Perspective

Meta-Energy: When Integrated Energy Internet Meets Metaverse

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SINCE the 18th century, fossil energy in the form of coal, oil, and natural gas has been used on a large scale. These fossil fuels have provided a vast amount of energy, such as electricity, heat, and gas, for industrial production and have been a major contributor to the development of the world economy [1]. However, electricity, heat and gas are currently managed by different operators, the lack of cooperation among which leads to a great deal of redundancy in energy distribution as well as unnecessary energy waste. Moreover, the extensive use of fossil energy has brought with it a series of problems such as environmental pollution, ecological crisis, energy shortages, etc., [2]. These problems have attracted a lot of attention from researchers, policy makers, and both national and international organizations [3]. Sustainable development of energy has always been a significant topic in the last decades [4]. Efficiently coordinating power supplies and demands by utilizing advanced information and communication technologies will be a way to alleviate the above-mentioned increasingly serious energy issues.

Internet of Energy (IoE) or Energy Internet, as a new form of energy industry development that integrates the Internet with energy production, transmission, storage, consumption, and energy market, has been proposed [5], [6]. This new generation of energy supply paradigm utilizes grid connectivity to improve the stability and flexibility of the power system with high penetration of renewable energy [7], [8]. Note that only electric power system is considered in the conventional IoE [9]. Recently, as more and more investigation on Integrated Energy System (IES) proceeds [10], cooperation over different types of energy is carried out to optimize the energy configuration over "energy dimension". Both IoE and IES are aiming at running energy system in a more efficient way even though they have different focuses [11], [12].

We have done many research works on IoE and IES in the last decade, e.g., [4], [10], [13]−[16]. By incorporating various energies in a cyber-physical network system, Integrated Energy Internet (IEI), as generalized IoE, is proposed in this *perspective*, which integrates information and telecommunications technologies to manage all forms of energy in a unified manner. However, the development of IEI has encountered bottlenecks hindering its further blossoming: 1) Different operators have erected technical barriers for energy transactions to protect security and privacy, resulting in inability of energy circulation and trading; 2) Cyber-network data management and network security issues lead to a mismatch between cyber network and physical network [17]; 3) The diversity of communication protocols and data types creates complexity in system modelling, control and other relevant issues. Taking into account the above findings, we have to find a sustainable way out for IEI.

On the other hand, advancements in artificial intelligence (AI) [18], digital twin, high-speed communication, and blockchain technologies have opened new opportunities to create Metaverse, a digital virtual world that mirrors the real world, and each user is allowed to create and edit them [19]−[22]. By utilizing the Metaverse's information interaction and decentralized data processing and storage architecture, the IEI will usher in a new era of development. This is where novel Internet technology shows its capabilities.

With the development of Metaverse and its supporting technologies, we find that deep integration of energy systems and Metaverse is inevitable to facilitate the next energy revolution. Metaverse and related technologies can provide a platform for intelligent energy control, intelligent management, and intelligent transactions, which is the basis for the future IEI, improving the depth of informatization and digitalization and guaranteeing efficient and stable operation of the entire IEI. Meanwhile, cooperation of independent system operators will be conveniently simulated and optimized, which plays an important supporting role in energy planning, operation and maintenance. To develop a Metaverse by mapping physical IEI into a virtual world and to make IEI interact with Metaverse will yield a new platform we would like to present in this *perspective*, called Meta-Energy, where various forms of energy are efficiently dispatched and traded. In the rest, we will explore the architecture of Meta-Energy, and discuss some problems for further investigation.

Meta-Energy mainly consists of two parts: cyberspace of the IEI and physical system of the IEI. The former refers to the mapping space of physical IEI in Metaverse. To be precise, it is rather than a "space", but a "world" due to global connectivity and eternity of Metaverse. The latter represents various forms of energy, which often complement each other, in the real world that support social and economic activities, including the operation of Metaverse. Each node in the physical network has its mapping in cyberspace, which is created by the digital twin technology. To construct a Meta-Energy system, various digital twin systems are interconnected through complex and controllable networks, thus exhibiting intelligent behaviour. In the cyberspace, as each node shares its state with others based on distributed data processing and storage technologies, prediction of energy supply and consumption, as well as energy dispatching and demand response, can be optimally designed, tested, and fed back to the physical IEI. This is fundamentally different from current energy

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system in many aspects, including real-time interaction, global information sharing, spatiotemporal accessibility, energy trading, and full-lifecycle device monitoring and management. The overall system is shown in Fig. 1.

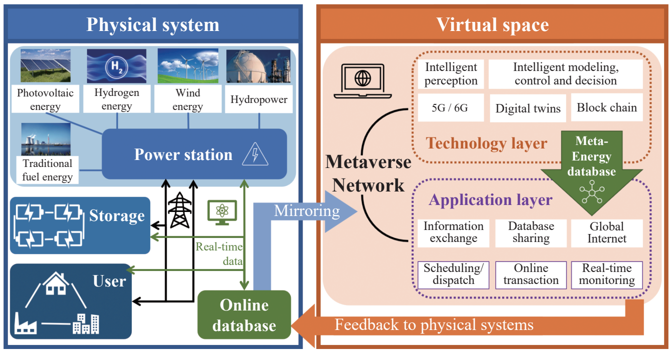

Fig. 1. The architecture of Meta-Energy.

According to the architecture of Meta-Energy described above, the intermediate layer connecting cyber and physical energy internet consists of four essential parts, including intelligent monitoring and perception, intelligent information communication and management, intelligent modelling and simulation, and intelligent control and optimization.

1) Intelligent monitoring and perception

Monitoring and perception is to measure and analyze necessary node information via the IEI, which is the basis for building the digital twin network of the overall system. The intelligent sensing can obtain real-time data from internal and external environment of the system, and then make decisions on the system's operational status. Note that there are different requirements for the amount, frequency and accuracy of measurements. Each terminal unit corresponding to a node of the IEI is equipped with wireless smart sensors/meters and needs to pre-process collected data. To perform non-intrusive monitoring, it makes use of event detection and feature extraction technique for energy disaggregation through estimating the power flow in/out of individual appliances based on a single smart meter. In addition, the intelligent perception system must deal with design of communication interfaces, data storage, and data processing issues based on advanced technology [23].

In Meta-Energy, information is globally linked to enhance real-time monitoring and perception as well as the speed of data processing, so as to ensure rapid response to the external environment. Various sensors and smart meters form a large-scale information network that can obtain multi-dimensional spatial-temporal correlation data. These data can be used to estimate assets, status, behavior and other attributes of the environment, equipment, facilities and other objects related to the distribution network. In the future research, there arises technique demand on low-power and high-performance-computing data acquisition terminals. At the same time, we suggest to develop parallel sensing [24] in Meta-Energy by constructing virtual sensors to extend small real data to virtual big data and then boost the performance of perception models. Moreover, more intelligent distributed data fusion technologies are needed to realize the holographic panoramic perception of the energy network.

2) Intelligent information communication and management

In order to use data from the perception system, integrated communication standards and protocols are essential. This is key for future efficient energy transactions, network optimization, intelligent modelling and control design in Meta-Energy system. With the emergence of a huge number of network traffic from data acquisition terminals in Meta-Energy, in order to ensure synchronization of the cyberspace and the real world with negligible time delay and high security, it raises new challenges for communication standards and protocols technologies in terms of self-configuring, self-organizing, self-healing and scalability.

What is more important, the huge amount of data or information collected by infrastructure nodes of the IEI requires reliable, secure, scalable, and transparent storage and transmission among nodes in Meta-Energy system. It needs to exploit universal data from different sources, e.g., metering data, energy demand side data, transaction data, weather forecast data, social media data, etc. The diversity of these data sources implies enormous potential of streaming data on energy. Edge computing and AI will be excellent candidates that enable timely processing and analysis of data while preserving privacy [25], [26]. However, it also poses potential risks for Meta-Energy system, as the data cannot be trusted. Moreover, with the data accumulating, the task of managing big data of Meta-Energy is becoming increasingly difficult. The blockchain technology, featured by distributed smart contracts, traceability and identity management, is an ideal foundation for information management. With the help of blockchain technology, data sharing is secure and resistant to cyber-attacks. In such cases, complex algorithms that access energy supply and demand data may be executed as smart contracts, which will be implemented on an Ethereum platform. The data sharing mechanism in Meta-Energy enables modelling of physical terminals and development of real-time control.

3) Intelligent modelling and simulation technology

Terminal nodes over the IEI, such as power generators, heat pumps, compressed-air energy storage facilities, have highly nonlinear operating characteristics. Due to the diversity of different types of components, digital models as virtual counterparts in Meta-Energy system must be established through a general modelling and simulation technology. Under this algorithm framework, the model is continuously iterated and improved with data and knowledge, ensuring that the operating status of the power system is accurately reflected in real time. Aiming at this, we consider to develop general data-knowledge-driven hybrid modelling methods for the terminals, which reflects the data-knowledge-based properties of the digital twin. In cases where there is a lack of data or creating a digital twin model is cost-prohibitive, transfer learning using historical data can be employed as an alternative.

In addition, simulation is performed based on the model and data from IEI digital twin. Meanwhile, the digital twin's network can interact with the physical system and its operators in real time, which contributes to actively correct the model. Meta-Energy can rely on more powerful computational capabilities to visualize large-scale, full-region, and multi-scale dynamics of the IEI [27]. Meanwhile, this brings opportunities to develop dynamic data-driven simulation technologies since more information shared from Metaverse can be leveraged to improve the performance.

4) Intelligent optimization and control

Conventional optimization and nonlinear control theories have played an important role in IEI. For example, variable gain control, as our pioneer work, has been shown to be an effective tool for managing disturbances and uncertainties [28], [29], thus offering great potential for improving power quality and ensuring safe operation of IEI. In addition, distributed optimization and game theory are employed to optimize allocation of energy resources or decision on transactions [14], [16], [30]. On the other hand, after building a corresponding virtual world, the optimization and control of IEI is facing new problems. As conventional methods are limited by scale, variable dimension and dependence on accurate physical models, scalable and transferable intelligent cooperative algorithms need to be developed for Meta-Energy.

As prerequisite, accurate estimation of load will assist authorities in managing energy production, management, control, and operation. It will be a good attempt to integrate reinforcement learning into the end nodes of IEI which will enable the prediction of demand, renewable power utilization, and prices for different types of energy. By learning from previous events, the reinforcement learning algorithm can also improve estimation and control performance when interacting with the environment. Fortunately, in Meta-Energy system, environment information is convenient to access, allowing the system to reach its full potential and achieve desired optimization and control performance.

Apart from new scientific and technical problems we proposed above, there are also other challenging problems along with the confluence of IEI and Metaverse. For example, stable energy transmission is an essential part of the overall energy system. The energy transmission network is the realization of physical support of the transmission mechanism. Its reliability depends on the physical network architecture and transmission mechanism. To build an interconnected global energy transmission network is critical for Meta-Energy construction.

Finally, we conclude this *perspective*. As a virtual world that exists in parallel and is intimately connected to the real world, Metaverse can build an IEI-oriented cyberspace. In the new global IEI era, the development of Meta-Energy will effectively accelerate deep integration of informatization and industrialization, so as to realize interconnection of all components of energy systems and promote inter-agency cooperation for the management of multi-energy flows. More flexible demand-side response can also be achieved. From this point of view, the emergence of Meta-Energy system is an inevitable trend in the development of energy systems in the future. We hope more researchers will join us to discuss the Meta-Energy related problems and make our contribution to the next energy revolution.

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