Edge-cloud Computing Systems for Smart Grid: State-of-the-art, Architecture, and Applications

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***Abstract*—The quantity and heterogeneity of intelligent energy generation and consumption terminals in the smart grid are increasing drastically over the years. These edge devices have created significant pressures on cloud computing (CC) system and centralised control for data storage and processing in real-time operation and control. The integration of edge computing (EC) can effectively alleviate the pressure and conduct real-time processing while ensuring data security. This paper conducts an extensive review of the EC-CC computing system and its application to the smart grid, which will integrate a vast number of dispersed devices. It first comprehensively describes the relationship among CC, fog computing (FC), and EC to provide a theoretical basis for the differentiation. It then introduces the architecture of the EC-CC computing system in the smart grid, where the architecture consists of both hardware structure and software platforms, and key technologies are introduced to support functionalities. Thereafter, the application to the smart grid is discussed across the whole supply chain, including energy generation, transportation (transmission and distribution networks), and consumption. Finally, future research opportunities and challenges of EC-CC while being applied to the smart grid are outlined. This paper can inform future research and industrial exploitations of these new technologies to enable a highly efficient smart grid under decarbonisation, digitalisation, and decentralisation transitions.**

***Index Terms*—Smart grid, edge computing, fog computing, cloud computing, Internet of Things, data fusion, container technology.**

I. Introduction

WITH the growing demand for low-carbon energy and smart energy system control, the quantity and diversity of Internet of Things (IoT) based intelligent devices in the smart grid are expanding rapidly [1]-[3] such as high-definition (HD) cameras [4], electric vehicles (EVs) [5], and intelligent domestic appliances [6]. These technologies can effectively improve energy utilization, clean energy penetration, and operation security in the smart grid. Cisco systems predicts that there will be approximately 50 billion intelligent devices connected to the Internet by 2020 [7]. National Grid predicts that the UK stock of EVs could reach as high as 36 million by 2040 [8]. A recent research reports that the world-wide number of Wi-Fi devices in smart homes will reach a remarkable 17 billion units by 2030 [9]. In the energy system domain, these new terminals have already formed a crucial physical basis to enable a low-carbon smart grid transition [10].

However, the existing control paradigm is still centralised, where the main computation is conducted at the cloud or control centre [11]. Although many mature intelligent cloud platforms have been in practical use, this operation framework creates dramatic pressures on communication channels because of limited bandwidth [12]-[15]. The 5th generation (5G) mobile network technologies can be a solution, but there are geographical constraints for the equipment at remote locations such as transmission lines and transformers [16]. In addition, the huge amount of heterogeneous data from various devices increases the computational and storage burden for cloud computing (CC) [17]. Thus, the latency of CC can be too high to perform some essential real-time tasks in the smart grid such as state monitoring of power equipment with fault alarms. These issues of bandwidth congestion, limited speed, and heterogeneous data compromise the applicability of CC to the future smart energy system, which will be decentralised with numerous remote ends.

To this end, fog computing (FC) is introduced to reduce the distance between edge devices and cloud centres [18], and edge computing (EC) is developed to solve real-time applications and provide privacy protection [19]. EC refers to the platform that integrates network, computing, storage, and application close to the local physical environment or data source to provide services [20]. Compared with FC, EC is closer to the edge devices, thus technically easier to support fast response [21], real-time data processing, and decision making [22]. However, the systems only deployed with EC also have downsides. For example, without the cooperation between independent prosumers in microgrids, the islanded units cannot meet the global optimal operation to accelerate the penetration of renewable energy sources [23]. By integrating EC with the CC system to form an EC-CC system, it can efficiently perform real-time tasks with massive data, combining their advantages but overcoming their shortcomings while applied to the smart grid.

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As shown in Fig. 1, the relationship among EC, FC, and CC can be linked to the nervous system of human beings. CC, which could be considered as the brains, makes decisions and sends orders to all body parts. FC works as the neural centre to make quick decisions and control certain parts of the body. Further, EC, which could be considered as super nerve cells, senses the outside world, receives the information from higher layers, and makes simple emergency decisions. Generally, for a fully functional computing system, EC is not a substitute for CC. However, as a functional complement [17], EC provides abundant local applications while ensuring high efficiency and low latency.

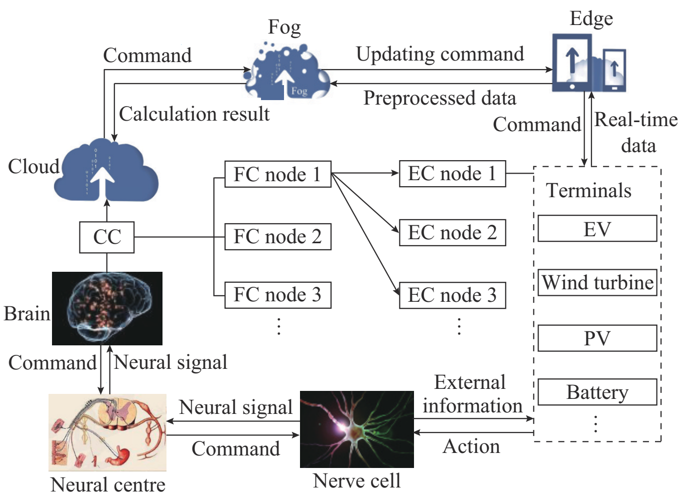


Fig. 1. Relationship among EC, FC, and CC.

It should be noted that this paper focuses on EC-CC system but not FC, because FC is a node of a tree network, analogous to the intermediate stage of EC and CC, as shown in Fig. 1 [24], where PV stands for photovoltaic. Specifically, from the perspective of EC nodes, FC nodes can be observed as tiny CC nodes to collect their results and perform global optimisation. From the perspective of CC nodes, FC nodes can be observed as aggregated EC nodes to obtain the data from edge devices [25], [26]. Therefore, we only focus on hierarchical EC-CC system, discussing the key structure and major applications in the smart grid.

The coordinated EC-CC system has already been widely developing in the smart grid such as hierarchical energy management systems (EMSs) [27]. However, there lacks a comprehensive and systematic review of EC-CC system utilised in broad smart grid. Therefore, this paper presents a comprehensive review of this emerging computing system and applications in the smart grid. All platforms, technologies, and applications reviewed are based on practical applications.

To present a comprehensive review of EC-CC system for smart grid applications, this paper ① summarizes the existing structure of EC-CC system used in the smart grid and presents a comprehensive structure that combines the existing structures; ② discusses the software platforms of EC-CC system used in the smart grid; ③ describes core technologies needed in applying EC-CC system to the smart grid, including data processing technologies and container technologies; ④ summarizes the current applications of EC-CC system in the whole energy supply chain, generation, transmission, distribution, and consumption of the smart grid; and ⑤ proposes a few future research topics to overcome the limitations of the existing EC-CC system while being applied to the smart grid.

The remainder of this paper is organized as follows. Section II illustrates the architecture of EC-CC system in the smart grid. Section III summarises the key technologies of the EC-CC system. Section IV and Section V conclude the applications of EC to the smart grid and consumer, respectively. Section VI recommends future opportunities and challenges, and Section VII concludes this paper.

II. Architecture of EC-CC System in Smart Grid

The architecture of EC in the smart grid focuses more on equipment safety and user experience, and the hardware and software are widely used to serve these applications.

A. Physical Structure of EC-CC System in Smart Grid

There are various versions of EC-CC architecture for smart grid applications [4], [5], [28]. A comprehensive architecture of EC-CC system is given in Fig. 2, which considers the common characteristics of different technology versions. In Fig. 2, PLC stands for programable logic controller and PDC stands for phasor data concentrator. The equipment with their applications can be sorted into four layers: perceptual layer, network layer, EC layer, and application layer. All the terminal devices are deployed in the perceptual layer to collect real-time data, which will be processed in the EC layer to perform local computation.

Then, the selected pre-processed data will be sent to the application layer to realize advanced functions and connect with other EC nodes. The application layer is the communication channel among these three layers. The specific meanings of each layer are described below.

The first layer is the perceptual layer, which contains sensors, monitoring devices, and other intelligent terminals to collect the data from the physical environment and equipment. This layer includes common smart devices such as smart meters and EVs, sensors in supervisory control and data acquisition (SCADA) systems, and phase measurement units (PMUs), which are widely used in the smart grid.

Then, the collected data are sent to the EC layer via the network layer 1, which is the communication channel between the perceptual layer and EC nodes. If the computing resources in the EC layer are directly installed on an edge device and only provide services for this device, then network layer 1 can be removed. Since the distance between the perceptual layer and EC nodes is small and the power for many edge devices in the perceptual layer is supplied by batteries, the communication methods for network layer 1 should be of short distance and low power. Certainly, traditional methods such as wireless local area network (WLAN) and Ethernet LAN can provide a stable connection between EC and terminals [19]. However, considering the aforementioned short-distance and low-power requirement of network layer 1, many other local wireless communication methods are more suitable in certain scenarios, including LoRa, ZigBee, Wi-Fi, and bluetooth. The above communication technologies have different characteristics [28], [29]. They should be used according to practical needs. For example, ZigBee is largely used in smart household energy systems because of its short communication distance, low-power consumption, and high data rate.

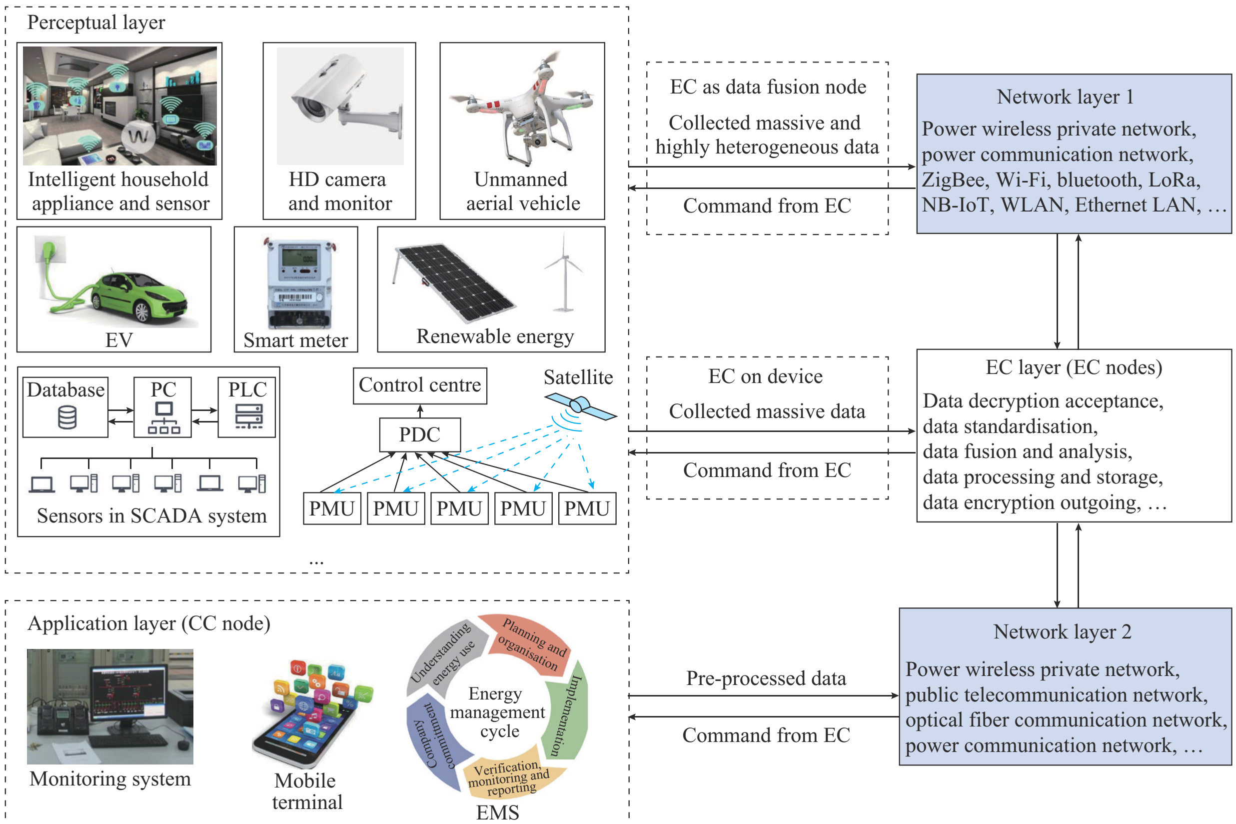


Fig. 2. A comprehensive architecture of EC-CC system in smart grid.

In the EC layer, the collected data will be standardised, processed, analysed, and stored in EC nodes with decryption acceptance and encryption outgoing. Quick actions can also be taken at EC nodes for emergency tasks such as load shedding. The commands of these quick actions will be directly sent back to the perceptual layer or related controllers. The record of these quick actions will be sent to the CC layer for operators or users at the cloud node to check and review.

Thereafter, only the key pre-processed data will be sent to the application layer via network layer 2. For network layer 2, the communication distance is much longer, and the data size is larger, which does not suit the above local wireless communication methods. As for EC nodes in remote areas with low requirements for data security, public telecommunication networks can be utilised to reduce the investment in communication. Finally, after receiving the data from EC nodes, the application layer can perform advanced functions such as real-time monitoring, early warning, benefits analysis, record storage, and data visualisation.

It is worth noting that the physical position of EC nodes is flexible, where the only requirement is close to proximity. EC devices can be installed on terminals to process the data in real time and make quick decisions without network layer 1. In addition, sometimes EC nodes are located at transmission links as a data fusion station, which collects the data from different terminals. For example, EC nodes provide an efficient fault processing system in a distribution network and domestic intelligent application system as the smart gateways [6]. Apart from the data fusion nodes, EC can also be integrated with cyber-physical system (CPS) units. Integrated with EC, CPS and distribution networks are more conducive to hierarchical intelligent control. In this comprehensive system, fusion analysis can be based on the four layers of EC, the three levels of CPS (unit level, system level, and systems-of-systems level), and the three layers of distribution networks (distribution master station layer, distribution electronic station layer, and distribution terminal layer) [30].

B. *EC Platform in Smart grid*

The key software of the EC-CC system in smart grid application is the EC platform, which realises all basic local functions and integrates various data sources. In a way, the EC platform devices enhance the efficiency and safety of the whole system. With the increasing quantity of terminal devices, many information and technology (IT) companies are developing EC platforms to deal with massive edge data. In 2006, Amazon launched Amazon Web Services (AWSs) Greengrass [31], and in 2018, it was revised based on machine learning to adapt to various operation scenarios of edge devices. In 2017, Microsoft launched Azure IOT Edge

[32], which supported the containerisation of CC load and can be installed on intelligent gateways. In 2018, Google launched Cloud IoT Edge [33], which promoted the deployment of artificial intelligence (AI) at the edge side. It is noted that EC platforms in the smart grid are more engineering-oriented.

This section introduces three mainstream EC platforms that can be used in the smart grid. Apart from the common performance of low delay, low cost, and high intelligence, the unique characteristics and service scenarios are also discussed.

1) EdgeBox EC Platform

EdgeBox was proposed by JiangHang Intelligence, which mixed virtual machines and containers to realise efficient resource management [34]. The components of EdgeBox are based on advanced deep learning algorithms, which can efficiently recognise images and videos. At present, AI components include the object recognition component, face recognition component, anomaly aggregation analysis component, limb behaviour analysis component, and electronic fence component, etc. The main application scenarios of this platform are abnormal detection of power lines and predictive maintenance of charging substations. The power consumption of EdgeBox has been minised, which enables EdgeBox to support fieldwork duration for 30 days. At the same time, the speed of recognising scene pictures reaches 0.8 s per picture, which can conduct real-time operation [10].

In general, this EC platform is designed for fault detection of power lines and substations based on image recognition with low-power consumption. The EC-CC system is utilised to improve the security of daily operations in the smart grid.

2) Transformer Terminal Unit (TTU) EC Platform

Based on the industrial advanced reduced-instruction-set-computer machines (ARMs) chip, a TTU EC platform is proposed for distribution transformers [35]. With the interface modularisation, the hardware interface module is connected to the main CPU to realise hot plug, plug and play, and automatic identification. The main application scenarios include: ① low-voltage (LV) circuit monitoring; ② automatic identification of LV electrical topology; ③ LV circuit impedance calculation; ④ lean analysis of station area line loss; ⑤ LV fault research and positioning; ⑥ distributed PV generation control with the auxiliary operation; and ⑦ optimization of EV charging points.

This TTU EC platform can not only perform monitoring and fault detection, but also extend its services to many other advanced functions such as PV-based auxiliary operation and the optimization of EV charging points. This enables more intelligent operations in the smart grid based on EC-CC system.

3) FogHorn EC Platform

FogHorn and Google launched a platform for deploying EC in 2018. FogHorn [36] combines a high-performance event processor, machine learning algorithms, and software development kit (SDK) to analyse collected data in real time and return a large number of calculation results immediately. FogHorn is mainly used in the charging station to improve resource utilisation, predict maintenance demand, and ensure a high level of customer satisfaction with faster response. Different from the previous two EC platforms, FogHorn EC platform is more concerned with commercial benefits, which enhances the economic value of EC platforms and can accelerate the penetration of EC-CC system in the smart grid.

III. Key Technologies of EC-CC System

There are many technologies of EC-CC system functions to be applied to the smart grid. Most of these technologies are widely used and illustrated in distributed computing such as data collection and transmission technologies. Therefore, only essential technologies are discussed in this section, which is also the basis for the following section of application scenarios.

A. Data Processing Technology in EC-CC System

For the EC-CC system in the smart grid, the data processing not only determines the efficiency of daily operations but also seriously affects the user privacy. This section reviews the existing research on data fusion, storage, and security to reveal the core technologies of data processing.

1) Data Fusion

The distributed computing of EC can effectively reduce data quantity pressure on CC, but the heterogeneity of data from different devices still causes a huge problem. Hence, data fusion technology is necessary for EC-CC system in smart grid applications. Data fusion at edge devices refers to the acquisition, processing, and synergistic combination of information to provide a better understanding of a certain phenomenon [37].

There are many studies on data standardisation and data fusion in the smart grid, and some of them can be applied to the EC-CC system. A decision-oriented format to combine data fusion technologies for smart grid management is proposed in [17]. The data cleaning technology is applied to deal with the massive and heterogeneous data and a Markov logic network is employed to handle data conflict problems in data fusion, which improves the efficiency of EC nodes to process the massive and heterogeneous data from the perceptual layer. Besides, the utilisation of machine learning methods highly enhances the capability of EC nodes to process big data. As an example, [38] designs a data-driven fusion model with the convolutional neural network (CNN) to realise the efficient performance of state estimation for the smart grid. The machine learning methods bring great benefits for EC nodes while processing massive and heterogeneous data.

The above methods are designed for the system level of smart grids, but data fusion also plays an important role for participants in smart grids. For example, for batteries in energy storage (ES) and EV, [39] presents a model-based data fusion method. In this model, the individual current and voltage measurements of cells are combined to reduce the measurement uncertainty and handle uneven current and voltage distributions. This data fusion method has more advantages to identify aging batteries with heterogeneous parameters. However, with growing categories of intelligent terminals like smart household appliances, the data fusion method still needs to be improved to meet new requirements.

2) Data Analysis

Data analysis mainly relies on computing methods in EC or CC. With the development of machine learning, various functions can be realised by historical data [40]. Taking CNN-based deep learning as an example, a series of algorithms have been proposed to process image-based intelligent monitoring and recognition [41]. In online security monitoring systems, the demand for image analysis is mainly required for the intelligent diagnosis and automatic early warning of defect scenes. Alexnet network model is used in the verification test in [4], where the performance of CNN has been significantly improved through using larger data sets, stronger models, and more optimised fitting technologies. Besides, CNN [42] and long short-memory network [43] have a strong ability of data prediction and have been widely used in time-series trend predictions. Recently, a long short-memory network has been widely used in trend prediction of power load and wind power. These methods are applicable in the EC-CC system to enable intelligent and flexible analysis for decision making in the smart grid.

3) Data Storage

The data collected by edge sensors and detectors should be stored in both EC and CC. For EC, the current operation and future prediction mainly depend on historical data. For CC, the self-learning and updating of computing models also need the analysis from previous information. Hence, data storage involves local storage and cloud storage in the EC-CC system. Improving storage efficiency and sending suitable data to the cloud are the key data storage technologies that need further investigation.

There are several methods for dealing with the issues of data storage. Firstly, the efficient pre-cache technology can effectively alleviate the latency of EC. The edge nodes can predict the traffic demand and pre-cache possible content in distributed nodes, which dramatically reduces the delay of downloading information from the remote data centre [44]. Reference [45] proposes a collaborative edge caching method, which is integrated with adaptive bit rate (ABR) streaming to improve storage benefits. This new method enhances the cache hit ratio and balances the processing load in the network. In [46], the distributed energy model service (DEMS) technology is used to realise the massive data management in distribution networks. The key idea of DEMS is "divide and rule" through vertical and horizontal segmentations. Specifically, the vertical segmentation enables the classification and processing of heterogeneous data, while the horizontal segmentation realises the distributed storage and operation of edge data.

4) Data Security

With the increasing complexity of the smart grid and the continuous upgrading of computer viruses, it is bound to bring a threat to data transmission [47]. Wi-Fi, ZigBee, bluetooth and other communication technologies applied in the smart grid are wireless without physical isolation, which is vulnerable to privacy leakage and cyber-attacks. For example, energy consumption can reveal private information about the living habits and income of a household. Even worse, hackers can easily determine whether a property is vacant, making it vulnerable to burglary [19]. Therefore, the data security technology is crucial in the EC-CC system.

There are some measures to reduce these risks such as a strong password policy, encryption, and two-factor authentication [48]. Based on these measures, integrated with the characteristics of the smart grid, some security methods are proposed. For example, low-power wide area network (LPWAN) terminal equipment with a private LoRa network has certain computing capability and can deploy lightweight encryption algorithms [49]. Therefore, smart gateways can encapsulate and encrypt the data uploaded by terminal devices. Some sensitive data can be processed directly at the edge without uploading to the network or CC, thus improving data security. In addition, [50] proposes a new cooperative detection strategy based on EC to solve false data injection attack in energy measurement systems. It not only designs detection rules but also evaluates the confidence of data sources.

B. Container Technology

Container technology is a virtualization technology based on the lightweight operating system layer. The applications of EC can be applied in containers to effectively reduce the complexity of EC-CC infrastructure [51]. Container technology mainly includes three key components: container virtue, container isolation, and cloud-edge collaboration. A functionally powerful container system of EC requires all these three to work together. In a way, containers replace the package management tools to control version upgrades and the dependencies of applications [52]. Compared with virtual machines, containers are lighter with higher installation speed. The deployment of containers is between milliseconds and seconds, much faster than virtual machines [35]. Therefore, container technology can realize the function expansion and update of EC-CC system, thus enhancing the flexibility, scalability and user experience of EC-CC system in the smart grid.

1) Virtual Technology of Containers

Virtual technology of containers, also known as hypervisor technology [53], can enable multiple lightweight virtual operating systems to share one hardware foundation. Each lightweight virtual machine is a container with an independent CPU, memory, disk, and network. The virtual technology of containers is key to smooth the transmission and fast iteration from the existing system to the future system [22].

Docker technology further promotes the development of virtual technology of containers. As an open-source engine of application container [54], Docker technology enables virtualisation application so that the operation on the virtual host can be replaced by the operation on programming [55]. Besides, because of lightweight, fast deployment, expandable and good isolated features [56], Docker has the following advantages: ① the speed of creating containers is much faster than directly creating virtual machines; ② hardware size can be reduced; and ③ version control is easier for operators.

2) Container Isolation Technology

Isolation is the key technology of containers for better performance [57]. At present, Docker relies on Namespace as an encapsulation method to isolate containers. The main objects of isolation include network, process, message, file system, hostname, IP, etc.

The container isolation technology can be classified as resource isolation and data isolation [58]. Resource isolation can prevent mutual interference between containers and control the operation of each container. Data isolation limits the ability of containers to access information. On one hand, container isolation technology can prevent the system from splitting after a single container malfunction. On the other hand, it can provide data privacy services for specific users [10]. Meanwhile, containers with isolation are easier for EC operators to update versions and upgrade each container independently.

3) EC-CC Information Interaction

As the micro virtual computers for EC, containers can be connected to each other by a pair of virtual network cards [35]. The collaboration between containers and the cloud requires EC-CC collaborative technology. This technology requires different collaboration for different cloud service modes such as infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS).

As shown in Fig. 3 [35], as for SaaS, the local application needs to be connected with the services on the cloud. Thus, the data will be updated timely on the cloud, and the computation model in EC can also be updated by the cloud.

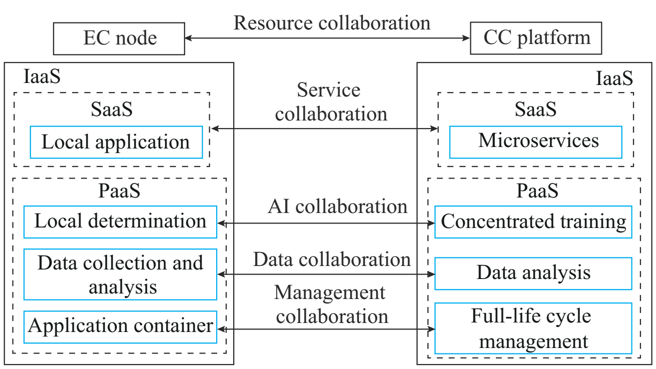


Fig. 3. IaaS, PaaS, and SaaS in EC-CC collaboration.

As for PaaS, AI collaboration mainly requires EC nodes to provide AI model training, operation, and model upgrading. Data collaboration requires EC nodes to collect terminal information, realise preliminary data processing and analysis, and upload the processing results to the cloud. The cloud provides storage, analysis, and value mining of massive data. Container management collaboration refers to the management strategy of the cloud for containers. EC nodes provide edge application deployment, operation support, and life cycle management. The cloud realises the full-life cycle management of edge applications, including application publishing, installation, uninstalling, updating, monitoring, and recording, etc. IaaS requires all the collaboration in PaaS and SaaS, but the cloud only provides the infrastructure without related platforms or software.

IV. Application of EC-CC System to Smart Grid

A. EC-CC System for Power Generation

Intelligent renewable energy generation has received extensive attention recently, and the concept of the smart power plant has also been mentioned more frequently [59], [60]. With big data, deep learning, industrial cloud platform, and other information technologies, a lot of functions and applications can be improved in power generation such as renewable energy output monitoring, equipment performance diagnosis, early warning, information security, and operation cost reduction [6]. To realise these functions, the EC-CC system is needed to provide efficient computation and flexible control strategies.

Among those functions, real-time monitoring of equipment, electricity subsidy settlement, and power generation prediction can be mainly completed by EC at the edge side. In this way, the operating pressure of the cloud is reduced effectively with the information protection of individual users. Reference [2] proposes a collaborative system between renewable energy and EC. In this system, EC is applied for microgrids and powered by renewable energy. Thus, this renewable-energy-driven EC system can integrate EC with the microgrid to incorporate a highly volatile renewable energy supply and maximise its usage to reduce carbon emissions.

Taking PV as an example, the structure of the EC-CC system in the PV generation system is shown in Fig. 4. The physical basis of an intelligent power plant is the equipment layer, which collects the information of equipment status and environmental conditions. Data pre-processing and intelligent analysis are deployed at the edge side to improve the sensitivity of operation response. In this system, edge nodes are installed on PV inverters and smart meters to process and store the collected data. The PV cloud platform mainly provides services such as information release, scheme recommendation, grid connection, electricity fee settlement, and periodic maintenance [61]. In this way, a fully functional EC-CC system for PV is established with fast response and intelligent operations.

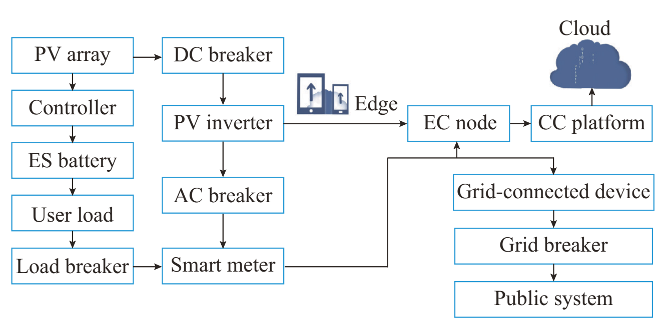


Fig. 4. Structure of EC-CC system in PV generation system.

B. EC-CC System for Transmission Network

EC-CC system can play an important role in improving the safety and security of transmission networks, including lines, transformers, and breakers, with a more efficient and intelligent monitoring system.

1) Transmission Lines

Currently, the inspection of transmission lines is mainly conducted manually, which wastes human resources and cannot guarantee the safety of all lines in real time [4]. The popularity of HD monitors improves the accuracy of automatic monitoring systems for power lines. Besides, the AI recognition technology based on deep learning can also help effectively identify some faults or dangerous conditions. However, if the images are always sent back to the cloud for analysis, it requires huge communication bandwidth and consumes massive computing power on the cloud. As a result, the image or video sampling frequency in a real security monitoring system is low, which cannot achieve real-time monitoring.

Therefore, for online monitoring of transmission lines, it is an urgent problem to transmit the collected data safely and timely to the data centre [62], [63]. The EC-CC system can significantly reduce communication congestion and response delay by being closer to the clients with much fewer communication hops. Apart from monitoring, the fault detection and operation reliability are also the main tasks for ensuring the security of transmission line, where the EC-CC system can play a key role.

As shown in Fig. 5, based on the EC-CC system in Fig. 2, the structure of the EC-CC system for transmission lines also consists of four layers, which are perceptual layer, EC layer, network layer, and application layer [4]. For power transmission lines, the perceptual layer includes various detecting devices and sensors, as presented in Fig. 5. The power controller, line vibration sensor, line temperature sensor, and inclination sensor are mainly used to collect the data of lines. While the micrometeorological station is here to collect the data of the external environment of lines. Additionally, HD camera and monitor, unmanned aerial vehicles, and inspection robots can inspect both line conditions and the environment. These data are sent to EC nodes in real time and processed locally. When an emergency happens, EC nodes will send emergency orders to the terminals and alarm to the related staff. As the cloud node, the application layer aims to monitor the state of power lines and update the recognised model in EC nodes. The software deployed at the application layer can be clustered like state monitoring software, fault diagnosis software, health management software, and remote operation software. With these functions, the security of transmission lines can be improved with lower-delay rate and higher-correct rate [64].

Based on EC technologies and machine learning technologies such as the image recognition methods, the real-time monitoring system of transmission lines is applied in the demonstration of 500 kV and 220 kV lines in Yubei District of Shaoxing City, China [4]. The stability and performance of the whole system are tested, which demonstrates good performance in reducing the transmission latency and saving the bandwidth.

2) Transformer and Breaker

At present, the online monitoring equipment of the substation has many problems: ① different design specifications and interfaces; and ② poor interaction between equipment and systems [65]. EC-CC system is an effective solution to aggregate heterogeneous data and provide collaborative platforms for equipment and systems.

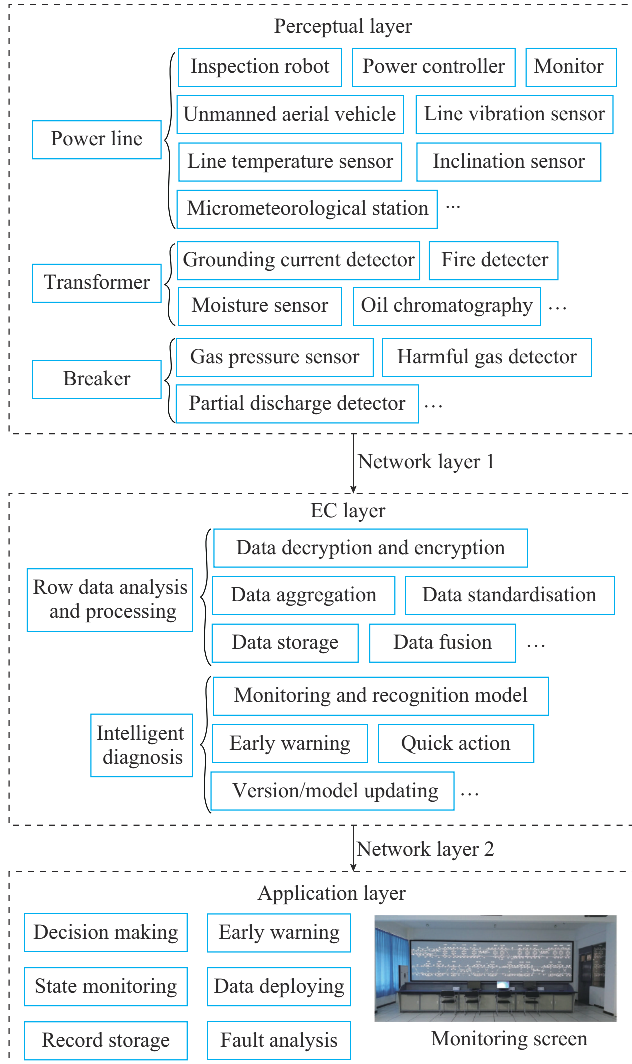


Fig. 5. Structure of EC-CC system for transmission lines.

The EC-CC system for transformers and breakers is similar to that for power lines, as shown in Fig. 5. All data are collected by sensors and detectors at the perceptual layer and transmitted to EC nodes and the application layer via communication networks. For transformers, the perceptual layer consists of a grounding current detector, fire detector, moisture sensor, and oil chromatography. For circuit breakers, the partial discharge detector, gas pressure sensor, and harmful gas detector are the main data collectors at the perceptual layer. These detectors are critically important for the safety of staff, equipment, and environment. For example, SF_6 is widely used in circuit breakers of gas insulated substation (GIS) with excellent performance of arc extinguishing [66]. However, it is also harmful to humans and the environment [67]. The main alternative solutions of SF_6 such as C_4F_7N and SF_6+N_2 are still poisonous to some extent. Thus, the real-time leak detection of harmful gas is essential for the safe operation of circuit breakers. Therefore, data analytics is applied to EC nodes to perform early warning and quick actions in an emergency without communication latency. Then, the records of actions and results are sent to the application layer. With the pre-processed data, CC can realise advanced functions with less data transmission and computation. Thus, the EC-CC system can highly improve the security of transformers and circuit breakers.

From the applications of EC-CC system in power lines, transformers, and breakers, it can be concluded that the value of EC-CC systems is concentrated on the safe operation of transmission networks. However, with the development of EC-CC system, along with emerging computing and communication technologies, there would be more application scenarios for EC-CC system in transmission networks such as real-time electricity markets and carbon markets.

C. EC-CC System for Distribution Network

The distribution network consists of various terminals with a number of them being intelligent devices, like EVs, smart meters, ES, PV, and other distributed energy resources (DERs). Therefore, there are many application areas of the EC-CC system such as heterogeneous data fusion, information quality optimization, comprehensive collaboration, and monitoring terminal expansion [30].

Similar to the applications for transmission networks, an essential function of using EC-CC system in distribution networks is fault processing, which is designed in [46]. The EC nodes process, monitor, and analyse faults as soon as they receive real-time data. Then, the analysis results will be transmitted to the cloud platform. In this mode, fault analysis and alarm tasks can be completed in milliseconds. EC nodes share the same information model as the cloud platform with a data backup mechanism. The aim of this fault processing system is to ① sense the faults at LV distributions in time; ② provide decision-making reference for operation and inspection; ③ accelerate the speed of fault clearing; ④ shorten the length of a power failure; and ⑤ improve power supply reliability and customer satisfaction.

There are other applications of the EC-CC system in the distribution network. Reference [68] focuses on the fault prevention of environmental risks. Based on the EC-CC system, a schematic diagram of damage monitoring for the distribution network is proposed. The external risks are mainly damaging, e. g., underground cables, cranes, heavy trucks, and sometimes tree falling for overhead lines. With the assistance of EC, the workload of manual inspections can be significantly reduced to alleviate time consumption and the use of labour. In addition, based on the TTU EC platform discussed above, the application in distribution network scenarios also contains LV circuit monitoring, LV circuit impedance calculation, etc.

In conclusion, the intelligent distribution network integrated with the EC-CC system has the following advantages.

1) Self-healing. With the massive real-time edge data, the potential overloading of power lines or transformers can be earlier detected by EC nodes. Then, if fast actions such as load shedding and line disconnection are deployed at EC nodes, they can be timely performed with an extremely short delay. Finally, when possible overloading is cleared, load and lines will be reconnected to the smart grid. In this way, the self-healing problem is addressed by the EC-CC system.

2) Security. Strong fault-tolerant characteristics and real-time abnormal prediction ensure the efficient operation of the equipments in distribution network. Additionally, it also predicts many risks that can damage or impact the operation.

3) Interactivity. The edge devices of the intelligent distribution network are close to the user, which enhances fast and stable communication between the user and the distribution network. The user can access power consumption information and plan future power consumption strategies.

As an evidence of the outstanding performance of EC-CC system, a novel intelligent monitoring system for the equipment in distribution network based on CC is designed in [64]. With the real-time processing in EC nodes, the pressure of transmission is relieved and the correct rate of fault diagnosis is improved with less delay. This effectively improves the efficiency and intelligence of mass data processing.

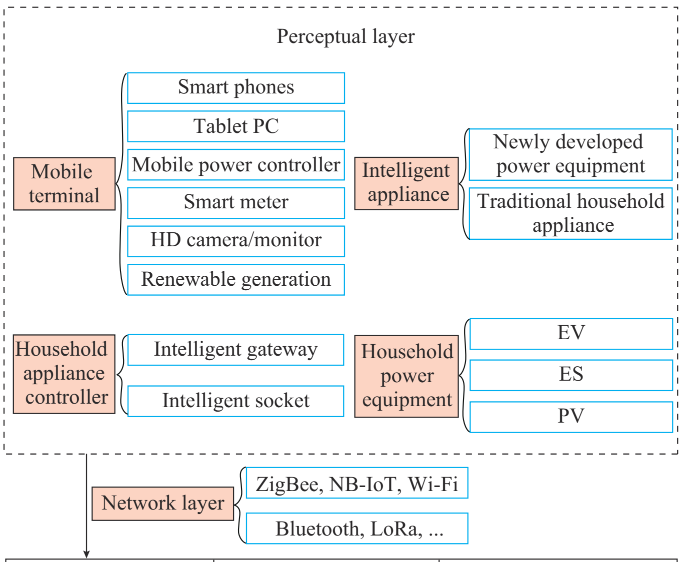
Compared with EC-CC system in transmission networks, those in distribution networks are more complex. It should firstly provide safe operations, which are the main functions of transmission networks. In addition, the safety-related functions are more elaborate in distribution networks, particularly LV networks, where faults and load peaks are comparatively hard to predict. In addition, distribution networks are closer to power consumers, which could have many interactions between smart grids and consumers. Information transparency and consumer satisfaction are crucial for EC-CC system applied to distribution networks.

V. Application of EC-CC System to Consumer

A. EC-CC System in Household Energy System

Various terminals in the modern household can generate massive edge data. Due to the privacy protection and low latency, EC is appropriate for applications in smart homes with small-sized data fusion nodes [69]. Based on EC in each household, the CC of the microgrid can realise more functions with less computation pressure.

The structure of EC-CC system in the household energy system is shown in Fig. 6. The terminals in the perceptual layer can be divided into four groups: ① mobile terminals such as smart phones, mobile power controllers, and tablet PCs; ② traditional intelligent household appliances such as heating systems, lighting systems, TVs, and air conditioners; ③ household appliance controllers such as intelligent socket and intelligent gateway; and ④ newly developed household power equipment such as EV, ES, and PV. EC nodes can also be logically abstracted into four types: intelligent devices, lightweight computing systems, intelligent gateways, and intelligent distributed system nodes [6]. They all have the common characteristics of digitalisation, networking, and intelligence, and can provide network, computing, and storage of massive data. The perceptual layer collects the data from household appliances and other information about smart homes such as the operational benefits of some profit-oriented equipment. Then, the data will be sent to EC nodes via the first network layer, which can be a household wireless network such as WLAN, ZigBee, bluetooth, and LoRa. Processed and stored by EC nodes, the records and operating results will be sent to the cloud via the network layer 2 such as public telecommunication networks or other industrial private networks. The main function of EC in smart homes includes protocol adaptation, real-time connection, data analysis, policy implementation, and resource management. Additionally, EC-CC collaborative architecture can avoid overloading, optimise the load curve, and maintain the balanced and stable operation of the energy system in smart home.



Platform layer	EC node	Application layer
Electricity information acquisition system	Emergency alarm Power quality analysis Power consumption analysis	Historical data archiving Consumption management
Non-intrusive monitoring system	Event monitoring Early warning Load clustering analysis	Updating event model base
Charging system of EV	Benefit analysis Translatable load Potential user demand	Charging scheme
Household ES system	Translatable load Benefit analysis Battery status assessment	Charging/discharging strategy
PV power generation system	Benefit analysis	Fault alarm Generating scheme
Intelligent household appliance management	User experience Behavior recognition Appliance state monitoring	Collaboration with grid Personal customization Maintenance service

Fig. 6. Structure of EC-CC system in household energy system.

As shown in Fig. 6, EC nodes and the application layer can be combined as the platform layer. Since EC nodes are mainly responsible for preprocessing and fast actions for application layers on CC, it is easy to consider the EC and CC at the same time and divide the platform according to functions. For example, the non-intrusive load monitoring system depends on smart power metering. It can realise event monitoring, early warning, and clustering analysis in EC nodes, and update the recognised model by the cloud. The household ES system depends on sensors at the battery and power meter to perform benefit analysis and battery checking.

Many functions of EC-CC system applied to household energy systems also exist in EMSs for smart homes such as the household ES system, the PV generation system, and the intelligent household application management. Besides, as a widely deployed EMS, the hierarchical EMS relies on the EC-CC structure for both computing and communication needs. Therefore, the EC-CC system provides an efficient solution for the hierarchical EMSs and the EMS is an important application of the EC-CC system applied to the smart grid. It should be noted that not only the EMS for smart homes requires the EC-CC system, the edge-cloud collaboration is also necessary for many other EMSs such as smart buildings and microgrids. Considering these scenarios can be the aggregation of smart homes, where the EMS strategy is very similar to that for smart homes, we only present the EC-CC system for the household energy system to illustrate the structure and possible functions of the EC-CC system.

B. EC-CC System in ES

The ES system is suitable for the areas with a large difference between peak and valley of electricity prices, power shortage, or unstable power supply. The ES management system can sense power consumption information and automatically switch the power source such as PV to the system when solar energy is insufficient. The ES system with EC can also receive electricity prices from the cloud platform to train the operation strategy model and make quick decisions on the edge [6].

The data collected by the devices at the perceptual layer include the state of ES, PV inverter, rigid load (RL), other flexible energy equipment such as EV, translatable load (TL), and adjustable load (AL). Then, all energy information is aggregated at EC nodes to analyse the benefits of the collaboration operation of these devices. In addition, considering all storage equipment, the charging and discharging schemes with the operation of TL and AL can be generated at EC nodes. Finally, the charging and discharging schemes and ES profits are sent to the cloud. The cloud platform provides additional data storage space and computes power capacity for local EC, then validates and optimises the results of each ES learning model with massive information.

Apart from sensing external information, EC also ensures the secure operation of ES more efficiently. EC nodes collect the information of electric characteristics and environmental parameters of the battery in real time through ES controllers. Then, the state of the ES battery can be evaluated by deep learning models based on the electrochemical model [10]. All timely data is processed locally at EC nodes, and the fault detection models applied in EC can be updated by CC periodically. Therefore, the EC-CC system can efficiently reduce the failure rate of batteries, thus improving ES safety and prolonging its service life.

C. EC-CC System in EV

Similar to the application to ES battery, the EC facilitated real-time monitoring and managing system of battery can also effectively guarantee the battery safety and lifespan of EVs. In addition, EC is also helpful to manage EV charging to achieve peak reduction and valley filling. Reference [6] focuses on the EC for charging piles and proposes the framework. However, the number and operation data of the EV are limited, and the data generated by sharing and automatic driving modes are not considered. Therefore, [5] designs a data processing framework for EV operation, as shown in Fig. 7, by combining the advantages of CC, FC, and EC.

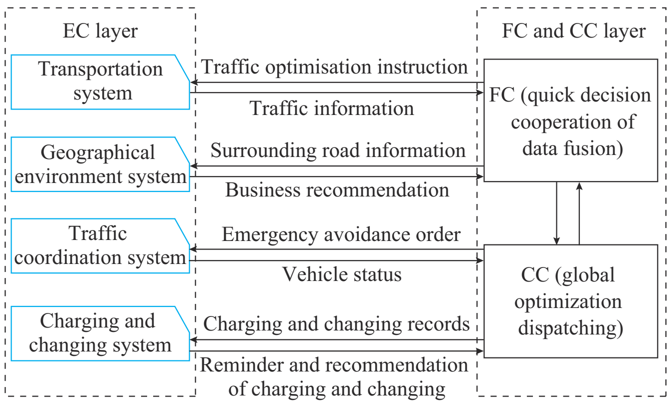


Fig. 7. Structure of EC-CC system for EV.

In the EC-CC system, the communication between edge nodes and data centres are all bidirectional. The data sources of EC nodes are traffic lights, battery sensors, and data centres of the charging point. The emergency data such as automatic driving failure, abnormal battery state, power control of the charging station, etc., are transmitted to the EC layer and processed immediately. Thus, the accuracy and speed of fault prevention processing are improved. At the same time, these data and other state information are also transmitted to the FC or CC layer through wireless communication. Then, the processed data is transmitted to the cloud server through data processing technologies such as approximate Bayesian Bootstrap algorithm, distributed local outlier factor (LOF) algorithm, and Hash Partition algorithm to release network broadband occupied by data transmission.

Compared with ES scenarios in Section V-B, EC-CC system for EVs also has the same functions as those for the safe operations of batteries. However, the integration of geographical information enables more functions in EC-CC system for EV users such as traffic optimisation and charging spot optimisation. Real-time geographical information is massive, heterogeneous, and frequently changes, which highly matches the advantages of the EC-CC system.

D. EC-CC System for Demand Response

EC deployed in smart homes and distributed renewable generations or loads is the key technology for demand response [70], [71]. Residential demand response can not only reduce the electricity costs of the consumers, but also improve the stability of power system operation [72]. By timely detecting the translational load and then reporting the results to the distribution network operator (DNO) or transmission network operator (TNO), EC nodes are able to satisfy the system when the requirement of demand response comes. In this way, the real-time ability of the demand response can be improved with efficient bandwidth resources.

Further, the EC-CC system can collect and analyse the power consumption at the edge side. In this way, the power consumption features of a certain user can be simulated on the edge. The user mode on EC can learn by itself with collected data and be justified and updated by CC at the same time. This user mode with EC can be realised by the self-learning engine in EdgeOS_H, which is an operating system for EC in the smart home system [73]. This system can help to predict the load and demand response resources of a certain user accurately and provide the expected load and the demand resource base in the related microgrid by summarising all the individual users.

VI. Future Opportunities and Challenges

Due to the immaturity of the existing technologies and the scarcity of research, some application scenarios have not been mentioned or studied. Therefore, based on possible applications and the current challenges of the EC-CC system, there are several future research possibilities.

A. Decarbonising Heating in Smart Homes

The power consumption and carbon footprint in homes or buildings are massive. With the EC-CC system, household appliances, EV, PV, and ES can perform cooperation functions to reduce carbon emissions and energy consumption. For example, with the real-time data of clean energy in the community and ES, the heating system can produce hydrogen programmatically via the electrolysis of water. Besides, different communities or buildings can also exchange clean energy to meet the optimal deployment of decarbonisation in a certain area. To realise these functions, the control strategy and data fusion ability in EC need to be upgraded with the growth of newly developed appliances in the smart grid and gas networks.

B. Decarbonising Transport with EVs

With the real-time information of transportation and charging piles, the aggregated vehicle-to-grid operations could be improved by the EC-CC system [74]. Limited by the inherent operational flexibility of energy systems, the large-scale integration of EV is forbidden although EV is currently accepted as the transportation solution of the future. Therefore, based on the EC-CC system on EVs, traffic networks, charging plies, and smart grid, the control methods of the EV energy system can be more flexible. Thus, with the optimal charging location of EVs, carbon emissions can be decreased. Besides, because the batteries in EVs are similar to ES resources, EVs can also accelerate the penetration of clean energy and provide auxiliary services for the smart grid. And these functions require the stable real-time bidirection flow of information between EVs and DNOs based on EC.

C. Standardization of Communication Methods

Data from various terminals are difficult to standardize, and rational protocols among power equipment are urgently demanded. With increasing intelligent household appliances, people are conducting the design and installation of do-it-yourself (DIY) style smart home [73]. This can be difficult for users without communication standardization, as devices are possibly produced from different manufactures with various communication methods and protocols. This problem also exists in other areas in the massive detectors and sensors. EC-CC system can be deployed with a unified communication adapter with all categories of drivers. However, after the EC node receives all the information, the data fusion methods in EC among power equipment need to be improved in future EC-CC system in the smart grid.

VII. Conclusion

EC-CC system is an effective solution to deal with the massive and heterogeneous data from various terminals in the smart grid. This paper conducts an extensive review of the state-of-the-art of EC-CC technologies and applications to the smart grid. To deploy the EC-CC system in the smart grid, the architecture of the EC-CC system is presented based on the common characteristics of different technology versions. This structure consists of perceptual, network, EC, and application layers to enable all basic functions of the computing system. Several software platforms are also introduced to provide the operating system of the EC-CC system in the smart grid. Then, data processing technologies and container technologies are discussed, where the challenges of EC-CC system applications lie in data fusion, data security, and container virtualisation. The practical application of EC in generation system, transmission system, distribution system, and power consumers are extensively introduced. Based on these scenarios, the EC-CC system is a promising computing method for future IoT-based smart grids with many possible applications.

To meet the requirement of decarbonisation, the carbon emission from smart homes, heating systems, and EVs could be reduced more efficiently with the EC-CC system. With the development of the EC-CC system, the intelligent terminals in smart grids can be fully utilised and integrated with emerging technologies, which is crucial for decarbonisation and the future smart grid.

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