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Energy Internet Access Equipment Integrating Cyber-Physical Systems: Concepts, Key Technologies, System Development, and Application Prospects

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ABSTRACT This paper systematically proposes a novel concept of energy Internet access equipment (AE) integrating cyber-physical systems (CPSs). First, based on the concept and characteristics of energy Internet AE, we comprehensively investigate its global system development, including overall framework and functions design, core hardware equipment development, and software system design and development. Among these, the hardware part containing five major types of equipment is used to achieve a unified connection of various distributed energy equipment; the software part, consisting of three categories of system platforms (i.e., local energy management system, cloud Web page system, and user-side APP), is applied to integrate energy management and distributed coordination control. Moreover, we carry out an initial practice for this proposed energy Internet AE. Based on this, finally, we prospect future application scenarios for the energy Internet AE from multiple aspects. As a unified interface platform, the proposed energy Internet AE is directly applied for end-users to connect various energy supply and utilization equipment to the energy Internet, so as to monitor and coordinate the distributed energy equipment in real time and, finally, to realize the bidirectional circulation of energy flow and information flow in smart grid. The biggest innovation of this paper lies in comprehensively proposing a novel concept of energy Internet AE from the perspective of the CPS, with an aim of hoping to provide some thoughts for end-users to access the energy Internet efficiently and conveniently through such equipment in the future.

INDEX TERMS Energy Internet access equipment, energy Internet, comprehensive energy systems, cyber-physical systems, unified interface platform, energy management, distributed coordination control, energy flow, information flow, bidirectional circulation, smart grid, distributed energy and equipment.

I. INTRODUCTION

Electrical energy has been widely utilized in various aspects of our daily lives and production. With the rapid development of economy and society, more and more countries have gradually begun to pay attention to demand response (DR) and integrated energy management (IEM). Energy management and optimization play a key effect in the sustainable development [1]. To this end, the United States and some European countries first proposed the concept of home energy management system (EMS) in 1970s, with the goal of improving electricity consumption efficiency and achieving energy saving and emission reduction. Since then, relevant research results of EMS have become increasingly abundant [2]–[5]. Currently, IEM can solve the problems of distribution network power supply, user power consumption and new energy

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utilization to a certain extent. However, the actual IEM systems still have many shortcomings when used in actual energy management and utilization. In particular, the existing energy exploration and exploitation models that rely on non-renewable energy sources are increasingly difficult to sustain. Therefore, high-efficiency, safe, reliable and sustainable energy use models will be the solution to the major problem of energy use faced by human and society [6].

In the above context, the *Economist* magazine published an article titled *Building the Energy Internet* in 2004 [7], pointing out that it is essential to build an intelligent energy interconnection network in the future. After that, in 2008, the US FREEDM Project initially proposed the implementation plan for building an energy internet [8]. Thereafter, the famous American economist Rifkin [9] first proposed the vision of developing energy internet from the perspective of energy and information integration in 2011. Successively, in 2012, the EU clearly stated that the core of the development of Industries 3.0 is to develop and accelerate the construction of the energy internet. For this purpose, Germany took the lead in proposing the E-Energy program, trying to build a new energy network [10]. In addition, Japan has also proposed the development concept of Digital Grid [11]. In China, the China Electric Power Research Institute conducted a preliminary study on the future development of China's power grid in 2011, in which the concept of flexible power distribution system was proposed [12]. After that, this institute jointly submitted a preliminary research report on energy internet in 2013 [13]. In 2014, the State Grid Corporation of China proposed the concept of Global Energy Internet and its preliminary implementation plan for the first time [14]. Moreover, in 2016, China clarified the country's energy internet development plans and goals [15], striving to initially establish an energy internet industry system by 2025.

It can be seen that energy internet is becoming a research hotspot for many scholars, who have different understandings of the concept of energy internet. Among these, Ma [16] points out that the energy internet should have the following meanings: multi-energy complementary in horizontal aspect, coordination of energy sources, networks, loads and energy storage systems in vertical aspect, dual synchronization of energy flow and information flow, data management everywhere, everything becomes intelligent via human-machine dialogue, terminal electrical energy sources continue to expand, renewable energy alternatives are generally applicable, and energy ecology continues to develop. In addition, Sun *et al.* [17] describe the energy internet more succinctly as a new generation of energy system that integrates energy systems and the Internet. For example, a representative energy internet framework and a typical application scenario of the energy internet [18] are demonstrated in Figure 1 (a) and (b), respectively. Here, the energy internet contains a number of energy local area networks which are connected to each other.

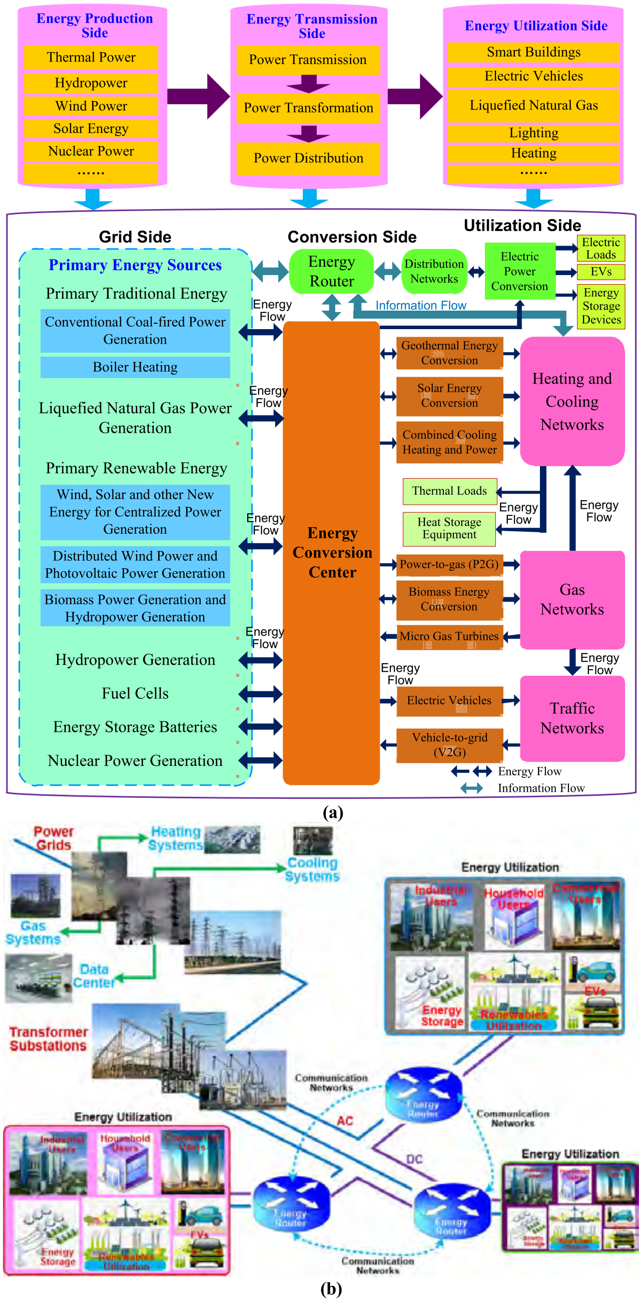


FIGURE 1. A basic framework and a typical application scenario of the EI. Here, (a) demonstrates a basic architecture of the energy internet system, in which energy flow and information flow are in dual circulation and coupled with multiple energy forms on grid side, conversion side and utilization side. (b) shows a typical application scenario of the energy internet, where power grids provide AC and DC power generation for energy utilization such as industrial, commercial and household users, energy storage, renewables utilization, and electric vehicles (EVs), via transformer substations and the core equipment in energy internet-energy routers. (a) Basic framework of a typical EI system. (b) A typical application scenario of the EI.

In the context of the above-mentioned development of energy internet, participants in the energy system are becoming more complex and diversified [19], and information interactions between the grid side and the user side are becoming more and more important and frequent [19]–[22]. Moreover, with the increasing number of power generation equipment from distributed new energy access to the power grid, the management, optimized utilization and coordinated control of these types of distributed equipment will be particularly important. This situation puts forward higher requirements for DR, and whose connotation has also been completely expanded. Therefore, the DR under the energy internet is required to be equipped with better monitoring techniques and have higher energy-saving benefits. This means such DR should have the capability of supporting the access of various distributed equipment or devices, thereby enabling end-users to perform active response in real time. To achieve this goal, the idea of cyber-physical systems (CPS) [23]–[25] is important to the implementation of DR under the energy internet. CPS is a multi-dimensional complex system that integrates computing, communication and control deeply, called 3C technology (i.e., computation, communication, and control). In addition, it can closely and organically combine the cyber space with the physical space, thus measuring and controlling the physical processes through sensors and embedded microprocessors, and meanwhile, the physical processes respond to the computational process [20], [21], [26], [27]. Based on this, in order to generate better trading mechanisms for supply and demand interactions and realize real-time matching of supply and demand information by the energy internet, thereby allowing each end-user to actively become a prosumer of energy while also conducting electricity trading all the time. This cannot be achieved only relying on current energy-using equipment itself, and is also not possible with energy router, which is the core equipment of the energy internet [28]. For this reason, it is necessary to provide an energy utilization facility as a medium device to effectively access to the energy internet. This kind of facility can not only uniformly connect all kinds of energy-using equipment of end-users to the grid, but also realize timely interaction of information between the power grid and end-users. It also possesses the capabilities of self-management, automatic control, remote response, humanized intelligent management and control, and so on. Such type of facility is called energy internet access equipment (AE), which is the research focus of this paper.

Currently, there are some research results for energy internet interface devices at home and abroad. Among these, Huang *et al.* [8] introduces the interface device used in the energy internet prototype system, which has been constructed by the US FREEDM Research Center. It uses energy router as a basic unit of the energy internet, and solid state transformer (SST) as the main circuit. Here, SST is used to extend a number of different energy interfaces to make distributed energy equipment and load equipment access to energy internet. In this study, the concept of plug-and-play is proposed. However, its implementation relies on standard communication interfaces, and it cannot identify the equipment type according to the load characteristics, thus limiting the plug-and-play capability of the loads without a standard communication interface. To this end, Shi [29] tries to design an energy and information integration interface for the energy router based on the idea of unification. This interface uses IEC61850 as communication protocol. However, it also needs to tackle the obstacle that the identification of the load device depends on the communication capabilities possessed by the load itself. Hu *et al.* [30] further describes the energy internet level equipment system as SST-energy router-energy switch, and investigates the operation mode of energy switch. The research work on energy internet interface device in above literatures mainly focuses on the access and control of distributed energy equipment, and does not involve detailed research on how these devices support the distributed energy transactions under the energy internet. For this purpose, Peng *et al.* [31] proposes the concept of wide-area cyber-physical associated interface device for the distributed new energy access to energy internet, and simulates the market-level applications. However, the proposed wide-area associated interface device is only used for distributed new energy equipment, and the consensus and settlement issues in the decentralized model in market transactions are not considered.

Therefore, according to the above research work and the concepts and characteristics of CPS, combined with the development trends and emerging technologies of energy internet in recent years, and in order to realize unified energy and information access to the system and transactions for various distributed energy devices, this paper, based on the concepts and characteristics of the energy internet, tries to apply the idea of CPS [6], [32] to the research and development of energy internet AE, and further deepen the concept of energy USB system (EUSBS) proposed by us in [20], [21], and [26]. Here USB contains two major implications: universal serial bus [20] and unified service bus [21], [26]. The former is a term frequently used in computer field, which means unified access of various distributed energy equipment and bidirectional circulation of energy flow and information flow when used in the energy internet AE. The latter means that EUSBS can be regarded as a unified service bus for energy internet-connected distributed energy equipment, to provide unified access services for all distributed energy-using and energy-supplying equipment (e.g., photovoltaics(PVs), fans, EV charging piles, distributed energy storage equipment, and industrial, commercial and residential end-users) through effective identification (i.e., hardware fingerprinting) to complete the aggregation, transfer, screening, analysis and uploading of various CPS data, thus finally achieving the two-way interconnection and communication of energy flow and information flow between the whole system equipment and the grid.

Therefore, based on the above two meanings of USB, this paper first propose the concept of energy internet AE. Combined with the characteristics and access requirements of energy internet, this paper elaborates the concept definition, main features and application fields of the energy internet AE, introduces the key technologies in the process of implementing, managing and controlling energy internet AE, and discusses in detail the system development of energy internet AE. Finally, the engineering implementation scheme

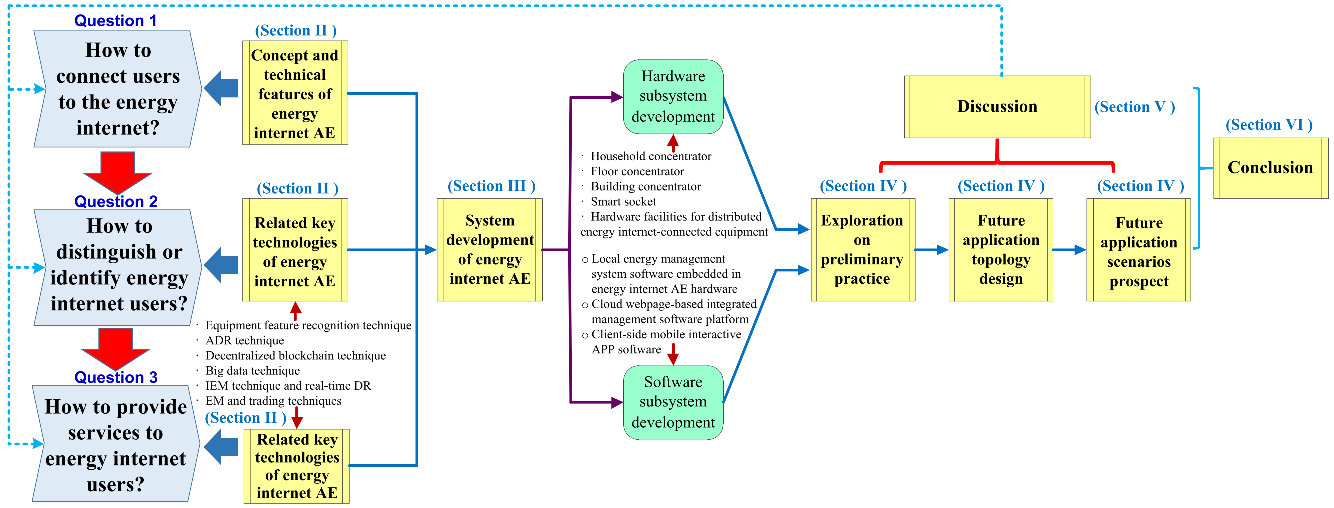


FIGURE 2. The logical relation between the sections in this paper.

and future application scenarios are briefly described and prospected, hoping to provide some useful reference for the further development of energy Internet AE, and some thoughts for efficient and convenient access for end-users.

The major engineering value and scientific significance of this paper can be summarized as follows: this paper systematically proposes the concept of energy internet AE from the perspective of CPS, and thoroughly and comprehensively investigates and summarizes its basic ideas, technical features, related key technologies, system development, preliminary practice and future application scenarios. This paper can provide some thoughts for end-users to access the energy internet efficiently and conveniently through the proposed energy internet AE in the future.

The remainder of the paper is organized as follows. We first introduce the energy internet AE proposal, and then describe its technical features and related key technologies in Section II. Successively, we comprehensively discuss the system development work of energy internet AE in Section III, including overall framework and functions design, and hardware part and software part development. In Section IV, we introduce the preliminary practice and prospect the future application scenarios of energy internet AE. In Section V, we conduct a short discussion. Finally, Section VI concludes this paper. In addition, the abbreviations used in this paper are listed in the Nomenclature section. The logical relation between the sections in this paper is demonstrated in Figure 2.

II. CONCEPT, TECHNICAL FEATURES AND RELATED KEY TECHNOLOGIES OF ENERGY INTERNET AE

In this section, we first introduce the energy internet, based on which, we define the proposed energy internet AE, and compare it with energy router. Then, we introduce the connecting modes of the energy internet AE to the energy internet. After that, we elaborate the major technical features of energy internet AE. Lastly, based on the technical features, we thoroughly discuss related key technologies of energy internet AE from the perspectives of equipment feature recognition technique, automated demand response (ADR) technique, decentralized blockchain technique, big data technique, IEM technique, and electricity market (EM) and trading techniques.

A. CONCEPT DEFINITION

1) CHARACTERISTICS OF ENERGY INTERNET AND ITS DEMANDS FOR ENERGY EQUIPMENT ACCESS

With the rapid development of the energy internet, its concept has gradually become clear. Energy internet has broad and narrow definitions. In a broad sense, energy internet is a collection of multiple networks, including power grids, gas networks, energy storage networks, heating and cooling networks, electrical transportation networks, and energy transportation logistics networks [6], [18], [33]. While in a narrow sense, energy internet is a network covering smart grids, distributed energy and various types of equipment and facilities on generation side, energy storage side, user side and EV side [34]. Although there are differences in scope, the energy internet can be summarized as a networking energy integration technology [35], which is an energy-to-peer exchange and sharing network that realizes bidirectional circulation of energy flow and information flow [21], [36]. Compared to power systems, the energy internet has the following characteristics [21], [33]–[36]: 1) high proportion of renewable energy; 2) nonlinear random characteristics; 3) multi-source big data characteristics; 4) dynamic characteristics under multiple time scales.

Therefore, energy internet is a huge energy asset market that can realize resource integration, energy trading and DR. In this market, energy is freely and equally traded and exchanged in the form of peer-to-peer, and users are energy prosumers. In addition, in this energy asset market, energy router [28], [29], [37] is the core equipment (see Figure 1(b), which is treated as an interface of energy production, consumption and transmission infrastructures [37], and controls the energy flow of the whole system. Therefore, for the energy internet, in order to give full play to its role, it is crucial to develop corresponding equipment to connect all energy-using and energy-supplying equipment, thereby making various energy equipment become observable and controllable in energy internet, and ultimately achieving the goal of providing a higher level of service to the energy equipment. Such services include [20], [21], [38]: energy-saving service [39], frequency control service, power balance service, new energy access service, DR service, and even other value-added services such as data mining and big data applications. To achieve these services, internet access devices are essential.

In general, first of all, as an energy network, energy internet needs to provide reliable physical interfaces for various types of terminal energy equipment, so as to realize the bidirectional circulation of energy flow between terminal energy equipment and the main power network, and monitor and control the operation status of the terminal equipment. Secondly, the energy internet as an information network needs to provide a unified communication interface for all types of terminal energy devices, so as to realize the interconnection of information between various types of terminal energy devices and superior management systems. In addition, as an open energy market, the energy internet needs to provide unified metering and trading methods for various types of energy terminals, so as to achieve the equal participation of terminal energy use in market activities. To this end, this paper proposes the concept of energy internet AE, which is elaborated as follows.

2) DEFINITION OF ENERGY INTERNET AE

Energy internet AE is firstly a kind of end-user-oriented cyber-physical terminal media equipment that provides an energy internet interface (i.e., unified identification) for all types of distributed energy-using devices and makes them observable, measurable, and controllable. Secondly, it is the medium for users to access the energy internet, as well as the medium for distributed energy-supplying equipment interacting with the energy internet in an observable and measurable, and even controllable state. At this point, it embodies various features of the energy internet at the user end. Lastly, it is the final execution equipment for above-mentioned various services in the energy internet.

For above purpose, energy internet AE includes a series of core devices (such as smart sockets, home/floor/building concentrators for energy management and coordinated control, and hardware interface devices for assessing various distributed devices such as fan, PV, EV charging pile, and energy storage) that can be connected to the energy internet as a hardware system, which implements functions such as monitoring, data acquisition, coordination optimization, real-time control, user-friendly interaction, and multi-protocol communication. In addition, energy internet AE also contains the corresponding software system platforms (such as local EMS embedded in the energy internet AE hardware part, cloud Web-based management system, client-side mobile APP software, etc.).

Based on various intelligent algorithms, these software platforms can implement some advanced applications, including local IEM, load forecasting under distributed generation (DG) integrated, power quality optimization and energy efficiency analysis, coordinated control of distributed energy internet-connected equipment, electricity use behavior analysis, timely inquiry of historical data, etc.

3) DIFFERENCE BETWEEN ENERGY INTERNET AE AND ENERGY ROUTER

Based on above descriptions, we can find that the energy internet AE developed in this paper is significantly different from the energy router mentioned above from five aspects, as shown in Table 1.

4) CONNECTING MODES OF ENERGY INTERNET AE

Compared with energy router, the energy internet AE possesses multiple more flexible connecting modes. Specifically, these conclusion modes include [20], [21]: i) single equipment accessing; ii) single-user access to the energy internet by an aggregation of multiple energy-using devices or distributed energy devices; iii) multi-user access to the energy internet in forms of building accessing, enterprise accessing, power plant accessing, and so on; and iv) multiple buildings or enterprises with certain connections as an aggregation access to the energy internet, such as regional access, group company access, and industry access. In general, energy internet AE should have cascading capabilities that enable bidirectional circulation of information flow and energy flow as well as aggregation and retransmission.

B. TECHNICAL FEATURES

Renewable energy resources are took as the main sources of energy supply in energy internet; thus, the energy internet is characterized by distributed, interconnected, user-centric, shared, open, intelligent, and peer-to-peer [33]–[38]. Based on this, as the energy internet-connected equipment, the primary purpose of energy internet AE's should be to enable effective access of the end-users' energy-providing equipment (such as DG and energy storage equipment), energy-using equipment (such as various types of user electrical equipment), EV and other energy equipment. This ensures that the energy internet node possesses the features of unified access and plug-and-play for energy-supplying and energy-using equipment. To this end, the energy internet AE developed in this paper has some basic technical characteristics of the energy internet, as introduced as follows.

- Cyber-physical integration feature. It manages energy flow, and must help devices access to the energy internet in a unified form, and should be a multidimensional system deeply integrating computing, communication, and control.

TABLE 1. Differences between the proposed energy internet AE and the energy router.

Comparisons	Energy internet equipment	
	Energy router	**Proposed energy internet AE**
Status	✓ The core equipment of the energy internet, aiming at the conversion and storage of various energy forms	✓ Intended for end users as an energy internet-connected equipment
Function	✓ Mainly used to realize the transformation and exchange of high-power high-voltage energy	✓ More focus on the accessing and controlling of specific energy-using and energy-supplying equipment
Focus	✓ Mainly for the energy flow of the main electric power grid, and more consideration is given to the safe and stable operation between large power grids	✓ Mainly for end users, more consideration is given to the economics, comfort and related value-added services of specific users
Control means	✓ Control the energy flow of the entire energy internet	✓ Control specific energy allocation (distributed equipment coordinated control) and final energy use behavior of energy-using equipment
Information collection means	✓ Collect directly	✓ Needs to combine with information collection equipment to complete

- Real-time. It can accurately monitor the operating status of the energy internet-connected devices in real time.
- Interconnectivity. It enables each node of the energy internet to cascade or even self-organize the network to achieve regional autonomy, or directly form a larger system on the cloud, thereby achieving comprehensive situational awareness of the behavioral characteristics of various power sources, loads, and even end-users within the grid.
- Perceptibility (observability). It can meticulously and comprehensively identify and sense the operating state and output of the connected power sources and loads, and use some technologies such as big data technique to perceive user's power consumption behavior characteristics.
- Unified access feature. It enables unified access (which is similar to plug-and-play) of power generation, energy storage and load devices.
- Controllability. It can control the connected devices.
- Interactivity. Its user interaction interface is friendly, which can understand the operation status of user's energy-supplying and energy-using equipment in real time and provide corresponding optimization suggestions. It should also have the function of allowing users to interact with the electricity sales company, including demand management contract determination, real-time electricity price information release, comprehensive energy utilization improvement recommendations, and even can be used for electricity sales companies to realize value-added service functions.
- Autonomy (intelligent). It must have certain computing power and be able to make judgments and responses independently or autonomously based on preset strategies and current energy utilization information.

In addition to the above eight basic technical features, in order to achieve multi-energy coordination and complementarity for different energy forms, the energy internet AE should also have the following two technical features: distributed energy access capability and multi-energy complementary characteristics. Among these, the latter is reflected in the fact that energy internet AE can independently and locally manage and optimize the utilization of various types of energy forms for end-users, enabling multi-energy complementarity and coordination and IEM.

C. RELATED KEY TECHNOLOGIES

The realization of energy internet AE and implementation of its control and management depend on some related key technologies. Among these, some of them are the core technical capabilities that energy internet AE must possess, such as equipment feature recognition technique, which realizes unified access of various types of distributed energy equipment. This is the key to achieving the unified access of various types of distributed energy equipment to energy internet for plug-and-play, monitoring and management. Besides, some technologies are key technologies involved in energy internet and smart grid, including automated real-time DR technique, decentralized blockchain technique, big data technique, IEM technique, and EM and trading techniques. These are the supporting technologies for implementing the concepts and technical features of energy internet as described previously, and can also be called the key technologies of energy internet AE. For example, the energy internet AE can integrate the big data analysis technology to realize the mining of end-user's electricity use behavior and habits, the decentralized blockchain technology to achieve plentiful distributed trading modes, and the automatic real-time DR technology to achieve mutual benefit and win-win between users and energy suppliers.

Therefore, the related key technologies discussed in this section are the core supporting technologies that achieve friendly interaction between end-users and energy internet, unify all types of energy equipment into energy internet, and make the main features of energy internet fully reflected on the user side. In a word, these techniques are crucial for energy internet AE, and they are briefly explained as follows.

1) EQUIPMENT FEATURE RECOGNITION TECHNIQUE

Energy internet AE must support unified access of multiple types of equipment to avoid manual configuration of access devices. However, currently, a unified communication protocol interface is not available for a wide variety of distributed energy and load devices, who cannot understand their identity information through inquiry. Therefore, energy internet AE must possess equipment feature recognition capability to achieve above functions. At present, load identification technology has been evolved from simple manual rule setting to two major methods [40]. Among these, one is mathematical optimization method used to minimize feature difference, and the other is intelligent pattern recognition method based on neural network, decision tree, support vector machine (i.e., SVM) and machine learning algorithms [41] such as deep learning. From the implementation point of view, the load identification technology can still be divided into two major schemes: intrusive and non-intrusive load monitoring and identification [20], [21]. Taking the decision tree algorithm as an example, what the decision tree needs to do is to divide the dataset in a proper way. The most important principle of dividing the dataset is to make the unordered data more orderly and classify similar data into one category.

Regardless of intrusive or non-intrusive load identification method, the key is to understanding the electrical characteristics of various types of electrical appliances, called load fingerprint identification. Power fingerprints include load start and stop, standby, and transient and steady-state features in various operating modes. Some general characteristics of power fingerprint are shown in Figure 3.

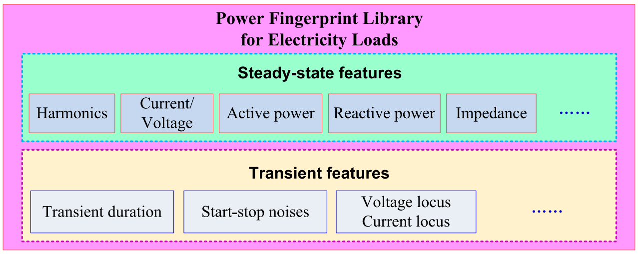


FIGURE 3. Some general characteristics of power fingerprint.

Based on Figure 3, we envisage a kind of power fingerprint system architecture as shown in Figure 4, which combines intrusive and non-intrusive detection devices to take advantage of the intrusive approach to accurately measure individual appliances and make full use of the user's interactive information to generate the device's power fingerprint and add it to the fingerprint library. This provides a basic implementation condition for non-intrusive detection devices. At the same time, on the one hand, the intrusive device can apply the information in the fingerprint library to provide a basis for load plug-and-play. On the other hand, based on non-intrusive identification, new fingerprint features can be discovered by intelligent methods and can be added to the fingerprint library to further improve it.

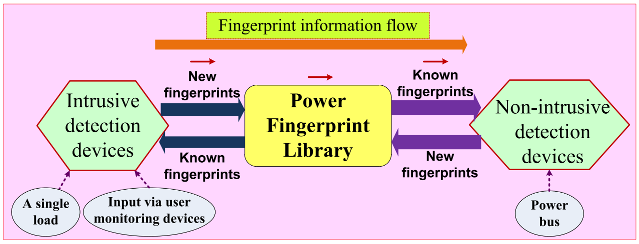


FIGURE 4. Overall framework of power fingerprint system.

2) ADR TECHNIQUE

In the context of energy internet, each energy system will accept multiple participants [22], and the number of responding entities will increase accordingly. Especially with the addition of human and social factors [6], the energy internet will evolve into an extremely complex cyber-physical-social system (i.e., CPSS) [24]. Consequently, in order to increase the participation of different types of responding entities more efficiently, broadly and accurately, it is urgent to introduce ADR technology in energy internet to replace traditional power DR technologies. Compared with the traditional DR, the ADR system, which is highly integrated with automation technology, communication technology and intelligent measurement technology, is out of the reliance on the government to issue notifications or the manual assistance from other entities, and can realize the real-time dynamic adjustment of the load by automatically receiving response signals from the cloud (e.g., Web-based cloud IEM software system mentioned previously). This means that ADR can respond reasonably to signals in the order of seconds or minutes in the framework of communication and control automation, thereby improving the real-time and flexibility of DR implementation.

The ADR system connects the energy internet AE (e.g., aforementioned intelligent terminals such as smart sockets, smart home concentrators, and energy internet devices for distributed equipment accessing) on the user side and the ADR cloud platform on the grid side. Its implementation involves multiple responding entities, including industrial and commercial users, residential users, load integrators, and power grid enterprises equipped with proposed energy internet AE [26]. In short, energy internet AE is responsible for collecting and uploading user-side data during the implementation of ADR, and receiving and executing instructions from the grid-side ADR cloud platform. To this end,

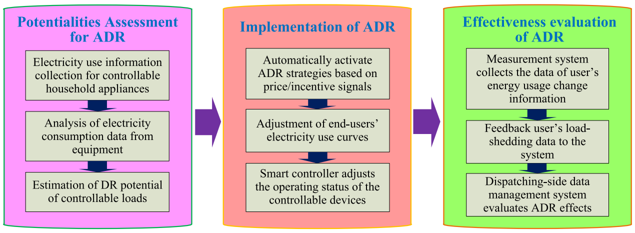


FIGURE 5. Overall functional framework of ADR system. Such framework is mainly composed of three parts, i.e., ADR potential assessment, ADR implementation, and ADR effectiveness evaluation.

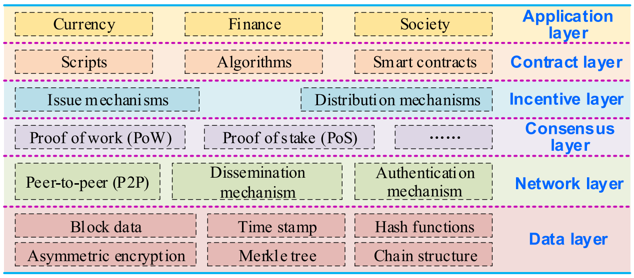


FIGURE 6. Key components included in blockchain technology framework. Such framework is composed of six major layers, i.e., application layer, contract layer, incentive layer, consensus layer, network layer, and data layer.

Zeng *et al.* [42] proposes a functional architecture for ADR as presented in Figure 5, which is mainly composed of three parts: ADR potential evaluation, ADR implementation, and ADR effect evaluation.

3) FULLY DECENTRALIZED BLOCKCHAIN TECHNIQUE

Energy internet AE not only provides access services for terminal energy equipment, but also undertakes energy market tasks for energy metering, trading, and settlement. The market entities and transaction types in the future energy internet will be greatly enriched. In order to meet the energy demands of massive distributed users, the decentralized transaction mode is an inevitable choice. However, with the disappearance of the centralized authority center, the transaction entities also face the problem of lack of trust [43]. Energy internet AE provides a guarantee for distributed transactions by introducing blockchain technology. Here blockchain technology is a type of chained data storage method in which a series of data blocks are arranged in chronological order, and it implements a secure and credible distributed ledger through cryptography technology [44]. Its biggest feature is to realize trusted peer-to-peer transactions through distributed consensus mechanisms without the mutual trust of each node. This can effectively solve the cost, efficiency and security privacy issues associated with relying on an authority center or caused by the trusted third party transaction method. Therefore, the blockchain can be used as a supporting technology for the trading models under the energy internet, an energy asset market. The overall architecture of the blockchain technology is illustrated in Figure 6. It consists of a data layer, a network layer, a consensus layer, an incentive layer, a contract layer, and an application layer [45].

4) BIG DATA TECHNIQUE

From the process of energy production, distribution and consumption, the data sources in the energy internet cover all aspects of energy production, energy transmission, energy trading, and energy consumption, and the data generation depends on the energy internet AE embedded in these links [21]. Under the realization of the energy internet, the massive data samples collected, transmitted and uploaded by hundreds of millions of energy internet AE need to be efficiently stored and managed through cloud storage technologies, and finally they are piggybacked on big data platforms for further data mining and analysis. Therefore, big data technology relies on the massive data samples collected by the underlying thousands of energy internet AE, and it is the technical cornerstone of the entire energy internet. At the application level, big data technology will cover all aspects of the planning, operation, transaction and management of the energy internet, and will play a role in assisting decision making in planning, scheduling, operation, management, and energy services of the energy interconnection system. This paper only briefly introduces the big data technology used in power service and transaction analysis for end-users' electricity consumption behavior analysis. The application structure of big data analysis for residential behaviors in electricity use is demonstrated in Figure 7. Specific processes are expressed as follows.

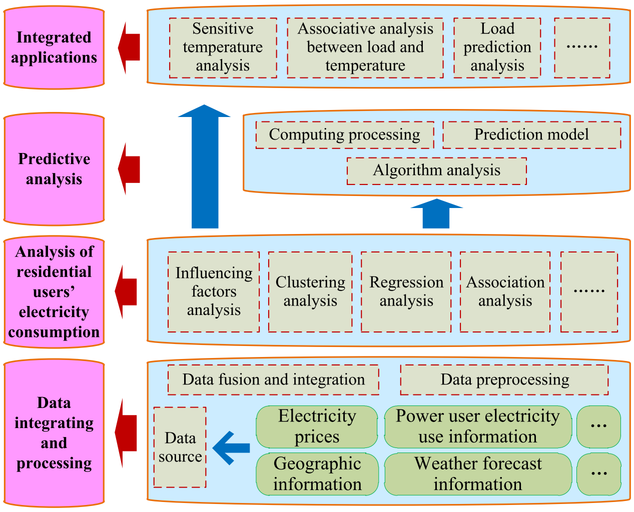


FIGURE 7. Electricity use behavior analysis for power end-users based on big data processing technologies.

i) Data integration and processing: use energy internet AE for data collection, and meanwhile, utilize data cleaning, storage and processing technologies to aggregate electricity consumption information, customer service data, geographic information data, and population and meteorological data to achieve massive, multi-source and heterogeneous data aggregation, management and integration, forming a user-side big data resource that is integrated and thorough.

ii) Analysis of residential electricity consumption: in reality, aiming at different application scenarios and analysis targets, use different data mining analysis methods (e.g., clustering analysis, regression analysis, and correlation analysis) to analyze the user's electricity consumption behaviors, so as to extract data features with a fine expression, providing an analytical basis for the application of the upper layer.

iii) Application level: the residential electricity consumption analysis results can be further applied to correlation analysis of load and environmental factors, load prediction analysis, and so on.

5) IEM TECHNIQUE

The integrated energy system characterized by multi-energy complementarity and energy cascading utilization is an important part of the energy internet. Compared with traditional power systems, the integrated energy system possesses some different characteristics. First, the networks of electricity, gas, heat and cold have their own modeling and analysis methods, leading to the need for new analysis methods after multiple energy networks are coupled. Secondly, due to the different physical properties of each energy medium, the dynamic process of each system is fast or slow. Therefore, the analysis of integrated energy networks involves multiple time scales. More importantly, the integrated energy network involves multiple market entities, and its system management optimization process will be constrained by incomplete information and control authority, resulting in the traditional centralized control method no longer applicable [46].

The above elaboration requires that energy internet AE needs to be able to provide access and management services for multiple energy network terminal devices, must understand the characteristics of integrated energy systems, integrates distributed IEM technologies, and ultimately plays the advantages of energy internet in decentralized autonomy and multi-energy coordination. Energy Hub (EH) is an important concept in solving the multi-energy coupling problem of integrated energy systems. Its model is demonstrated in Figure 8. This model describes an integrated energy regional hub that supports multiple energy forms input, conversion, and output, and can convert various types of energy as needed.

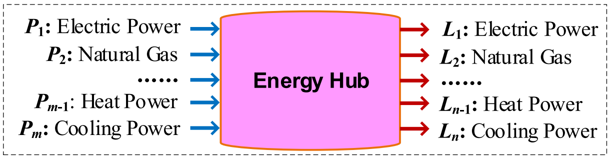


FIGURE 8. **Energy hub model.**

Compared with traditional centralized control methods, decentralized management models are more suitable due to the numerous types and numbers of entities in integrated energy network. Among these decentralized management models, the decentralized peer-to-peer Web-of-Cells (WoC) technology [47] (which is proposed by ELECTRA, i.e., European Liaison on Electricity Committed Towards long-term Research Activity) and the multi-agent system (MAS) with a certain hierarchy are two representative modes, which are described below.

WoC technology divides a large network into a number of functionally complete and equal-sized units based on a certain topological or regional boundary [48]. Each unit here is called a cell. As illustrated in Figure 9, each Cell has a centrally located operator, called CO (cell operator), who can monitor and control its own internal energy network, but it does not exist in isolation. In contrast, it will have market rules-based energy and information exchange with neighboring cells. Ultimately, all the small units are interconnected to form a WoC distributed decision-making system. The biggest feature of WoC is the autonomy of each cell and equivalence between cells [48].

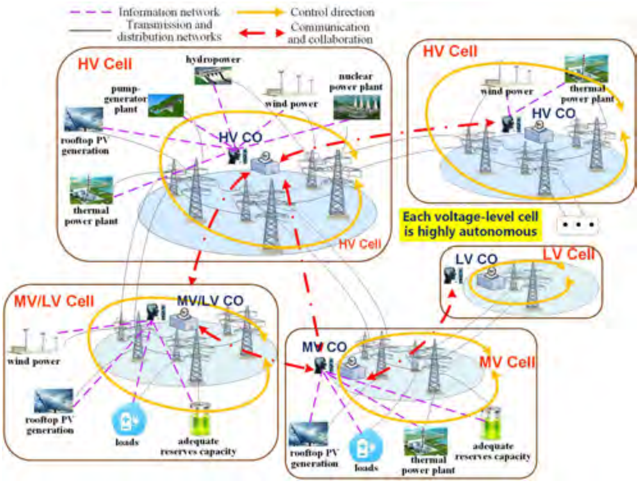


FIGURE 9. **Overall framework of power fingerprint system.**

MAS is a distributed decision-making architecture with both centralized and decentralized features. It consists of multiple agents with simple structure and functions. Each agent can only control part of the resources and part of the information. The overall task to be completed is transparent to each agent. On the one hand, each agent must make decisions based on the information it has mastered. On the other hand, it must receive the instructions issued by the superior agent. Therefore, the whole system completes the optimization decision and control tasks through hierarchical multiple agents [49].

In addition, integrated demand response (IDR) [50], [51] is also an important tool in integrated energy system management. Through IDR, the traditional DR tasks can be introduced into the integrated energy system from the power system, and the multi-energy complementarity technology can guide users to optimize the energy structure, improve the energy efficiency of EM and the comprehensive energy utilization efficiency, strengthen the new energy consumption capacity, and establish a more green energy utilization model.

6) EM AND TRADING TECHNIQUES

Under the realization of the energy internet, traditional trading models and pricing methods in EM will be transformed [19]. For the user, the unified access of power generation equipment, energy storage equipment and controllable loads can be realized through the energy internet AE, and in turn, individual power suppliers can sell surplus electricity to the grid or other residential users. For the power supply company, the massive user power consumption data collected by energy internet AE can be used for data mining, and then the decision-making instructions derived from the data analysis can realize wide-area non-interruptive load control and scheduling processing through ADR. At the same time, on the basis of power data analysis, in addition to traditional power trading, power supply companies can also provide users with auxiliary services such as load peak transferring, cutting, interrupting and stopping, preferential electricity prices, and voltage control to obtain more profits.

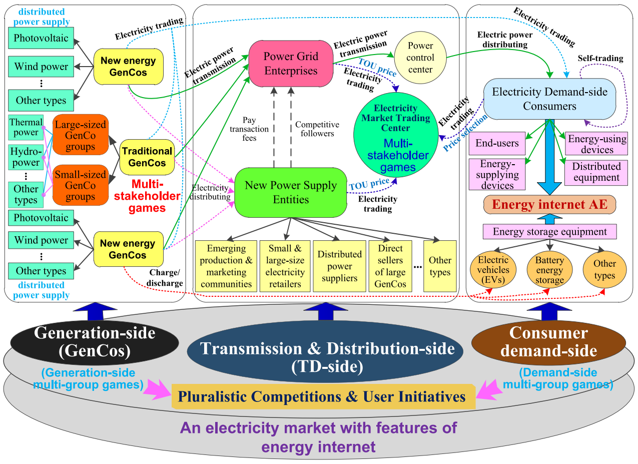


FIGURE 10. **Illustration of the self-organized coupling network framework of WoC. Such framework contains multiple cells with different voltage levels, and it can be seen as a complex cyber-physical-social network structure due to the consideration of social factors, such as game relationships between different cell operators who are seen as different stakeholders in the context of an ever-growing and open EM.**

Figure 10 demonstrates a structural model of the EM in the context of energy internet [22], where the EM under the background of energy internet has introduced a large number of new power supply entities such as distributed power suppliers, small-scale power sales companies and new production and sales groups to participate in market competition. The allocation and management of its resources will be developed from the traditional centralized overall balance to distributed and decentralized local micro-balance.

Therefore, in the new situation of the EM, the functions of the proposed energy internet AE can be defined as a local decision-making system in which users can participate in EM trading and energy-flow controller for DG and distributed energy storage in the EM. Under this circumstance, the price and incentive signals in the EM are the necessary basis for the energy internet AE to make control decisions.

III. SYSTEM DEVELOPMENT OF ENERGY INTERNET AE

In this section, we focus on the system development of the proposed energy internet AE based on CPS. To this end, we first introduce the idea of CPS. Based on this, we then design the overall framework and functions of the energy internet AE. Lastly, we thoroughly discuss the hardware part and software part design, respectively. Among them, the hardware part mainly contains five categories of energy internet AE, and the software part consists of three major software systems.

A. CPS

The cyber-physical systems, i.e., CPS, are considered to be the third wave of information technology after computers and the Internet. The core of CPS is the organic integration and deep collaboration of 3C technology (e.g., computing, communication and control). Currently, CPS have been widely applied in smart home systems, health care systems and intelligent transportation systems. In short, CPS can be summarized as four aspects of ‘‘sensing’’, ‘‘knowing’’, ‘‘connecting’’ and ‘‘controlling’’ [14], as shown in Figure 11(a). Based on this, the system construction modes of CPS are usually divided into two kinds [52]: one is a component-based construction mode, as presented in Figure 11(b), and the other is a hierarchically partitioned mode, as demonstrated in Figure 11(c). In Figure 11(c), we propose a construction model of CPS for the energy internet AE based on a four-level partitioning method; thus, the overall system of the proposed energy internet AE includes four layers: a physical layer, a communication layer, a service layer, and an application layer. Among these, the physical layer contains specific devices and possesses capabilities such as measuring, computing, and analyzing; the communication layer realizes real-time data transmission between different layers; the service layer is the core of data processing with capabilities of data mining, user interaction, and so on; and the application layer can provide various services for end-users to complete specific tasks.

B. OVERALL FRAMEWORK AND FUNCTIONS DESIGN

1) OVERALL FRAMEWORK DESIGN

According to the four-level system construction mode of the CPS as demonstrated in Figure 11(c), the overall framework of the energy internet AE developed in this paper is designed in Figure 12.

In Figure 12, the physical layer refers to all developed device entities access to energy internet system, which mainly includes energy internet AE hardware facilities and communication devices, user-side energy-using and energy-supplying devices, and user terminals. Among these, energy internet AE hardware facilities are the core part of the

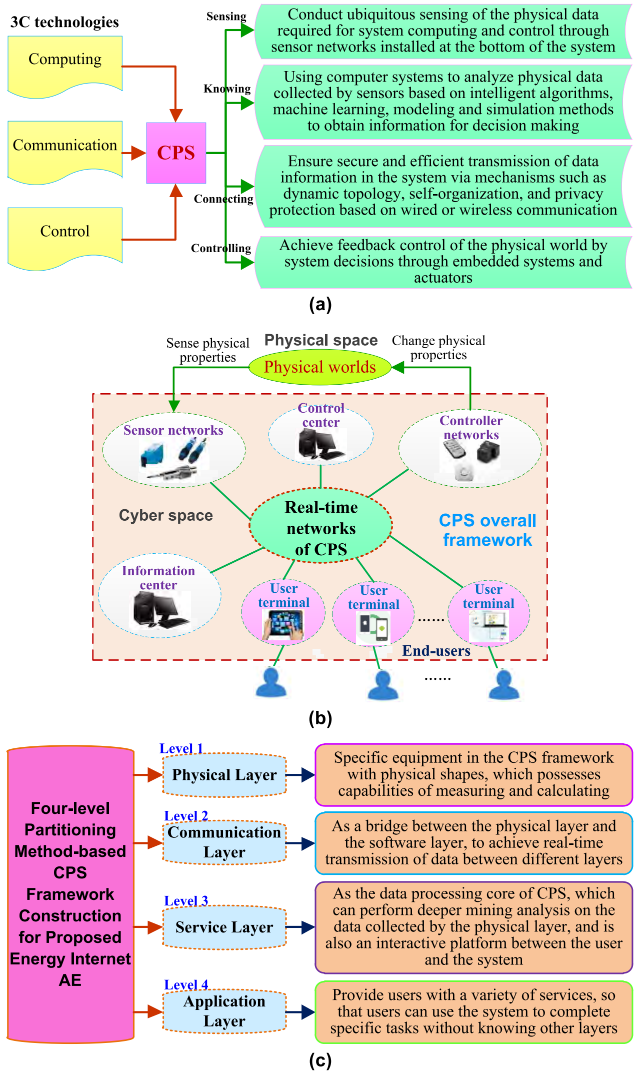


FIGURE 11. **System construction models for CPS and a specific construction model of CPS for the proposed energy internet AE, where (a) demonstrates four major aspects of CPS, including sensing, knowing, connecting and controlling, (b) illustrates a component-based construction mode of CPS, and (c) presents a specific construction model of CPS for the proposed energy internet AE based on four-level partitioning method.**

overall framework in Figure 12, which mainly implements functions such as data acquisition, real-time calculation, coordinated control, and interaction execution. The user-side distributed energy-using and energy-supplying equipment are the main targets of DR implementation. The energy internet AE hardware facilities collect and analyze its information and power consumption data and execute DR commands. The user terminals are the main physical carrier on which supply side and demand side can interact.

The communication layer covers communication modes (e.g., wireless communication such as WiFi, ZigBee, infrared, radio frequency, and wired communication such as power carrier, Ethernet, and fieldbus, transmission protocols (e.g., TCP/IP, RS232, RS485), and connection forms (e.g., point-to-point connection, star connection, tree connection). Communication layer is a bridge connecting the hardware part and software part of energy internet AE, thus we must reasonably choose the communication method. In addition, the switching between the primary and backup communication modes should be flexible, and the connection mode must be highly stable, such that we can achieve efficient and reliable data transmission.

The software layer includes localization EMS software embedded in energy internet AE hardware facilities, Web page end energy management platform, and client-side Android-based APP software. On the one hand, as the core of data aggregation and data processing, this layer can use the data collected by the devices in physical layer to perform global optimization of DR. On the other hand, the software layer is the carrier platform and interaction platform for various advanced applications developed in the system.

The advanced application layer is a general term for various advanced applications related to energy management embedded in the software layer, including electrical detection, power quality, energy efficiency analysis, load forecasting, information management, and so on. This layer can provide customized services for end-users, enabling users to easily perform data processing, view historical information, modify system parameters, modify optimization targets, etc., thereby achieving end-user localized energy management, including power consumption optimization and ADR.

2) FUNCTIONS DESIGN

The energy internet AE proposed based on CPS in this paper is a new type of hierarchical EMS applied to end users in the context of energy internet. Therefore, energy internet AE is an organic combination of hardware system part and software system part [20], [21], as demonstrated in Figure 13. In Figure 13, the functions of energy internet AE designed in this paper contain five aspects, as follows.

The functions of energy internet AE include: i) enables real-time accurate measurements of users' electricity use and environmental data; ii) supports multiple communication methods with good adaptability in different application scenarios; iii) identifies common distributed energy equipment, and implements unified access and coordinated control of distributed devices in the system; iv) performs user power consumption behavior analysis, establishes power optimization models for specific users, and formulates DR strategies according to the operating condition of the power grid; v) in the case of user authorization, the grid can control the user's energy-using devices and distributed energy-supplying devices to achieve DR. Therefore, through energy internet AE, the supply and demand interaction between distributed energy equipment and the grid and the two-way integration of information flow and energy flow can be realized. As elaborated in [21], when a distributed device is connected to the energy internet AE, on the one hand, the energy internet AE and the distributed device implement bidirectional energy interaction to complete related functions such as cutting off

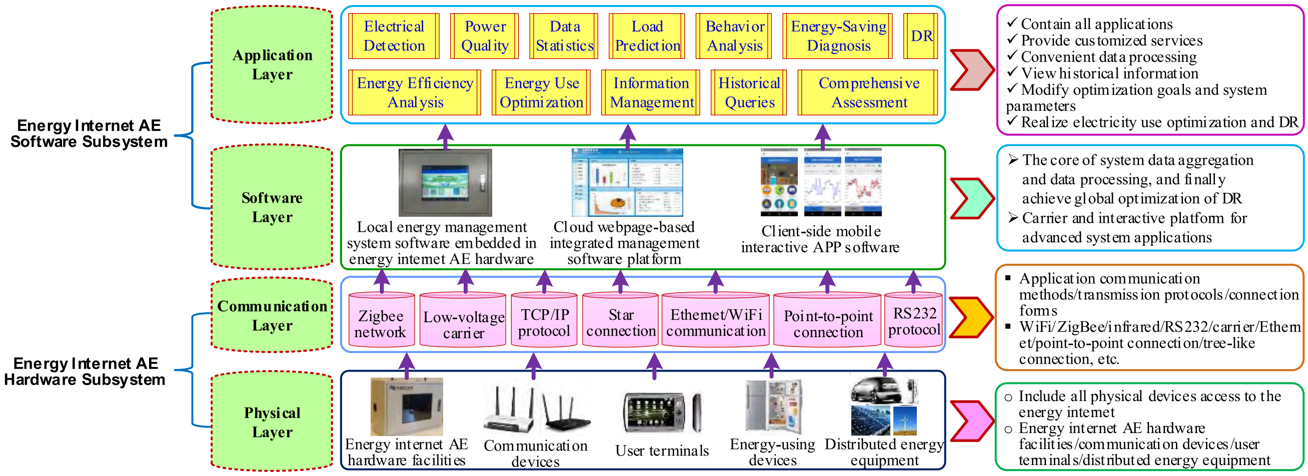


FIGURE 12. Overall framework design of the proposed energy internet AE based on the idea of CPS. Here the CPS framework is constructed based on four layers, including application layer, software layer, communication layer, and physical layer. Among these, the application layer and software layer form the energy internet AE software subsystem, and the communication layer and physical layer form the energy internet AE hardware subsystem.

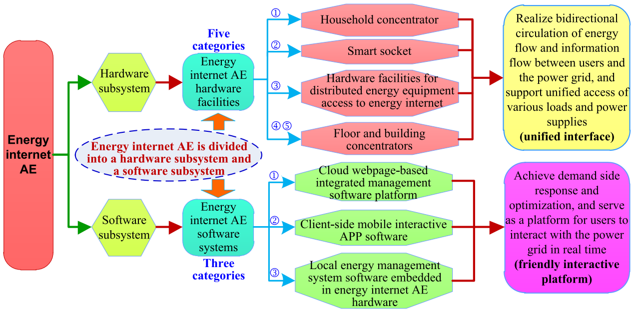


FIGURE 13. Basic functional architecture design of the proposed energy internet AE.

and connecting circuits; on the other hand, the energy internet AE interacts with distributed devices to implement device identification, commands uploading and issuing, and so on.

In a word, the proposed energy internet AE has the following eight characteristics: cyber-physical integration, real-time, interconnectivity, perceptibility, unified access, controllability, interactivity, and autonomy. It can be seen that energy internet AE has the basic characteristics of the energy internet and is an energy internet access device in a strict sense.

C. HARDWARE PART DEVELOPMENT

1) FUNCTIONS AND OVERALL FRAMEWORK DESIGN

The hardware part is the focus of energy internet AE development and one of the core components of energy internet AE. Therefore, this section focuses on the research and development of the hardware part. The hardware part possesses some basic capabilities such as data measurement, multi-mode communication, coordinated optimization, real-time control and bidirectional friendly interaction, which are briefly introduced as follows.

i) Data measurement function: Supports unified access of various energy-using and energy-supplying devices on industrial, commercial and residential user sides, and enables real-time electric parameters collection and environmental monitoring for the accessed equipment.

*ii) Support multiple ways of communication:*Supports multiple common communication protocols, such as ZigBee protocol, wireless WiFi, low-voltage power carrier, RS232/485, Bluetooth and GPRS, and can flexibly configure and freely combine various communication modes according to actual environment needs.

*iii) Coordinated optimization and real-time control:*In the case of user authorization, the hardware part enables coordinated optimization and real-time control of the user's electrical appliances to achieve ADR. For all types of distributed energy-using and energy-supplied devices that are accessed, the hardware part can automatically identify their types (i.e., identification, which is similar to fingerprint identification), and perform unified and coordinated control of distributed energy equipment according to the DR optimization results from the back-end cloud data server.

*iv) Bidirectional friendly interaction:*The hardware part has simple user interfaces that enable two-way friendly interaction between the grid side and the user side.

Based on above functions, the overall framework designed of the hardware part is illustrated in Figure 14, where the core hardware module is developed based on TMS320F28335 DSP chip. It can be seen from Figure 14 that the hardware facilities represent the hardware part of energy internet AE, and they are mainly divided into five categories, including: household concentrator (to achieve centralized energy management of household energy internet-connected equipment), floor concentrator and building concentrator (to achieve centralized energy management of floor/building energy internet-connected equipment), smart socket (to achieve unified access, distributed collection and simple

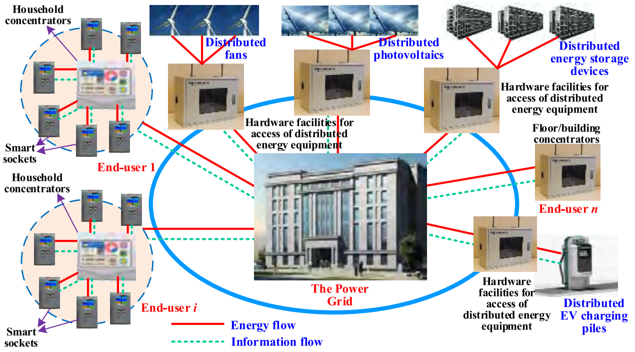


FIGURE 14. **Overall framework design of energy internet AE hardware subsystem.**

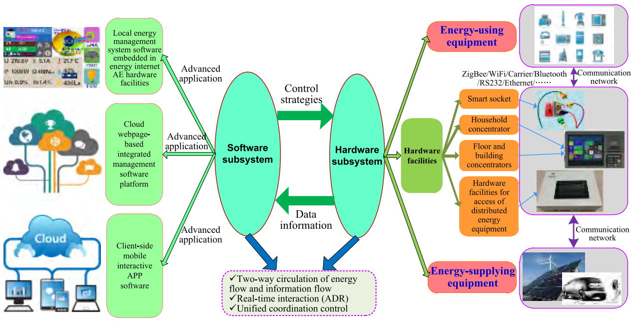


FIGURE 15. **Principle of hardware-level and software-level cyber-physical integration applied in the proposed energy internet AE.**

control of energy internet-connected equipment, especially energy-using equipment), and energy internet access devices for accessing of distributed energy internet-connected equipment (to achieve unified access of energy-supplying and energy storage equipment connected to energy internet nodes).

Therefore, by configuring a complete set of energy internet AE covering the above five types of hardware facilities, any node of the energy internet enables energy-using equipment access and energy-supplying equipment access, thus it has the characteristics of a unified interface, and is the most important engineering practical significance of developing energy internet AE. This also means that, based on the full configuration of energy internet AE, all energy internet nodes introduced above can be viewed as a unified node model that can adapt to the unified access of any energy-using or energy-supplying equipment. In addition to the smart socket, the other four categories of energy internet AE hardware facilities have similar design requirements and similar external designs, and the internal specific details of them show some differences depending on the functions implemented.

On the whole, based on above-mentioned five categories of hardware facilities and the design concept of CPS, the energy internet AE is able to tightly couple the physical processes to the cyber processes. Therefore, we merge the physical layer and the communication layer in Figure 12 into a hardware part, called the hardware subsystem of energy internet AE. In addition, we merge the software layer and application layer in Figure 12 into a software part, called the software subsystem of energy internet AE. The two subsystems are demonstrated in Figure 15. In this way, the connection between the physical and information levels of the energy internet AE, that is, the interaction between the physical level and the cyber level, can be more clearly clarified. Specifically, the hardware subsystem transmits the energy consumption data information of various connected energy devices to the software subsystem in real time. In turn, the various platforms that implement advanced applications embedded in the software subsystem deliver the control strategies to various terminal energy devices in real time, thus realizing the two-way circulation of energy flow and information flow, real-time interaction between the grid side and the user side, and unified coordination control of the energy internet-connected energy equipment, especially distributed new energy equipment. Based on Figure 15, the development of the above five types of energy internet AE hardware facilities are briefly introduced below.

2) MAJOR HARDWARE FACILITIES DEVELOPMENT

i) Household concentrator: It is the most important and core type of hardware facility in the entire energy internet AE, and also a core functional component to help industrial /commercial/residential end-users access to the energy internet, thus enabling data collection, user interaction, data communication, and localized energy management. In the household concentrator, users' power consumption optimization results obtained based on embedded multi-objective energy management optimization algorithms can be automatically released to the smart sockets, thereby achieving automatic management and electricity use optimization of energy equipment without user interventions. In addition, through the household concentrator, the calculation results and collected data can be uploaded to the upper server (such as the cloud data server on grid company side) for the DR analysis of the whole network, as well as IEM, optimization and control. Therefore, the household concentrator is the key core device for the proposed energy internet AE to realize intelligent localized IEM. The main functional modules involved in the research and development processes of household concentrator are shown in Figure 16.

ii) Floor concentrator and building concentrator: Among them, the floor concentrator is a floor-level energy internet AE with data acquisition and communication functions. The building concentrator is a building-level energy internet AE that also has data acquisition and communication capabilities. The prototype of the floor/building concentrator is shown in Figure 17.

iii) Smart socket: It is the data acquisition device located in the lowest level of the entire energy internet AE architecture, and has the functions of control, analysis and communication. It needs to be used with the above-introduced

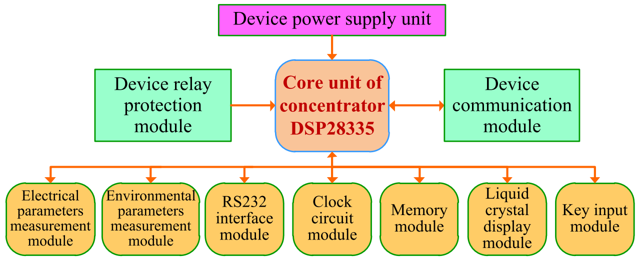


FIGURE 16. **Main functional modules need to be developed in the household concentrator.**

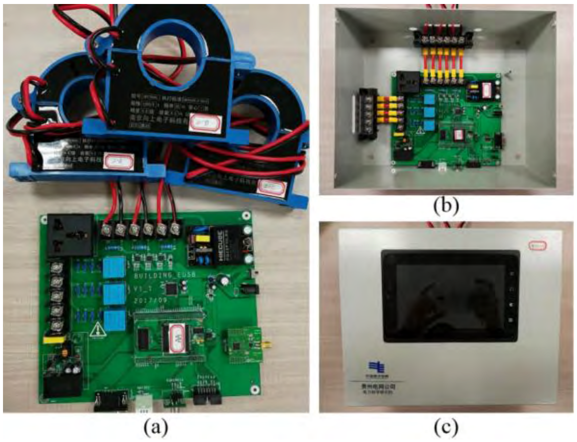


FIGURE 17. **Physical display of floor/building concentrator prototype, where (a) presents a schematic diagram of a three-phase current transformer connected to a circuit board, and the floor/building concentrator's circuit board here is equipped with less than three on-board current transformers and relays when compared with the circuit board of the developed household concentrator, thereby its circuit board area is much smaller, (b) demonstrates the internal wiring of the floor/building concentrator, and the 5P wiring terminal on left side is used to measure the three-phase voltage and supply power to the concentrator, and the 6P wiring terminal at the top is used to connect external high current transformers, and (c) shows the overall appearance of the floor/building concentrator.**

household concentrator to control the working status of various energy-using devices. Its action command is issued by the household concentrator at the master node of the ZigBee network.

iv) Energy internet AE hardware facilities for distributed energy internet-connected equipment: It is mainly used for unified access of distributed energy equipment such as fans, PVs, EV charging piles, and energy storage devices. Its action instructions come from concentrators, including the household concentrator, floor concentrator and building concentrator, which can perform real-time monitoring and communication on various connected distributed energy devices, realize unified coordinated optimization and control, and upload the collected data to the upper cloud server in real time.

3) EXPERIMENTAL MEASUREMENT

Based on the KS833 standard source, this paper takes the household concentrator as an example and conducts an experimental test on its electrical measurement accuracy. The test statistics are shown in Figure 18. It can be seen from Figure 18 that the household concentrator has high precision

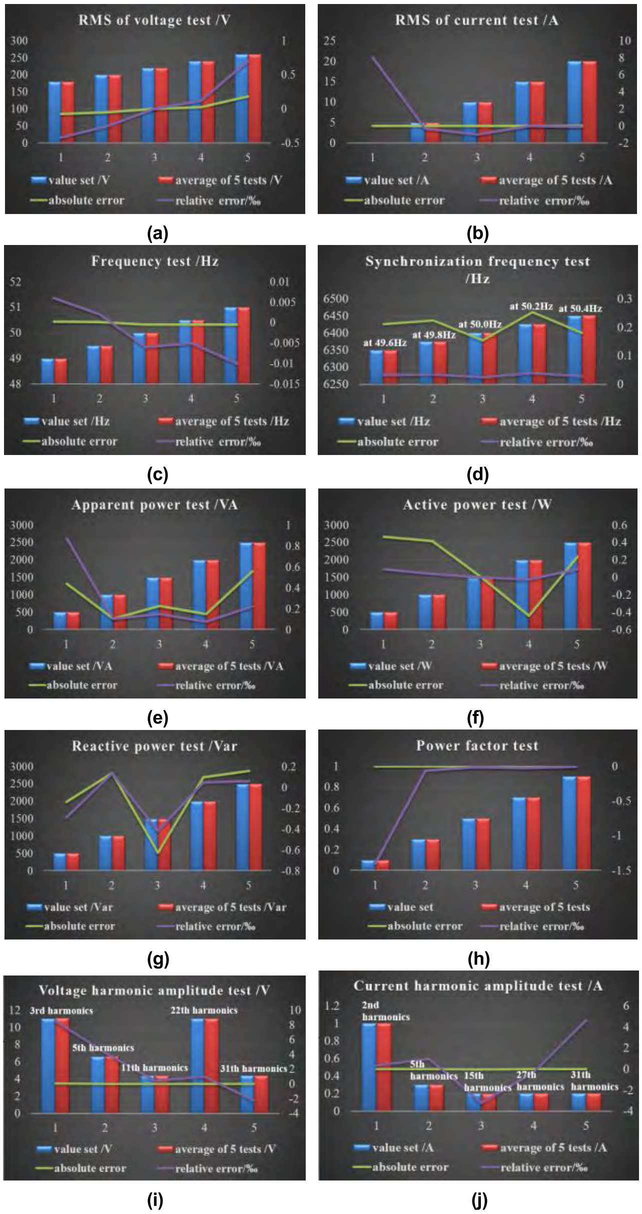


FIGURE 18. **Illustration of the statistical testing results for the developed household concentrator, where (a) shows the root-mean-square (RMS) of voltage (unit: V) testing results with a maximum relative error of 0.705%, (b) shows the RMS of current (unit: A) testing results with a maximum relative error of 8.000%, (c) shows the frequency (unit: Hz) testing results with a maximum relative error of 0.01%, (d) shows the synchronization frequency (under the signal with different frequencies) testing results with a maximum relative error of 0.039%, (e) shows the apparent power (unit: VA) testing results with a maximum relative error of 0.873%, (f) shows the active power (unit: W) testing results with a maximum relative error of 0.094%, (g) shows the reactive power (unit: Var) testing results with a maximum relative error of 0.417%(take a positive value), (h) shows the power factor testing results with a maximum relative error of 0.00014%(take a positive value), (i) shows the voltage harmonic amplitude (unit: V) testing results at different harmonic orders with a maximum relative error of 8.545%, and (j) shows the current harmonic amplitude (unit: A) testing results at different harmonic orders with a maximum relative error of 4.650%.**

for measuring various electrical parameters. This provides a good data foundation for end-user electricity use behavior research, user-side DR analysis, and distributed energy equipment management, optimization and coordinated control strategies formulation.

D. SOFTWARE PART DEVELOPMENT

As discussed previously, the software part of the proposed energy internet AE is mainly composed of three types of software systems, i.e., the local EMS software embedded in energy internet AE hardware facilities (especially the concentrators), the cloud webpage-based integrated management software platform, and the client-side mobile interactive APP software, as demonstrated in Figure 19. The software part possesses the capabilities of data aggregation and management, background efficient data processing, user energy use behavior analysis and potential mining, coordinated optimization and interactive control intelligent decision making, and timely release of commands.

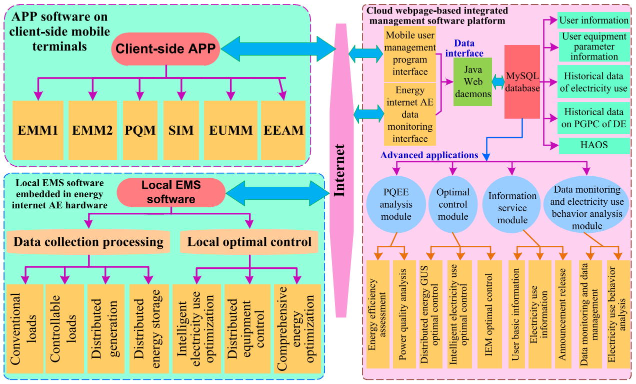


FIGURE 19. Illustration of the overall framework design of the energy internet AE software subsystem. Here, EMM1, equipment management module; EMM2, electrical monitoring module; PQM, power quality module; SIM, statistical information module; EUMM, electricity use mode module; EEAM, energy efficiency assessment module; PGPC, power generation and power consumption; DE, distributed equipment; HAOS, historical data of optimization results; PQEE, power quality and energy efficiency; GUS, generation, utilization and storage.

Therefore, for end-users, especially commercial and household users, the software part can complete the tasks such as localized IEM, load forecasting with DG in different scenarios, management and optimization of controllable loads, and unified coordinated control of distributed devices. The overall architecture of the energy internet AE software part as illustrated in Figure 19 is based on above-mentioned three parts, which are briefly introduced as follows.

i) Local EMS software embedded in energy internet AE hardware: This software system is mainly installed on aforementioned concentrators, including the household concentrator, the floor concentrator and the building concentrator. The embedded advanced intelligent algorithm library ensures that this software system performs local IEM on the basis of the energy supply and energy consumption data collected by the terminals installed on each household, each floor and each building. In this way, we can achieve unified management, optimization and coordinated control of various accessed energy devices, especially distributed energy equipment.

ii) Cloud webpage-based integrated management software platform: It consists of Java Web based daemons and MySQL database. Based on the embedded intelligent decision algorithm, the software platform can realize some advanced applications, such as power quality, user energy saving and energy efficiency analysis, optimization and coordination control, user energy use behavior analysis and energy potential mining.

iii) Client-side mobile interactive APP software: This APP can be used on both mobile phones and tablets, so that end users can access the above-introduced cloud webpage-based integrated management software platform through the Internet in different environments. In addition, through this APP, we can also access and read the electrical operation data of various energy-using and energy-supplying devices on end-user side at any time, and remotely implement coordinated control of some devices through the energy internet AE hardware facilities such as concentrators and smart socket.

IV. EXPLORATION ON PRELIMINARY PRACTICE AND PROSPECT FOR FUTURE APPLICATION SCENARIOS

In this section, we conduct a preliminary application analysis on the developed energy internet AE. Based on this, we design an application topology for the future deep use of energy internet AE. Lastly, we prospect the future application scenarios for the proposed energy internet AE.

A. PRELIMINARY APPLICATION ANALYSIS

We preliminarily used this developed energy internet AE for the analysis of the electricity usage of some buildings in a certain university, including two student dormitory buildings of No.3 and No.7, and an art building. For these two kinds of buildings, we have installed energy internet AE hardware facilities and distributed power generation/energy storage equipment, and the equipment configuration is shown in Table 2.

The field installation diagram of the energy internet AE is illustrated in Figure 20, where 100 sets of household concentrators, 200 sets of smart sockets, and 11 sets of energy internet AE hardware facilities for distributed energy internet-connected equipment are installed. Besides, the PV power supply equipment with a total of 66.99 kW and the energy storage batteries with a total of 207.36 kWh are installed as well.

Each installed equipment in Figure 20 connects to the server through the school's WiFi and establishes a communication connection with the server to transfer data. The device with liquid crystal display in Figure 20(a) is a field-installed household concentrator, next to which is an original distribution box of the student dormitory (see Figure 20(b) and (c)), we can see that the household concentrator is connected in series between the power grid and the original distribution box. Figure 20(d) shows that multiple household

TABLE 2. Equipment configuration statistics in the demonstration project.

Items	No.3 dormitory	No.7 dormitory	Art building	Total
Number of households	48	47	5	100
Household number	Floor 2, rooms 201~216	Floor 4, rooms 401~407	Floor 3, rooms 302~303	/
Number of household concentrators	48	47	5	100
Number of smart sockets	96	94	10	200
Computers	/	/	1	1
Hardware facilities for access of DE[1]	4	4	3	11
PV module type	MS[2] 290Wp	MS[2] 290Wp	MS[2] 290Wp	/
Number of PV modules	66	66	99	231
PV installed capability	9.57kW*2sets	9.57kW*2sets	28.71kW	66.99 kW
PV inverter	10kW*2sets	10kW*2sets	10kW*3sets	10 kW* 7sets
Energy storage unit	Two sets, each set of 54 batteries with 12 V, 80AH	Two sets, each set of 54 batteries with 12 V, 80AH	/	216 sets
Energy storage capacity	103.7kWh	103.7kWh	/	207.4 kWh
Energy storage inverter	10kW*2sets	10kW*2sets	/	10 kW* 4sets

[1]DE=distributed energy equipment; [2]MS=monocrystalline silicon.

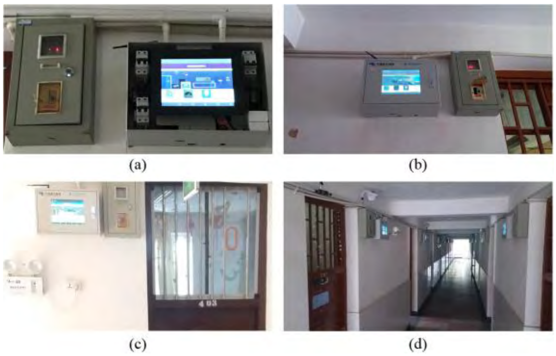


FIGURE 20. Illustration of the field installation of the developed energy internet AE, where (a), (b) and (c) demonstrate that the developed household concentrators have been installed at different locations and are connected in series between the power bus of grid and the original distribution box, and (d) shows that multiple energy internet AE household concentrators have been installed in the selected student dormitory building.

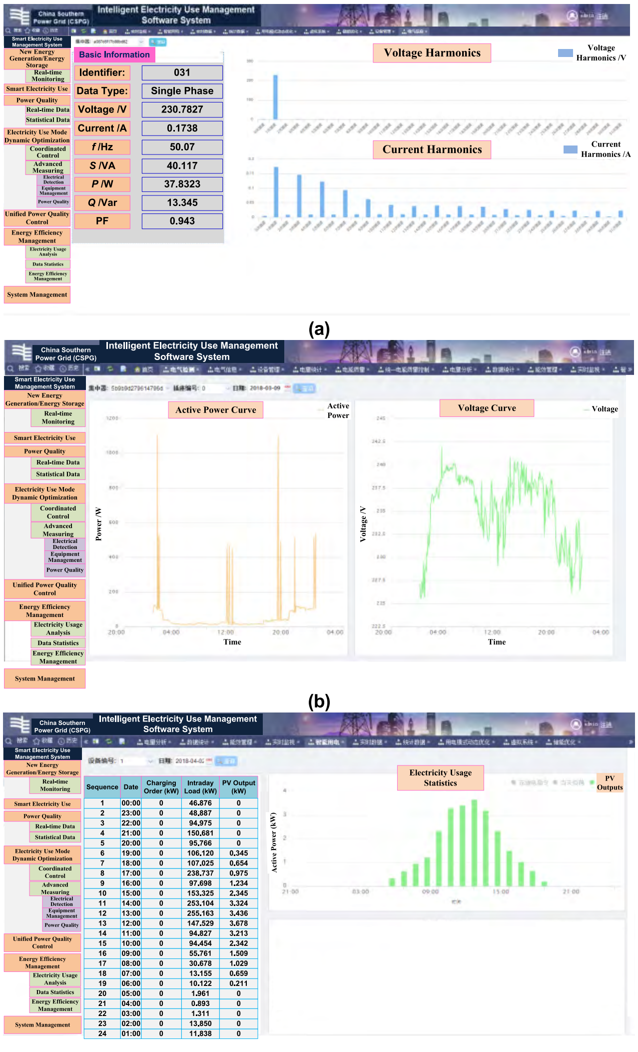
FIGURE 21. Illustration of the field installation of the distributed energy equipment, including energy-supplying and energy storage devices, where (a) shows that the PV panel arrays have been installed on the roof of No. 3 student dormitory building, (b) presents that the energy storage battery pack has been installed, (c) demonstrates that the inverters used for the PV panel arrays and energy storage battery pack have been installed at the scene, and (d) shows the main control center of the energy internet AE.

concentrators have been installed in the student dormitory building. Figure 21 illustrates a field installation diagram of distributed PVs and energy storage equipment, where (a) is a schematic diagram of the installation of the PV panel array on the roof of the No.3 student dormitory, (b) is the installation diagram of the energy storage battery pack, (c) shows the inverter installation diagram of the two types of distributed devices of PV panels and energy storage batteries, and (d) presents the schematic diagram of the main control center of the energy internet AE.

After completing the hardware configuration of the energy internet AE introduced above, next step is software system debugging. After that, the energy internet AE can start trial operation. Currently, this system is operating in a good condition, which is mainly reflected in the following aspects: the energy internet AE hardware facilities can collect data, communicate and execute commands normally; the software platform allows real-time interactions between users and the system and allows users to view real-time data and process the data, and users can also change the configuration of the system; and through the back-end database, users can view more detailed historical data and manage the data.

Figure 22 (a) shows a real-time electrical monitoring data interface of a household concentrator displayed on the local EMS software, where the left side is the measured basic electrical data, and the right side is the measured values of voltage and current harmonics. It can be seen from this figure that, the grid frequency is normal at this time and and the grid is at a valley of power consumption, the voltage is higher and the current is too small, the voltage harmonic amplitude is not large, and the current more harmonic components. Hence, at this point, there may be some running appliances in the dormitory such as a charger, display or standby computer.

Figure 22 (b) shows the power and voltage waveforms collected by a smart socket numbered 0 in one day. It can be seen from this picture that there are two peaks of power consumption at noon and night, especially from 20:00 to 01:00 in the morning, and during which there is always a base load of about 100W, and occasionally a high power load is connected. From this we can infer that the user continues to use the computer for a long time at night, and



Basic Information

Identifier:	031
Data Type:	Single Phase
Voltage /V	230.7827
Current /A	0.1738
f /Hz	50.07
S /VA	40.117
P /W	37.8323
Q /Var	13.345
PF	0.943

(a)

(b)

Sequence	Date	Charging Order (kW)	Intraday Load (kW)	PV Output (kW)
1	00:00	0	46.876	0
2	23:00	0	48.887	0
3	22:00	0	94.975	0
4	21:00	0	150.681	0
5	20:00	0	95.766	0
6	19:00	0	106.120	0.345
7	18:00	0	107.025	0.654
8	17:00	0	238.737	0.975
9	16:00	0	97.698	1.234
10	15:00	0	153.325	2.345
11	14:00	0	253.104	3.324
12	13:00	0	255.163	3.436
13	12:00	0	147.529	3.678
14	11:00	0	94.827	3.213
15	10:00	0	94.454	2.342
16	09:00	0	55.761	1.509
17	08:00	0	30.678	1.029
18	07:00	0	13.155	0.659
19	06:00	0	10.122	0.211
20	05:00	0	1.961	0
21	04:00	0	0.893	0
22	03:00	0	1.311	0
23	02:00	0	13.850	0
24	01:00	0	11.838	0

(c)

FIGURE 22. Illustration of the analysis interfaces of the cloud-based intelligent electricity use management software system (i.e., the aforementioned Cloud webpage-based integrated management software platform), where (a) demonstrates the real-time electrical monitoring data interface of a household concentrator numbered 31 displayed on the software system platform, and here, the left side of the interface shows the basic electrical data measured by the concentrator, and the right side is the measured value of various orders of voltage and current harmonics, indicating that the grid frequency is normal and the power consumption is in a valley state; (b) illustrates the waveforms of the power and voltage data collected by a smart socket numbered 0 in one day, indicating that there are two peaks of power consumption at noon and night during the day; and (c) shows the power generation information of a certain installed PV module in one day, and here, the left column shows the power generation data for each hour, and the right column presents the power generation histogram statistics for the current day, indicating that the maximum power generation of the PV module appears at 12:00 noon and is about 3.678kW, which is may be due to weather conditions that cause the PV module not to operate at full power output.

uses some electric appliances such as an electric kettle and a hair dryer during that time. From the voltage waveform on the right side, it can be seen that the dormitory basically maintains a high voltage level from 02:00 in the morning to 18:00 in the evening, and the 20:00 to 02:00 am is the peak period for students' electricity consumption with a low voltage level. The measurement results are the same as the general knowledge.

Figure 22 (c) shows the power generation information of the No. 1 PV module on a certain day, where the left column is the power generation data for each hour, and the right side is the power generation histogram of the day. It can be seen from this figure that the maximum power generation of the PV module appears at 12:00 noon on the same day, which is about 3.678 kW. It may be due to weather conditions that it is not running at full power output. This may be due to weather conditions, resulting in the PV module not operating at full power output. Certainly, the statistical information such as the active/reactive/voltage curves and usage of power of the corresponding electrical equipment can be viewed and obtained through the client-end mobile interactive terminal APP introduced previously in this paper.

It should be noted that since the developed energy internet AE installed in this university is still in a trial operation stage, there are still some problems need to be tackled, which are summarized as follows. First, the distributed energy capacity configuration is too small, resulting in load regulation effect is not obvious. Second, the campus network is blocked or unstable, causing slow access to the background server and loss of data packets. Third, the theoretical algorithms for the unified coordinated control and dynamic optimization of intelligent electricity use modes of distributed energy equipment have not been fully transplanted into the aforementioned software systems, resulting in a more refined energy management strategy that could not be developed. Therefore, at present, we can only conduct basic analysis of the university's building electricity consumption. In the future, we still need to further improve the power consumption optimization and distributed energy equipment coordination control functions described previously.

B. FUTURE APPLICATION TOPOLOGY DESIGN

A typical application topology of the proposed energy internet AE is demonstrated in Figure 23, where the energy internet AE hardware facilities are not only the sensors of the entire system, but also the actuators of the system. At the same time, each hardware device forms a communication network based on some commonly used protocols such as WiFi, ZigBee, power carrier and Bluetooth. These hardware devices transfer the data information to each other and finally upload it to the energy internet AE software subsystem to achieve a deep integration of physical system and cyber system, which is the CPS concept described in previous sections. In Figure 23, for intrusive detection methods, we need to install a separate measuring device for all loads, which makes this method costly and difficult to promote. However, due to the direct and accurate measurement of the power consumption data of the target energy equipment, the intrusive identification method can achieve very good load identification accuracy. In contrast, the non-intrusive method only requires us to install the measuring devices on the electrical

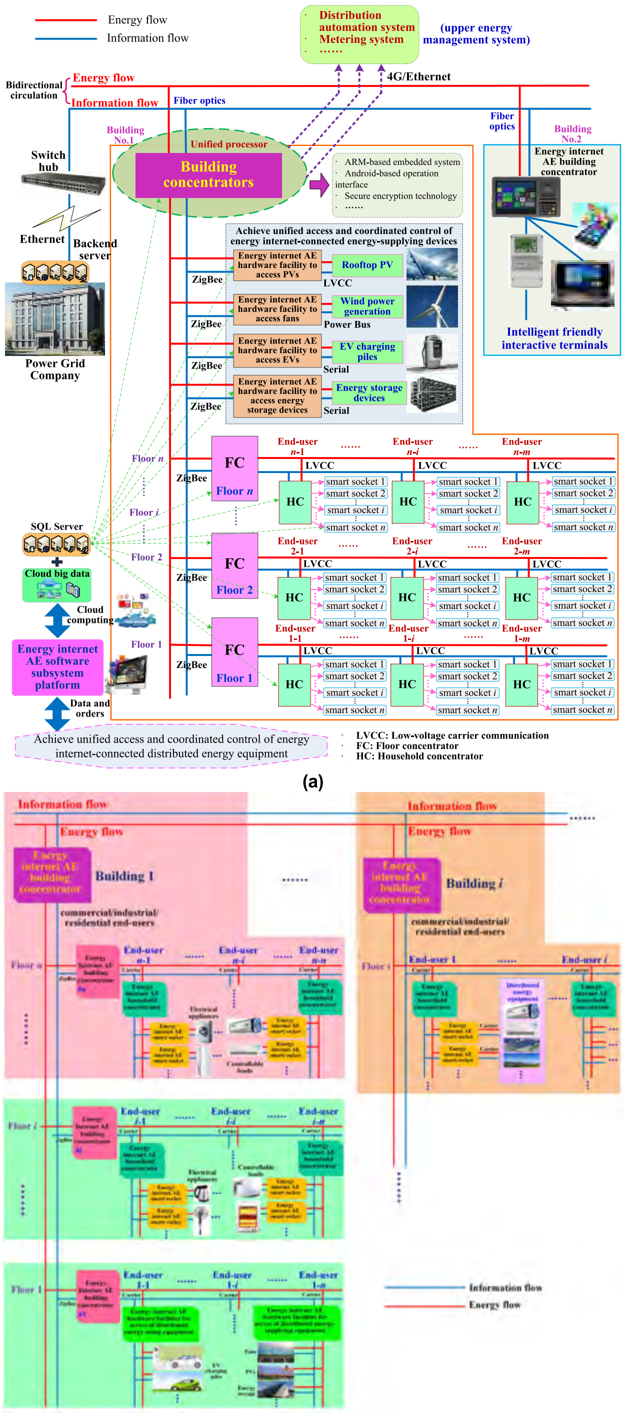


FIGURE 23. **Illustration of the design of a typical application topology structure of the proposed energy internet AE in a certain intelligent building clustering. Here, the concentrators as the core of energy internet AE can achieve unified access and preliminary plug-and-play of all distributed energy-using and energy-supplying devices, such that they can be connected to the energy internet nodes. (a) shows the overall application topology structure design, and (b) demonstrates the application topology architecture of energy internet AE for all the floors of each intelligent building.**

united bus with multiple power loads. Combined with load decomposition technology, and based on the identification and classification results of power loads according to various types of load characteristics that are known in advance, we can achieve the effect of connecting all the energy devices in an end-user unit to the system through only one energy internet AE. In this way, its cost is significantly reduced compared to the intrusive detection scheme, and its installation is simple and application prospect is very broad.

C. PROSPECT FOR FUTURE APPLICATION SCENARIOS

According to Figure 23, we design a future application scenario for the developed energy internet AE, as demonstrated in Figure 24. In Figure 24, the energy internet AE hardware facilities act as a ''unified processor'' to achieve the following functions: i) it realizes uplink communication through 4G/Ethernet with demonstration points, distributed devices and software platforms, which facilitates real-time mastery of the identity and electrical topological relationships of all distributed energy devices, and fine-grained management of distributed energy devices; ii) it realizes data sharing with upper distribution automation systems and metering systems through ARM-based embedded systems and encryption technologies; and iii) it implements downlink communication with user mobile interactive APP terminals and smart meters through communication methods such as WiFi, ZigBee and low-voltage carrier. Based on this application scenario and the investigations carried out in [20] and [21], we conduct the following prospects for the future application scenarios of the developed energy internet AE.

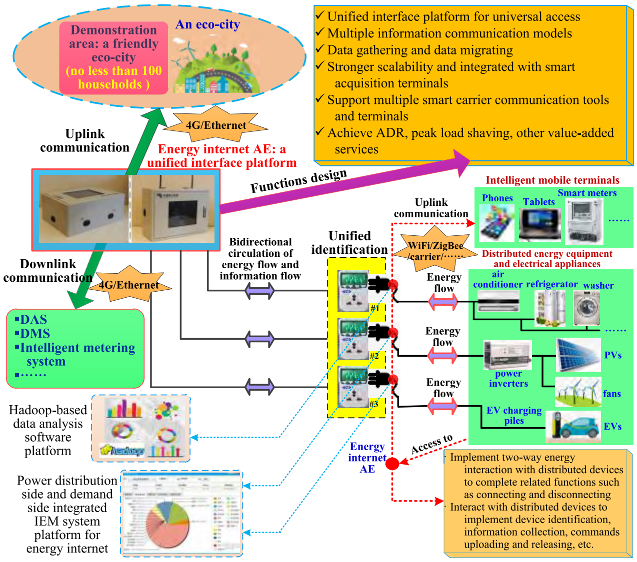


FIGURE 24. **Illustration of a topological structure envisioned in the future demonstration application scenario, where the demonstration area can choose a friendly eco-city with no fewer than 100 households. Here, DAS means distribution automation system, and DMS means distribution management system.**

i) Unified identification and differentiated billing for all types of energy-using equipment. Taking EV as an example, when the charging head of the EV is inserted into a device with an energy internet AE function such as an EV charging pile, the billing system can automatically recognize the EV number and some important information such as the car model and the battery, and realize the functions such as automatic deduction. In addition, for distributed energy-supplying devices such as DG and energy storage equipment, which may transfer energy to the system in reverse, energy internet AE can also automatically complete the charging function based on the identification of the device identity.

ii) Energy monitoring and control for small and medium-sized industrial and commercial users and smart buildings. For various energy-using devices that access to the energy internet AE, the energy internet AE collects detailed electricity use and energy consumption information at the device level and reports it to the higher-level system. When necessary, the energy internet AE can also remotely disconnect the connected energy-using devices according to the control signals from the upper systems.

iii) Refined load forecasting and modeling of small-sized power distribution systems. If the energy internet AE is widely installed in a small-sized power distribution system (such as an intelligent area power network [53]), the energy equipment information and electrical topology information collected by the energy internet AE can be used to realize refined load prediction and load modeling with the support of the background big data analysis system.

iv) Peak shaving and load leveling of small-sized power distribution systems. A large number of proposed energy internet access devices can also realize the purposes of peak load shaving and suppressing the intermittency of renewables in the system by coordinating and controlling the energy-using and energy-supplying equipment with the support of the distributed device coordination control system in the background. In addition, energy internet AE can be used as an automatic market trading terminal for small users, and collect micro-resources of small users to participate in auxiliary services market trading.

Certainly, in addition to the above-mentioned four typical application scenarios, the application field of energy internet AE will be very extensive in the future. It can be said that the various applications, conveniences and services that the energy internet brings to end-users are all functions that energy internet AE should have in the future. Therefore, the energy internet AE can be applied to the following fields in the future:

- Energy use information collection field (e.g., used to replace terminal meters).
- Load control field (e.g., load shedding at low voltage conditions, precise load control).
- Home energy management field (e.g., automatic management of home energy as a host).
- Energy-saving service field (e.g., perceive user power usage characteristics to recommend energy-saving solutions).
- Sales terminal areas (e.g., provide business decision-making and data support for electricity pricing as an interactive medium).
- Energy trading terminals (e.g., as the medium for the EM entities to conduct quotation, contract transmission, and contract execution tracking).
- DR field (e.g., accurately identify the load to achieve ADR).
- Microgrid controller field (e.g., used as a controller for the home microgrid to achieve power balance control).
- Integrated energy services and related value-added services (e.g., used to discover unsafe and uneconomical electricity use behaviors of users, as well as used for precision advertising).
- Finance and other fields (e.g., used to make portraits of customers and rate customer credits, and used for customer equipment operation and maintenance, and crowdsourcing mode of integrated energy services).

V. DISCUSSION

In this paper, we systematically propose a novel concept of energy internet AE based on CPS. Concretely, we thoroughly investigate its technical features, related key technologies, system development, preliminary practice and future application scenarios. The energy internet AE proposed in this paper is a hierarchical system platform used for unified access of distributed energy equipment. Moreover, it can interconnect the energy flow and information flow between grid side and user side. This is of great significance for achieving goals such as unified coordination control of distributed equipment in industrial/commercial/residential users, IEM in home/commercial buildings, ADR, and energy and electric power market transactions. Actually, the development of energy internet AE involves a number of related key technologies as elaborated above, which poses many enormous challenges for the ultimate realization of energy internet AE in the future. Among these, the first core challenge lies in how to implement a unified interface for plug-and-play of distributed energy equipment based on the proposed energy internet AE and key technologies of energy internet. Further, the second core challenge lies in how to achieve real-time response optimization on the user demand side. Here, the second core challenge involves investigations on DR modeling (e.g., DR mechanisms analysis, DR resources modeling, optimal DR strategies based on multi-objective optimization coordination), rapid optimization of real-time response of massive distributed energy devices, and industrial/commercial//household energy management, which can provide solid theoretical support and optimization tool support for the distribution network side and demand side IEM and demonstration project construction for the energy internet. Therefore, the challenges of investigating and developing energy internet AE in the future will be multi-faceted.

To overcome the above-mentioned challenges, we can start with the following several aspects:

First, we can carry out research on key technologies of power fingerprint identification for load equipment based on artificial intelligence, and build a complete power fingerprint database based on load identification technology.

Second, we can develop software and hardware systems for energy internet AE equipped with above power fingerprinting technology. Among these, the software systems include localized EMSs embedded in energy internet AE hardware facilities (especially concentrators), Web-based cloud IEM software system, Android/Apple operating system-based user mobile application APP, and so on. The hardware systems contain smart sockets, smart household/floor/building concentrators, general hardware interface devices for access of various types of energy equipment such as fans, PVs, EV charging piles, and energy storage equipment, and so on.

Third, we can carry out research on retail market management models based on DR mechanisms in the electricity spot market environment.

Lastly, we can carry out research on the application promotion of energy internet AE and the construction of its IEM demonstration projects.

In fact, based on the initial operation of the demonstration application, we found that the energy internet AE has the following problems need to be addressed immediately. First, the distributed energy capacity configuration is too small, which results in poor load regulation. Second, the campus network is blocked occasionally, which causes slow server access. Third, the network is not very stable, which causes packets to be easily lost. To this end, we need to summarize the experience of solving these problems during the application, such as rational design of application configuration schemes, construction of more efficient and stable communication networks, and acceleration of the transfer of theoretical research results to the system, which can lay a solid foundation for the further improvement of the energy internet AE and the future verification of the research results of DR theories and methods. This will be of great significance for the future research and development of the energy internet and smart grid.

In addition, this paper focuses on the technical aspects of information flow in the development of energy internet AE, and pays less attention to technical problems in energy flow. However, how to realize effective management and control of energy flow is a key challenge to realize unified access and plug-and-play of various energy-using and energy-supplying devices of the energy internet. Therefore, aiming at numerous problems, such as the access and exit of energy equipment, especially for power supplies with intermittent and fluctuating characteristics such as wind power and PVs, may affect the security, stability and efficiency of the system, the focus of the follow-up study in this paper is to accelerate the migration of a series of intelligent algorithms (e.g., machine learning methods [54], [55]) that we have developed to effectively manage and control energy flow into the software and hardware systems of energy internet AE to match different application scenarios, such that realizing the interconnection of energy flow and information flow in the energy internet system in a true sense. This will have important practical significance for the substantial improvement of the application performance of energy internet AE and the intelligent development of the energy internet.

VI. CONCLUSION

In this paper, we systematically propose a novel concept of energy internet AE based on the idea of CPS. The main contributions are summarized as follows:

1) This proposed energy internet AE is a multi-layer system platform used to achieve unified access of distributed energy equipment, which can interconnect energy flow and information flow, thereby achieving coordinated control and optimized utilization of end-user's distributed energy equipment such as electrical appliances, PVs, fans, EV charging piles, and energy storage devices. This provides a technical solution for the plug-and-play of user equipment under the energy internet in the future, and also provides new insights for IEM and multiple trading modes in the market environment.

2) This proposed energy internet AE is a local decision-making system for end-users to participate in EM transactions, and also an energy flow controller for DG and distributed energy storage in the EM. Moreover, the effect of connecting all the devices in a user unit to the system can be achieved by only one energy internet AE, thus the cost is greatly reduced compared with the intrusive detection solution, the installation is simple, and the application prospect is very broad.

3) The application analysis of the electricity consumption of several student dormitory buildings shows that the energy internet AE developed in this paper possesses the capabilities of performing preliminary real-time monitoring and coordinated control of distributed energy equipment, and can achieve unified access and IEM of various distributed equipment to a certain extent.

As the proposed energy internet AE is still in the initial stage of operation based on the demonstration application project, there are still some limitations or shortcomings in the current obtained results. More in-depth implementation of distributed equipment coordination control, electricity use optimization and DR functions will require further theoretical research and application analysis in the future based on field installation conditions.

The next step of this paper will focus on implementations of in-depth mining and analysis of end-users' power usage behavior, as well as non-code identification of distributed energy equipment, so as to improve the intelligence and automation levels of energy internet AE proposed and developed in this paper. At the same time, we will further expand the functions of energy internet AE, such as conducting intrusive and non-intrusive power equipment identification studies to investigate the electrical characteristics of different electrical appliances, and to achieve automatic identification of accessed devices through machine learning or clustering methods, which will help users analyze their electricity usage and develop a personalized DR mechanism, with an aim of hoping to provide some thoughts for end-users to access the energy internet efficiently and conveniently through energy internet AE in the future.

NOMENCLATURE

AE	access equipment
CPS	cyber-physical systems
DR	demand response
IEM	integrated energy management
EMS	energy management system
EVs	electric vehicles
SST	solid state transformer
USB	universal serial bus or unified service bus
EUSBS	energy USB system
PVs	photovoltaics
ADR	automated demand response
EM	electricity market
DG	distributed generation
EH	energy hub
WoC	web-of-cells
MAS	multi-agent system
CO	cell operator
IDR	integrated demand response
RMS	root-mean-square

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Authors' photographs and biographies not available at the time of publication.

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