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万物互联视角下的能源物联网：现状、技术和案例分析

宋航[1,2,3,✉]，问翔[3]，翟华[1]

（1. 北京理工大学 深圳汽车研究院, 广东 深圳 518118；
2. 国防科技大学 电子科学与技术博士后流动站, 湖南 长沙 410000；
3. 西安电子科技大学 杭州研究院，浙江 杭州 311231）

摘要：[**目的**]万物互联 (IoE) 时代酝酿着的新一代物联网（IoT）的发展，正在通过选择和组合其中的新信息、新功能、新应用，来实现其多样化发展。基于物联网技术的能源物联网，将物理事物之间的信息交换和能源交换，在同一张动态网络中连接起来。能源物联网催生着新的服务模式和能源的组织、交换、管理方式；它不仅涵盖能源即服务（Energy-as-a-service）和产销者（Prosumer）等新概念，还引领智慧建筑、智能抄表、智慧电网、分布式能源、虚拟电厂等创新应用。[**方法**]文章分析了能源物联网的现状，包括其关键的行业驱动因素、潜在的技术和应用，及其相关的研究进展。[**结果**]从学术和行业应用的角度讨论和比较了能源互联网与能源物联网的定义，并分析了面向能源物联网演进的一些主要阶段和需要关注的问题。[**结论**]文章为能源物联网的进一步研究和实践提供有益的参考。

关键词：物联网；万物互联；能源物联网；能源即服务；智慧建筑；智能电网；虚拟电厂；能源互联网

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论文二维码

Energy Internet of Things in the Perspective of Internet of Everything: Current Status, Technologies and Case Analysis

SONG Hang[1,2,3,✉], WEN Xiang[3], ZHAI Hua[1]

（1. Shenzhen Automotive Research Institute, Beijing Institute of Technology, Shenzhen 518118, Guangdong, China； 2. Postdoctoral Mobile Station of Electronic Science and Technology, National University of Defense Technology, Changsha 410000, Hunan, China；3. Hangzhou Institute of Technology, Xidian University, Hangzhou 311231, Zhejiang, China）

Abstract: [**Introduction**] The new generation of the Internet of Things (IoT) is being fostered in the era of Internet of Everything (IoE), realizing its diverse development by selecting and combining new information, functions, and applications. The Energy Internet of Things (Energy IoT) which is based on IoT, envisions a future where physical things are connected through a dynamic network that exchanges information and energy. The Energy IoT is giving rise to new service models and methods for organizing, exchanging, and managing energy; It covers not only new concepts such as Energy-as-a-Service and Prosumer, but also leads to innovative applications in smart buildings, intelligent metering, smart grids, distributed energy, virtual power plants and more. [**Method**] This paper analyzed the current status of the Energy IoT, including its key industry drivers, potential technologies and applications, challenges and related research areas. [**Result**] This paper discusses and compares the definitions of Energy Internet and Energy IoT from academic and industry perspectives. And it analyzes some major stages and issues of future research in the Energy IoT. [**Conclusion**] This paper

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provides a useful reference for further research and practical applications in the field of Energy IoT.

Key words: Internet of Things (IoT); Internet of Everything (IoE); Energy Internet of Things (Energy IoT); Energy-as-a-service; smart building; smart grid; virtual power plant (VPP); Energy Internet

0 Introduction

With the development of the Internet of Energy [1-3], people can use the detection system to monitor the urban power consumption data in real time. By combining cloud and edge computing analysis, the smart grid can automatically adjust the power quality. Utilizing intelligent buildings built with new materials and design techniques combined with digital technology, the construction of intelligent communities serves to improve the efficiency of various energy consumption systems and reduce energy waste [4-5]. When data flow and energy flow are rapidly moving beyond bespoke detailed solutions tailored for specific problems, e.g., smart building, smart metering, smart grid, Distributed Energy Resource (DER), Virtual Power Plant (VPP) and smart mobility, we have built up on reusable and more general purpose infrastructures and tools, referring to them as the Internet of Energy, or Energy Internet of Things (IoT). In the Internet of Energy, the enormous innovation potential of IoT technologies lies not only in the new production of energy as-a-service but also in all activities performed by smart grids, including energy production (DER, VPP, energy prosumer) and recycling (smart grid, maintenance, recycling) phases.

It is drawn upon its combination with monitoring devices and actuators from Operational Technology (OT). The Internet of Energy helps regulate and monitor industrial systems, and it flexibly integrates and reorganizes production resources, thus enhancing OT capability in the smart value chains that facilitate distributed energy, information and decision-making [6-9].

1 Energy As-A-Service and Smart Energy

In the upgrading Industrial 4.0 era, industrial scenarios involve applications and prototypes for collaborative cloud. The proof of improvement paves the way for considerations towards using information and communication technologies and Cyber-Physical System (CPS) approaches in real-world environments once the exact operational requirements are satisfied. Then, subsequent follow-up projects, such as IMC-AESOP [10], FAR-EDGE, Productive 4.0, and Arrow-head [11] have continued this line of thought and expanded more toward cloud utilization. Among them, following the IMC-AESOP model, energy as-a-service [12] will be introduced in the following Fig. 1.

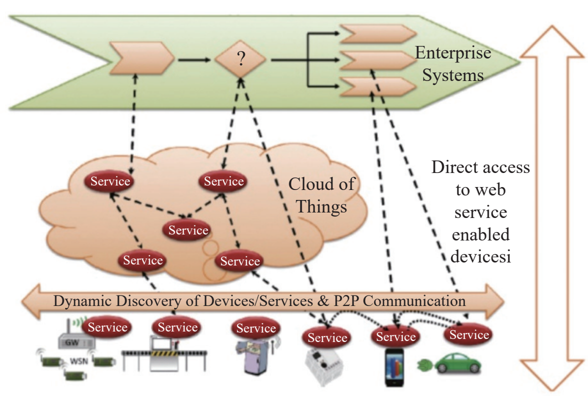

Fig. 1 Energy as-a-service in the cloud, where energy and information flow re-organized [13]

As shown in Fig. 1, energy flow is a kind of service, often along with information mapping from the industrial process environment to a "service cloud", (i.e., the energy of devices/services and applications distributed across the different layers of the enterprise expose their characteristics and functionalities). The IMC-AESOP service cloud was developed as the follow-up energy-driven cloud collaborative approaches (as shown in Fig. 2), dealing with visionary approaches bundled around the cloud. Additionally, these devices and systems in Fig. 1 can access and use those "services" located in the cloud (e.g., supported by a collaborative and distributed middleware/cloud-based OS), then they have the potential to change significant parts of modern factories pertaining to devices, systems, and processes.

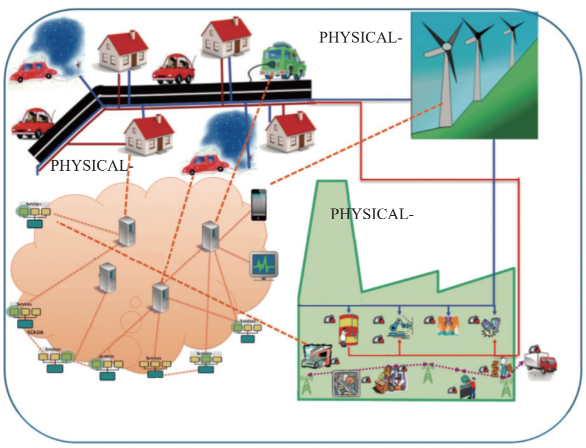

Fig. 2　Smart energy infrastructure view: A distributed dynamically collaborative cloud for CPS in the Smart City domain, including information and energy exchange and control (e.g., V2G, DER, VPP, smart grid platform, V2X communication in the upgrading industrial 4.0 applications) [10]

Smart energy infrastructure gives a cloud-based collaborative vision with technologies and methods that even take a more key role as they empower the backbone of the Smart City [14] approaches under development, such as IoT/ Energy Internet. For distributed large-scale process monitoring and control systems, e.g., Supervisory Control And Data Acquisition (SCADA) [15], Distributed Control System (DCS) or CPS, industrial automation and industrial Internet/ industrial IoT [16] (where technologies have to be selected and used in an industrial context about integration, real-timeliness, distribution, event-based interaction, service-enablement, etc.) are approached from different angles.

Fig. 2 describes the distributed, autonomous/intelligent, proactive, reusable systems, which expose their functionalities, capabilities, and structural characteristics as services located in a "service cloud", (service in the "cyber-" part in Fig. 2). These services support various applications (such as the "physical-" part related heating, electricity generator, energy, and logistic business for mobile apps together with their monitoring and management). As Fig. 2 shows, the functionalities of each system or even device can be offered as one or more services of varying (potentially cross-layer) services. Hence, although the traditional hierarchical view coexists, now there is a flat information-based architecture that depends on a big variety of services exposed by the CPS/IoT and their composition.

As shown in Fig. 2, around the "cyber-" part, a five-level pyramid model in enterprise links many components (devices, systems, services, e.g., those in the bottom level) of a wide variety of scales, from individual device/service-as-a primitive IoT level, IoT grid-as-a-service level (under a local machine controller) to systems of different levels. For example, control, monitoring and supervisory control systems perform SCADA, DCS and CPS functions in the multi-industrial model around Energy IoT, as shown in Fig. 3[17]. These use cases will be further discussed in the next section.

2　Technologies and Use Cases of Internet of Energy

2.1　Smart Buildings

Smart buildings [18-19] help reduce the uncertainty of the controlling or management process, by some IoT products and OS developed and available on the IoT market benefiting the building or home environment, such as smart lights, smart TV, and robot vacuum. However, adding a Wi-Fi module to the current electrical device and connecting it to the cloud is not enough for a smart home. In a smart home environment, besides the connected device, cheap wireless sensors and controllers should be deployed to rooms, pipes, and even floors and walls. These things need "smart management" along with the right parts of Fig. 4, the physical layer of smart buildings.

The left part of Fig. 4 describes how data and control actions owned by stakeholders are shared with each other due to the formidable cost of data

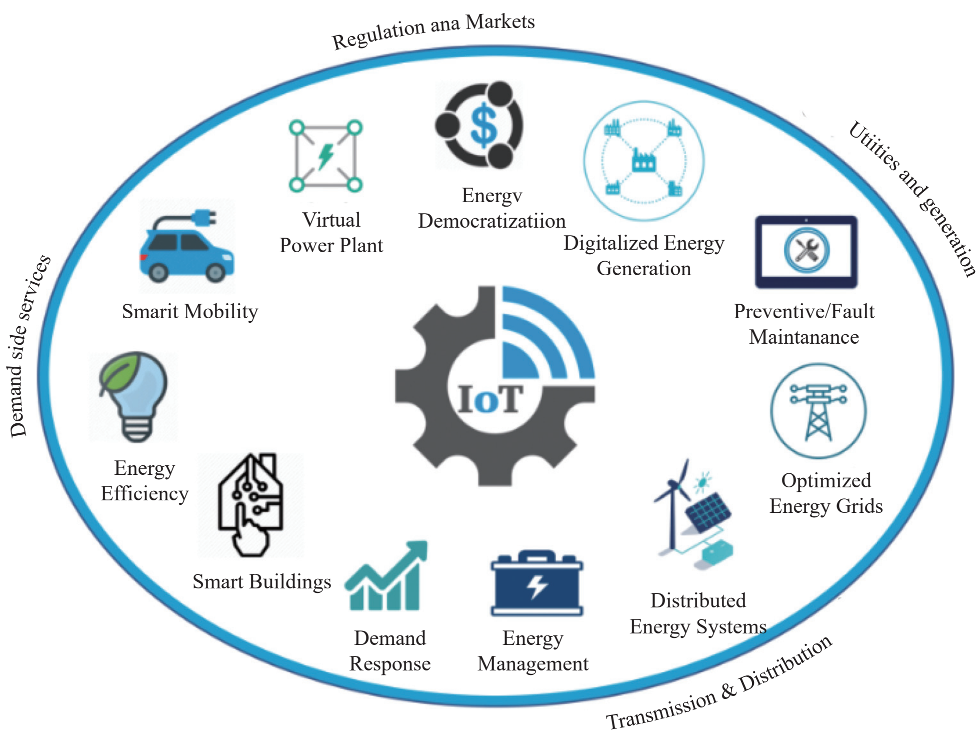

Fig. 3 Multi-industrial model around Energy IoT and its smart value chains [17]

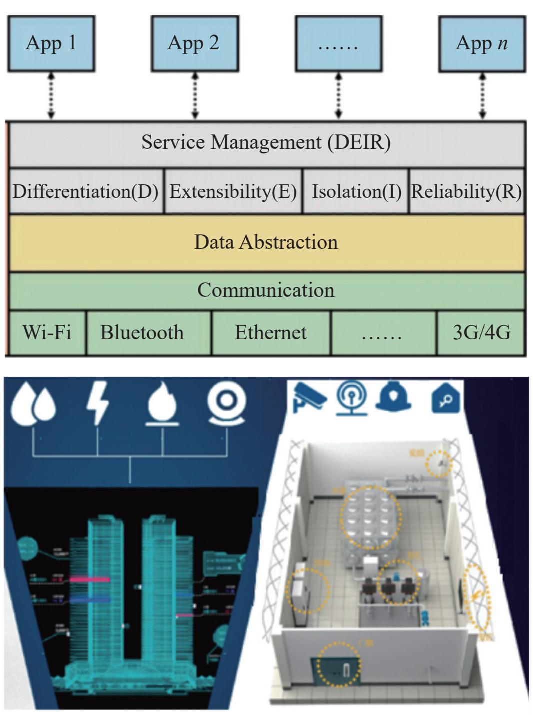

Fig. 4 Smart building/ home use case allowing for the four-layer structure of IoT [9]

transportation over the communication layer of IoT. The platform layer of IoT in Fig. 4 plays the role of data abstraction and service management, supporting the heterogeneity of both products and APPs.

As shown in Fig. 4, the demand for geographically distributed data processing applications, i.e., secure monitoring and fire precaution, requires data sharing and collaboration among buildings and enterprises in multiple domains, which is facing the challenge of distributed but collaborative metering for geographically distributed data. As the left part of Fig. 4 shows, the smart building framework consists of the physical assets (the right part of Fig. 4) within the building, the digital assets that create a fabric throughout the connected space, and the use cases that are enabled by the marriage of physical and digital assets.

2.2 Smart Metering and Energy Efficiency

Smart metering [20] is one of the scenarios in which IoT is applied to achieve efficient energy use, and it plays an important role in distributed energy systems as they turn from energy consumers to the so-called "energy prosumers" in their development of buildings, industries, countries, and universities. To obtain energy efficiency from applications capable of controlling, measuring, and managing energy consumption in buildings, grids and households, countless researchers have provided new hardware solutions (sensors, controllers or smart meters) and integrated IoT platforms. Despite the efforts done to make users understand the importance of reducing energy consumption in public spaces, work environments, or at home, this problem continues, and it is necessary to find a solution to it. The following example is a metering platform-based energy use case.

In Fig. 5, through these platforms, devices allow for remote control by users or central management via LAN/WAN or WAN/cloud-based communication and enable functions like scheduling (e.g., remotely powering on or off heating systems, controlling ovens, changing lighting conditions, etc.). Smart energy-enabled automation of building operations, notably with climate-energy control and fault diagnosis in HVAC systems as the two use cases in smart buildings, which have had benefits of more than a decade of technology evolution, such as IoT, cloud/edge analytics, and mobile devices. The IoT benefits related to optimizing the control of building operations and secure building

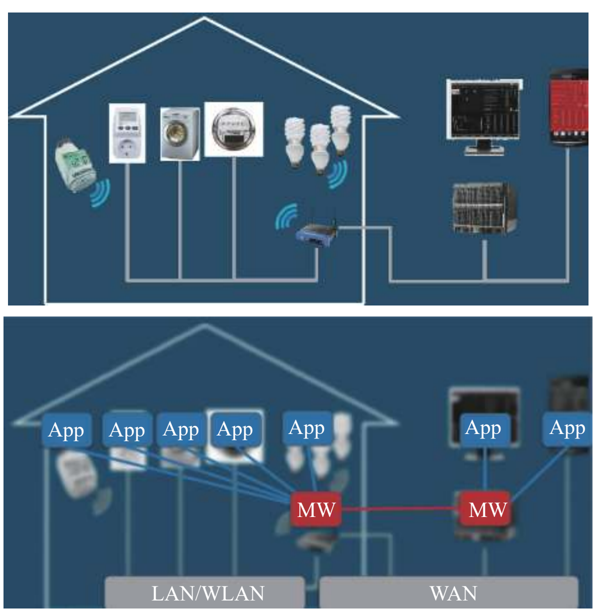

Fig. 5　Energy management use case based on the heterogeneous metering platform, with MiddleWares (MW) deployment on the edge of WAN/LAN [3]

access are well documented and reveal some of the most directly attributable outcomes from smart buildings. Optimizing and improving the operations of the facility can lead to a variety of recouped costs and start from major savings on bills related to heating, cooling, lighting, and maintenance. For example, on average, 50% can be saved by moving to a connected lighting system [3]. This can be achieved by creating a digital control tower for building operations, which provides real-time insight and leverages Artificial Intelligence (AI) to calibrate services across a building.

The application layer or apps, develops the interaction interface for both configurations (e.g., the configuration of players/workers who are rewarded or penalized depending on their behavior in energy savings within a work environment) and development. In the example, several tools are established, such as the collaboration between players (e.g., deciding on meeting times) and the necessary contextual information at any time that allows players to make decisions that could be taken in order to be rewarded (e.g., turning off the monitor when the work is finished).

2.3　Smart Grid

To stabilize and facilitate buildings, industries and countries (or participate) in energy trading as well as for structural condition monitoring and proactive maintenance, the smart grid [21] is presented. As for buildings, smart grids offer semantically annotated properties of the technical equipment within specific energy flexibilities (i.e., for shifting electrical and thermal loads). Based on the above mentioned, the following use case employs the technologies developed in a Sustainable Smart Town (SST) to dynamically discover the flexibilities of smart energy and analyze its potential as well as their demand for applications that are necessary to manage and offer energy to the smart grid or the energy market. Other aspects, such as achieving better efficiency and resource management, reducing carbon emissions and costs, improving demand response systems and Micro-Grids (MG)/ DER, or improving knowledge and system automation by data correlation (such as temperature, humidity, luminosity, or other sensors, weather information, user, segment and building profiles) may be included in two kinds of use cases, namely industrial/commercial environments and energy IoT (i.e. Internet of Energy) environments. The former one is described below and the latter one will be discussed in the next section.

Fig. 6 shows the SST of Fujisawa in Japan [22] with an IoT-based energy platform (in the center of the figure), in which information can be used by energy retailers, grid operators, and renewable energy to deploy fitting applications to buildings, factories and individuals. The SST uses semantic enrichment of grid data and data analytics to enhance smart grid applications and reduce the need for manual engineering, maintenance, and setup of energy systems. As for the use of Renewable Energy Resources (RER) and an increasing number of energy production and self-consumption solutions for homes and businesses, the town's first green technology logo is a 400-meter-long solar panel, followed by wind power generation.

Fig. 6 Smart grid in Japanese SST [23]

The primary consideration of the SST project is the regional characteristics based on the concept of living comfort, energy-saving and recycling, and smart community lifestyle, including the imagination of future life mode planning of the energy, security, mobility, health, and so on. The SST also encourages Electric Vehicles (EVs) and bicycles for individuals to commute freely.

2.4 DER

Smart energy environments can benefit from IoT approaches by sensors and intelligent devices that have transformed the energy industry by allowing access to a deeper understanding of how energy is spent and what factors influence its consumption. Stimulated by IoT technology, RER and DER call for a large number of proposals and approaches nowadays. They are based on the definition of MG by IEEE standard 2030.7–2017, as "a group of interconnected loads and DER with clearly defined electrical boundaries that act as a single controllable entity concerning the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes" [24]. The following use case is based on the grid-connected DER, also from an IoT view. DER decreases the cost of electricity transmission infrastructure by using RER between grids and supply consumers (prosumers). Further, grid-connected DER mode, together with the MG management system at the different control levels, manages the connection of MG to a utility grid defeats the risk of unavailability owing to natural resource features and offers other benefits related to participation in the electricity market as a prosumer [25].

Fig. 7 illustrates a conceptional MG structure, which is adapted to the role of generation, transmission, distribution, operator, and consumer of the smart grid. As can be seen in Fig. 7, the maintainer, and aggregator act as a service provider in the market domain. The performance of each entity is clarified as follows:

1) MG Aggregator: This participant is in charge of gathering information about energy marketing participants for MG.

2) MG Operator: This party monitors MG and controls its performance through local and remote services.

3) MG Maintainer: This agent is responsible for the accurate performance of MG by providing maintenance services in case of failure according to the received reports.

4) MG Controller: Aggregator, maintainer, and operator interact through this part with each other and DER, facilitating the energy management system (EMS) control level.

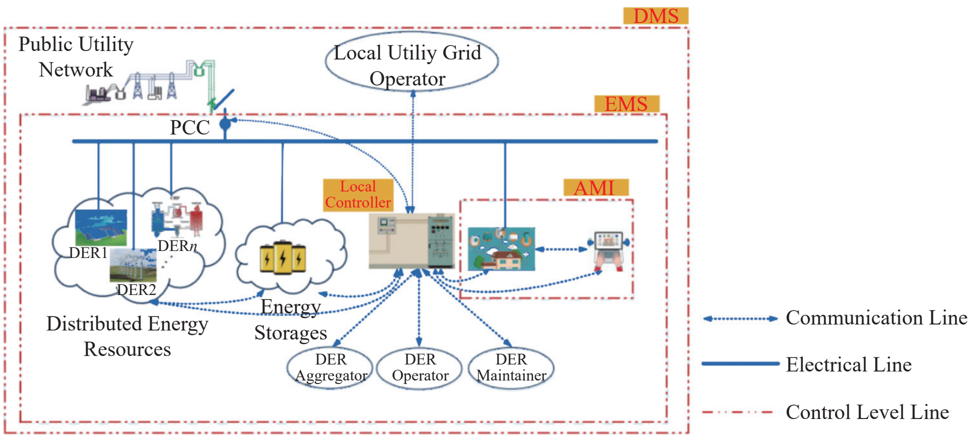

Fig. 7　MG structure in a distribution management system (DMS) [26]

5) Local Utility: Local utility is the MG utility neighbor who connects to MG through the point of common coupling and interacts with MG to coordinate the provision of ancillary services in grid-connected mode.

2.5　VPP and Vehicle-to-Grid

A VPP is a system that integrates several types of power sources to give a reliable overall power supply [27]. The sources often form a cluster of different types of dispatchable and non-dispatchable, controllable or flexible load-distributed generation systems that are controlled by a central authority, and can include natural gas-fired reciprocating engines, small-scale wind power plants, photovoltaics, run-of-river hydroelectricity plants, small hydro, biomass, backup generators, and energy storage systems.

This system has benefits such as the ability to deliver peak-load electricity or load-following power generation on short notice. Such a VPP can replace a conventional power plant while providing higher efficiency and more flexibility, which allows the system to react better to load fluctuations.

In Fig. 8, the main difference between a consumer and a prosumer is that a consumer simply purchases and uses products or services, while a prosumer produces and consumes them. For example, a consumer simply purchases energy units from a utility company, while a prosumer buys solar panels and generates their energy. Traditional consumers are not involved in the production or customization processes. They are end-users of products and services. Prosumers, on the other hand, are customers who not only buy and use products but also contribute to the production or customization of products or services. From a marketing and business perspective, prosumers are engaged users who are invested in the growth and optimization of your products and services. For example, Vehicle-to-Grid (V2G) [28] makes valuable contributors to product development and marketing strategies by enabling EVs to be used even when not driven. Bidirectional charging means that your EV battery is being charged from renewable energy sources, such as solar and wind power, during peak production. This enables EV owners to earn money by selling the excess energy stored in their vehicle's battery back to the grid. V2G-enabled EVs can be considered as a type of DER that can be integrated into a VPP.

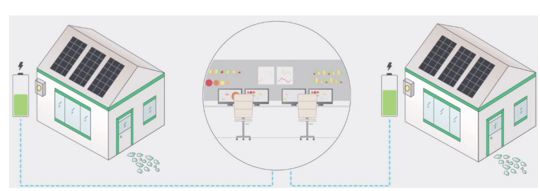

Fig. 8　Either end as a prosumer for real-time smart management of VPP in Energy IoT [3]

The relationship between VPPs and V2G is that V2G-enabled EVs can be integrated into a VPP to provide grid services and increase the efficiency of renewable energy sources. By aggregating the energy stored in the batteries of these vehicles, a VPP can provide additional capacity to the grid during periods of high demand. For example, during a heatwave when many people are using air conditioning, a VPP can use the energy stored in V2G-enabled EVs to help meet the increased demand for electricity. V2G-enabled EVs can also be used to provide ancillary grid services such as frequency regulation, which helps to stabilize the grid. By using V2G-enabled EVs to provide these services, a VPP can reduce the need for traditional fossil fuel-powered peaker plants that are used to meet periods of high demand.

As shown in Fig. 8, public or specific services are provided by either participant of the collaborative edge. Considering the amount of data, the data transportation pressure and privacy protection, this data should be mostly processed and consumed at the edge, such as the home or building. With an edge gateway running a specialized edge operating system, the energy and information among vehicles or mobile things can be connected and managed easily between grids of Energy IoT, where the data can be processed locally to release the burdens for the Internet.

2.6 Use Cases in China

In order to effectively promote the deep integration of energy and information and promote structural reforms in the energy field, the National Energy Administration organized the implementation of the "Internet +" Smart Energy (Energy Internet) demonstration project. The construction of the Energy Internet demonstration project can establish a new energy industry development model that closely links energy production, transmission, storage and consumption with the Internet, promotes energy use in the direction of intelligent equipment, multi-energy collaboration, information symmetry, decentralized supply and demand, and open transactions, activates the potential of energy supply and consumption, and forms a new energy production and consumption system and control system. At the same time, the project makes full use of Internet means, is market-oriented, and takes enterprises as the main body to tap the economic, environmental, and social benefits brought about by the deep integration of the Internet, energy systems and energy markets.

A total of 55 "Internet +" smart energy (Energy Internet) demonstration projects were selected for the first batch. Among them, the Beijing Yanqing Energy Internet Comprehensive Demonstration Zone was applied by the Yanqing Park Management Committee of Zhongguancun Science and Technology Park. It took the lead in launching green transaction services and promoted the development of green services that used smart grids as a distribution platform, intelligent electricity consumption through the Internet of Things, and Internet finance.

The city-park dual-level "Internet +" smart energy demonstration project applied by Guangdong Power Grid Co., Ltd. to support the energy consumption revolution is the first project to pass the acceptance test. The project built the world's first ±10 kV, ±375 V, ±110 V multi-voltage level multi-terminal AC-DC hybrid distribution network, developed a number of key technologies and equipment for flexible direct distribution networks, coordinated control and operation strategies for AC-DC hybrid grids, and built a DC micro-grid integrating solar storage and charging. Based on the smart energy big data cloud platform, the project realized the integration and management of internal and external energy data, the fusion of multi-source heterogeneous data and the provision of data resource services.

3 Internet of Energy and the Analysis of Upgrading Stages

3.1 Energy Internet

The Energy Internet is a new development form of the energy system. It realizes the integration of energy flow, information flow and business flow. More and more business model and service model innovations are stimulated in the Energy Internet. Energy Internet can be understood as comprehensively using advanced power electronic technology, information technology and intelligent management technology to connect a large number of new power networks, oil networks, natural gas networks and other energy nodes composed of DER devices, distributed energy storage devices and various types of loads and prosumers (e.g., MG mentioned above), with the objectives of energy and information two-way flow in a shared business network. It was in 2014 when economist Jeremy Rifkin first introduced the concept of the Energy Internet in his book, which aroused widespread interest in the third industrial revolution [29]. He said, in the coming era, we need to create an Energy Internet so that hundreds of millions of people could produce green renewable energy in their homes, offices, and factories. The extra energy should be shared with others, just as we shared information on the Internet.

The information flow in the Energy Internet includes state monitoring data, energy (resource) user management data, energy supply network data, etc. Some key concepts in Energy Internet include prosumer, MG, VPP, smart grid and smart energy, and some of them have already been introduced. A VPP is based on some new technologies such as energy big data analytics, cloud/edge and IoT, and it is described as a cloud-based distributed power plant. It aggregates the capacities of heterogeneous DER to not only enhance power generation but also facilitate trading or selling power on the electricity market.

3.2 Internet of Energy

With the development of cloud, Hadoop and virtualization technology (e.g., NFV)[30], the distributed redundant storage and data management, as well as energy big data analytics are included. In the stage of Energy Internet, the management and sharing of resources with edge computing will achieve closer to the user's prosumer and sharing of energy, as discussed above, when considering data or energy generation, especially from the view of "edge autonomy". From the perspective of the collaboration between energy "edge autonomy" and "cloud autonomy", the advanced stage of Energy Internet development will go from energy use and sharing over the Internet to green autonomy of energy over IoT. All energy-related resources will be integrated with the concept of the IoT to achieve broad connectivity, autonomy, sharing and collaboration. This new stage may use another new term, i.e., the Internet of Energy. It is a technological term that refers to the upgrading and automating of electricity infrastructures for energy producers and manufacturers. The term is derived from the increasingly prominent market for IoT technology, which has helped develop the distributed energy systems that make up the Internet of Energy.

Internet of Energy, or Energy IoT, is one of the scenarios in which IoT is applied to achieve efficient energy use, and it plays an important role in distributed energy systems as they turn from energy consumers to the so-called "energy prosumers" in their development of buildings, industries, countries, and universities. Over the platform of Energy IoT, a number of energy-consuming devices (e.g., switches, power outlets, bulbs, televisions, etc.) are integrated by IoT connectivity, which can allow them to communicate with utilities to balance power generation and energy usage and optimize energy consumption as a whole. The IoT platform provides a functional architecture as device (app control)-middleware (horizontal)-communication networks.

3.3 Characteristics of the Internet of Energy

The Internet of Energy allows energy production to move forward more efficiently and cleanly with the least amount of waste. Other characteristics are as follows:

1) Benefits of using it include increased efficiencies, significant cost savings, and a reduction in the wastage of energy.

2) Ultra-high voltage (UHV) transmission is a system that allows energy to be transmitted rapidly over long distances. UHV solves the problem of energy production being located too far from load centers. China first implemented UHV in 2009, but its development is constantly expanding to meet demand.

3) While the UHV extended the coverage, the "edge autonomy" will push the edge intelligence to self-organized MGs.

Taking China and energy usage as an example, although China is one of the world's largest producers of renewable energy, it still experiences shortages and energy crises because it cannot deliver energy at a level that can sustain its population. This results in power outages and gaps. The infrastructure for a massive number of EVs with sufficient charging stations is one of the solutions, together with storage sites under construction —— particularly in cities that use the most energy —— to store excess energy efficiently and close to where it will be needed. Economic benefits are provided for companies that supply renewable energy, such as solar and wind, since more energy will be retained and sold, in addition to providing relatively low storage costs.

The technological benefits of the Internet of Energy are as follows:

1) Integrate traditional and emerging energy generation to achieve cleaner, safer and more economical energy delivery.

2) Operators will realize transparent and visible monitoring and analysis in energy circulation and also realize two-way communication over prosumer smart meters and consumption pattern analysis.

3) Intelligent devices that collect and analyze massive data will be able to enable emergency plan operation according to emergencies.

4) The intelligent IoT devices will achieve distributed energy management based on real-time data and situational awareness rather than based on historical data mode.

5) When a component needs attention or repair, the predictive ability of maintenance will remind the operator in time to reduce unnecessary uninterrupted inspection.

6) The adaptive analysis will enable the system to automatically balance energy load, reduce local pressure, and prevent overheating. A large number of distributed MGs and medium-sized energy and power plants can be combined with the self-organization mode of VPPs. With this edge concept, the coverage of MGs can be isolated from the central main grid (e.g., the SST use case), and energy supply can be realized from some internal energy sources, such as roof photovoltaic equipment, wind or thermal energy, power plant (or energy storage station on the edge) for "edge autonomy". In addition, more or not enough energy on edge will collaborate with other MGs in energy "cloud autonomy".

3.4 Energy LAN as an Edge Autonomy Use Case

As IoT devices and services are already integrated with smart grids/MGs and smart buildings/offices/factories, the release of power is done via remote connectivity, which can allow them to communicate with utilities to balance power generation and energy usage and optimize energy consumption as a whole. These devices allow for remote control by users, or central management by a cloud-based interface, and enable distributed functions like "edge autonomy", as shown in Fig. 9.

In Fig. 9, the smart local grid is upgrading from a utility-side IoT application. In this stage, systems gather and act on energy- and power-related information to improve the efficiency of the production and distribution of electricity. It progresses towards the use of advanced metering infrastructure for energy devices, Internet-connected devices for prosumers, as well as electric utilities which collect data from end users and manage distribution automation [31]. All these make IoT devices to be like transformers that push the smart grid to the Energy Internet and the Internet of Energy.

From the developmental views, the benefits and business values of the Internet of Energy are as follows:

1) Data at the micro level, resource management at the macro level, and the two tendencies combine at the edge.

Energy data is from user-oriented to "things/devices oriented", and resource/energy management is from low-level mode to high-level mode as cloud/edge, which can coordinate a wider range of energy resources. Fig. 9 is a basic unit of the Internet of Energy in a LAN diagram, which can be implemented in a family, factory, building, etc. The energy mode based on distributed self-

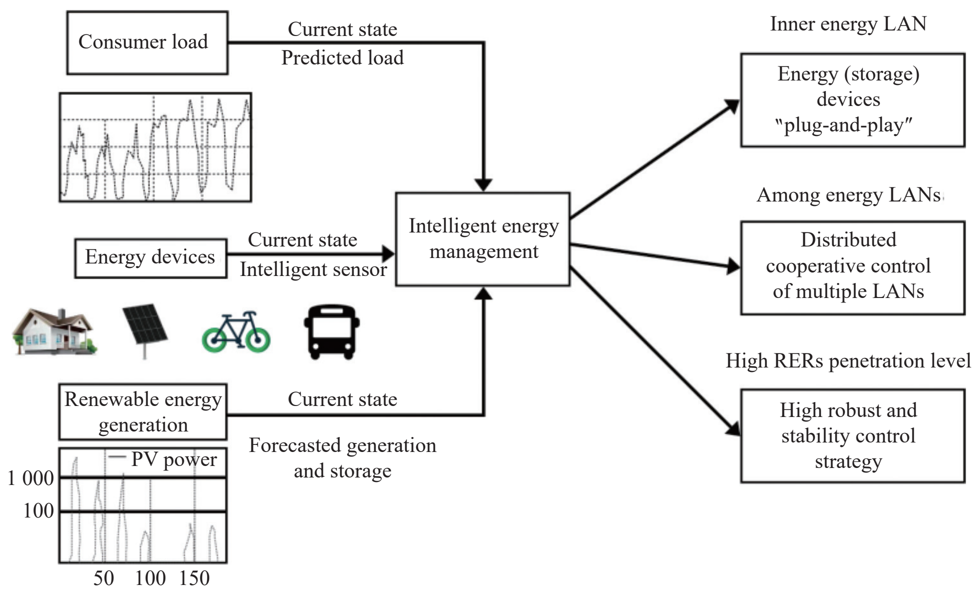

Fig. 9　Energy LAN on the edge as a smart local grid [3]

sufficiency is divided into three parts: consumption load and state prediction, the "plug-and-play" and other energy devices, and RER generation. In the LAN grid center, intelligent energy management realizes the real-time consumption and RER generation of monitoring and management. The LAN unit connects to the upper grid (MG or DMS in energy WAN) through the grid gateway (EMS as mentioned above).

2) The systematic combination of the energy network and consumption network.

Internet of Energy is an intelligent wide area network that combines energy and IoT deeply and organically. At the different levels of country-to-country, district-to-district (in a region), point-to-point (in a family), and even granularity (in MG or IoT grid/PIoT level), we should realize the combination of sharing and unification, sharing and hierarchical autonomy (edge/cloud level), green energy cycle, and ecological environment protection.

3) Integration of the Internet of Energy and ecological environment.

Energy consumption is due to human dissatisfaction with the pursuit of comfort from science and technology, resulting in the consumption of materials and energy to meet human needs. But energy is facing depletion, forcing us to weigh energy consumption and scientific and technological development. Energy is something like water and air to humans now. The attitude towards energy should be viewed over a longer historical period. The earth itself is an ecosystem, and the speed of biological evolution and the ability to adapt to the transformed environment is in balance, with species extinction serving as a piece of circumstantial evidence. If we break this balance, we may open a Pandora's Box, which will have an impact on the environment, water, and air, and challenge the survival of organisms. Earthquakes haze, and pollution may result from the breakdown of this balance. Therefore, human beings need to look at energy, technology, the environment, and human beings (biology) from a larger perspective. The Western exploration of unknown laws is open, while the Eastern exploration of unknown laws is convergent. However, uncertainty theory (e.g., Schrodinger's cat) tells us that the laws under certain conditions may get different results when the conditions go further to the micro or step back to the macro.

4　Conclusion

With the increasing infrastructure of DERs and the increasing complexity of energy production structure, as cities evolve towards smart, the user-side energy consumption curve becomes more dynamic. Energy data, whether in terms of quantity, type or dynamic randomness is far ahead of the traditional energy era. Using human resources only cannot timely, effectively and accurately judge and control the supply and demand curve of distributed energy. At this point, an effective auxiliary tool —— the Internet of Energy —— is needed to replace the human brain in optimizing, analyzing, judging, making decisions on massive amounts of data and issuing instructions. Therefore, in the Internet of Energy, AI will be well applied to support the development of the Energy Internet. But we must be cautious with the development and utilization of energy. If we can raise our cognition of the impact on the ecological environment through the IoT and promote the dimension of the integration of things, energy (e.g., service) and ourselves (e.g., relation in smart local grid or IoT grid), with a granular and deeper understanding of Internet of Energy, we may find the sustainable way for the utilization of energy.

Renewable energy is the main, and non-renewable energy is the auxiliary and gradually eliminated. In coming years, as the world works toward harvesting renewable energy sources, the use of non-renewable resources is expected to fall, which will reduce the need for outdated infrastructures that handle resources such as coal and oil. Numerous types of distributed renewable energy generation technologies and systems on the Internet of Energy will increase the permeability, connectivity, and proportion of renewable energy in the energy market. It is necessary to predict and study a series of new scientific and technological problems, and the first is to explore whether nuclear energy should be eliminated from the long-term comparison of energy benefits and environmental damage. With more overall characteristics , the dynamic energy supply, incorporating time-sharing, planning, and demanding considerations will be used to restrict each other with price (electricity price and energy generation cost), realize the multi-objective overall optimization of green energy consumption, sustainable energy supply, dynamic regulation and energy storage, as well as ecological environment protection, and ensure the current and long-term consistency, encompassing energy self-evaluation, self-optimization, self-planning, self-evolution and self-balance. Related markets are shown in Fig. 10.

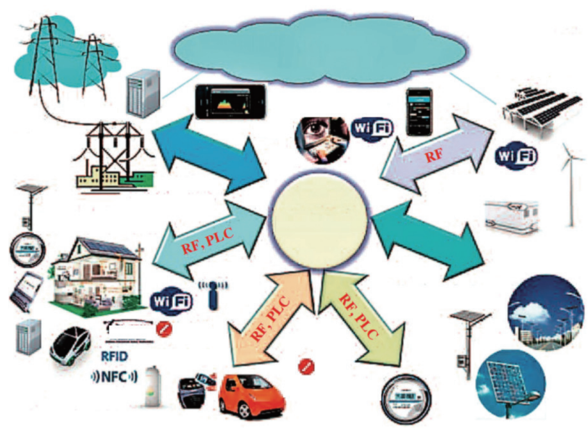

Fig. 10 Markets of Internet of Energy [32]

The Internet of Energy will not only change the expected operation mode of the Energy Internet but also consider the response from the user's (DER and RER as energy prosumers) side. It explores the local and regional changes of load, by predicting and adapting to environmental changes (e.g., temperature drop, earthquakes, and other emergencies). Considering the random characteristics of new energy access, new energy (consumption and storage) modes, and new technology innovation, such as edge/cloud in the control, optimization, and scheduling of energy, the Internet of Energy will face greater challenges. Fortunately, there still is an opportunity to choose the correct way. A comparative analysis of smart grid, Energy Internet and Energy IoT concepts is shown in Tab. 1.

Perhaps we can imagine that before the real energy crisis comes, the Internet of Energy will meet the needs of human energy consumption just like the alternation of the sun and the moon, the cycle of the seasons. We will not feel like a system but a gift from nature. The autonomy of the Internet of Energy can consciously reduce the damage to the ecological environment, to the extent that the ecological environment can repair itself, and provide intelligent planning for the energy

Tab. 1 A comparative analysis in the evolution stages of energy systems

Evolution stages	Essence	Objectives	Source	Capability	Stages	Technical Views
Smart Grid/ Smart Energy	Smart	Decentralized energy system, centralized energy system	Electricity, hydroelectricity, thermal power	Coverage	From 2nd industrial revolution	Digitalization, automation and other intelligence; IoT only for condition monitoring of power equipment
Integrated Energy System [33-34]	Energy integration	Collaborative optimization between different energy sources	Natural gas, thermal energy, wind, light, water, biomass and other types of energy	Regional multi-energy system	From 2001, proposed by the United States	Integrated energy system is the physical carrier of Energy Internet
Energy Internet	Energy sharing	Distributed energy system Peer-to-peer open, plug and play, two-way transmission, highly intelligent, real-time response	Wind, light, water, electricity, nuclear and other types of energy	Coverage, connectivity, deep integration with information and communication technology	The period from 2014 and beyond, when the world reaches 10 energy-consuming products per capita, may just be the beginning.	Big data, interactivity, edge computing and IoT for monitoring, management and the innovative representation of energy systems in the 3rd industrial revolution
Energy IoT/ Internet of Energy	Energy autonomy network	Smart & connected energy system. Balancing and cycling of energy supply, energy storage and energy consumption. Integration of energy supply equipment networks and electricity consumption networks. Integration into smart (eco) cities, smart planet	Modular, plug-in and networked energy (produce, storage and consumption for oneself); VPP arise	Regional (cross-regional) load balancing and balanced forecasting, phase-out of high-consumption energy and access to low-consumption new energy sources; energy cloud autonomy	In the future, the IoT will be fully applied when personnel hold hundreds of portable appliances, each household holds thousands of appliances and each business runs tens of thousands of appliances.	Micro-scoping, convergence, sustainability, cloud computing and big data to form energy cloud autonomy. IoT for monitoring, management, forecasting and overall optimization. Smart, environmentally friendly, recycling, and bioenergy
Energy Eco Network (EEN)	Searching for the tiniest particles of energy, possibly all derived from bioenergy. In addition to operating every individual asset in the VPP, the central control system uses AI algorithms to adjust to balance reserve commands from transmission system operators to grid conditions——just as a larger, conventional power plant does. Furthermore, the VPP can react quickly and efficiently when it comes to trading electricity, thus adjusting plant operations according to price signals from the power exchanges.Decentralized units create collective intelligence.With a pool of several small- and medium-scale installations, electricity is either consumed or produced from a VPP, a real energy plant or an energy reserving unit. Individual small plants can in general not offer services as balancing reserves or offer their flexibility on the power exchanges as their production or consumption profile varies strongly, they have insufficient availability due to unforeseen outages or they simply do not meet the minimum bid size of the markets.					

consumption of human technological development, avoiding the energy consumption produced by human beings.

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作者简介：

SONG Hang

SONG Hang(First Author, Corresponding Author)

1979-, Male, PhD, professor and senior scientist of Shenzhen Automotive Research Institute(SZARI), Beijing Institute of Technology University, adjunct professor of Xidian University, and an expert of the Shenzhen Internet of Things Industry Association (SZIOT). He has worked as a postdoctoral researcher at NUDT (the National University of Defense Technology, China), as the chief scientist on the Industrial IoT of Nanjing Qiyuan Information Technology Inc., and as a project scientist on the automated driving project in a Fortune 500 company. He is also a special advisor of the "YU TU Forum" (held by the Henan Provincial Library of China), where he contributes more to the science and technology popularization of the Internet of Things (which has been reported by mainstream newspapers and magazines many times, such as Henan Daily), and has served in many conferences as keynote speaker as well as presented session talks internationally. With about 20 years' research and practice of IoT, the projects he has devoted to are funded by the Postdoctoral fund of China and ICT enterprises. He has authored over 40 papers and two IoT-related books. The recent Chinese book about IoT has attracted tens of thousands of readers since it was published in 2019. His research area includes Internet of Things, Industrial IoT, V2X, Cloud/Edge Computing, Wireless Sensor Network (WSN), 5G/6G, IoT security, connected and autonomous vehicles(CAV), Energy IoT and reinforcement learning (e-mail) agonii111@163.com.

WEN Xiang

WEN Xiang

1977-, Male, received Bachelor, Master, and Ph.D from Xidian University respectively in 2000, 2003, and 2014, in Detection Technology and Instrumentation, Circuit and System, and Signal and Information Processing. He serves as an associate researcher at the Hangzhou Research Institute of Xidian University currently. He is a member of the China Electronics Society, awarded the third prize for provincial level scientific and technological progress twice. He engages in research and engineering practice in radar system design and radar signal processing. In recent years, he has led and completed multiple key research and development projects as well as horizontal projects (e-mail) wenxiang01@xidian.edu.cn.

ZHAI Hua

ZHAI Hua

1990-, Female, received Master from University of Electronic Science and Technology of China in 2014, in electronics and Communication Engineering (e-mail) huazhai@126.com.

（编辑　孙舒）