and aggregated vehicle-to-grid operation

Regarding the mobile energy system, EVs have been accepted as the transportation solution of the future in order to reduce fossil fuel use and carbon emissions [48]. The large-scale integration of EVs will introduce inherent flexibility to the operations of energy systems. Current academic studies have demonstrated the effectiveness of EVs in balancing the control of power systems via means such as frequency regulation, peak shaving, and vehicle-to-grid (V2G) operations [49].

An efficient communication network is a precondition to aggregate dispersed EV charging. However, installations of cable networks are impractical in most cases, and coverage of telecom signals is weak in some underground parking lots. LPWAN is a general solution for EV communications since the adapted modulation scheme is sensitive to end receivers, even with over 150 dB decay. Thus far, both NB-IoT and LoRa technologies have been successfully tested in actual parking lot demonstrations. Based on LPWAN, EVs connected to an IoET are aggregated as a storage pool to respond to energy systems and allow greater integration of variable renewables.

4.5. Energy distribution network and multi-energy system

Multiple forms of energy conversion, such as power-to-gas systems, power-to-heat systems, and combined heat and power systems, are integrated into energy hubs for higher energy utilization efficiency [50,51]. Performing the role of grid nodes, energy hubs are interconnected in the energy distribution network (EDN). The EDN is a novel concept of integrating flexibilities in the demand side by interoperating different energies such as electricity, gas, and heat within a local area. With highly flexible energy interoperations, EDN can actively respond to variable renewable energy, leading to a larger renewable share in power systems.

Energy flowing through the heat and gas networks of an EDN creates a harsher environment for sensing and communication than an electricity network. To tackle the issue, the ultra-low-power mode of LPWAN enables NB-IoT and LoRa modules to last for several years without battery changing. The reachability of IoET collects more details of multi-energy systems, allowing highly efficient interoperations.

5. Conclusions

The NB-IoT and LoRa technologies are two representative breakthroughs of wireless LPWAN in the communication sector. Compared with GPRS, LPWAN is a better solution for low energy consumption and improved coverage. Compared with the area IoT of ZigBee and WiFi, LPWAN enables massive connections covering long distances at the cost of minimum construction work and maintenance. Based on LPWAN, an IoET allows extensive connections of energy devices under wireless-to-cloud architecture at very low cost and without expert knowledge. The IoET hence extends the reachability of the energy information system to match the requirements of demand-side applications. The establishment of an IoET can stimulate the DSM applications of smart appliances and smart home systems, microgrids and distributed energy systems, active distribution networks and aggregated demand response, EVs and aggregated V2G, and EDNs and multi-energy systems. In conclusion, the IoET paves the way to aggregate DSM flexibilities on the demand side in order to enable higher integration of renewables in energy systems.

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Compliance with ethics guidelines

Yonghua Song, Jin Lin, Ming Tang, and Shufeng Dong declare that they have no conflict of interest or financial conflicts to disclose.

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