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What Is Energy Internet? Concepts, Technologies, and Future Directions

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ABSTRACT The climate change crisis, exacerbated by the global dependency of fossil fuels, has brought significant challenges. In the medium to long term, extensive renewable-energy-based electrification is considered to be one of the most promising development paths to address these challenges. However, this is tangible only if the energy infrastructure can accommodate renewable energy sources and distributed energy resources, such as batteries and heat pumps, without adversely affecting power grid operations. To realize renewable-energy-based electrification goals, a new concept—the Energy Internet (EI)—has been proposed, inspired by the most recent advances in information and telecommunication network technologies. Recently, many measures have also been taken to practically implement the EI. Although these EI models share many ideas, a definitive universal definition of the EI is yet to be agreed. Additionally, some studies have proposed protocols and architectures, but a generalized technological overview is still missing. An understanding of the technologies that underpin and encompass the current and future EI is very important to push toward a standardized version of the EI that will eventually make it easier to implement it across the world. In this paper, we first examine and analyze the typical popular definitions of the EI in scientific literature. Based on definitions, assumptions, scope, and application areas, the scientific literature is then classified into four different groups representing the way in which the papers have approached the EI. Then, we synthesize these definitions and concepts, and keeping in mind the future smart grid, we propose a new universal definition of the EI. We also identify the underlying key technologies for managing, coordinating, and controlling the multiple (distributed or not) subsystems with their own particular challenges. The survey concludes by highlighting the main challenges facing a future EI-based energy system and indicating core requirements in terms of system complexity, security, standardization, energy trading and business models and social acceptance.

INDEX TERMS Energy Internet, energy management, smart grid, Internet of Things, communication.

I. INTRODUCTION

Recently, the depletion of easily accessible traditional fossil fuels and growing concerns about the environmental repercussions of fossil fuel use have resulted in significant research focus on the development of alternative energy resources. Electricity generation has traditionally relied heavily on fossil fuels, which has resulted in environmental damage and increased atmospheric carbon dioxide (CO_2) levels [1], [2]. In addition, the traditional power grid faces other issues that hinder changes to a more sustainable energy system, e.g., (i) its centralized structure with one-way power flows, (ii) inadequate participation of consumers, (iii) weak market mechanisms, and (iv) other sustainability and economic challenges [3]–[5]. In attempting to address these issues, the concept of a smart grid has become a popular and highly researched paradigm [6]–[8]. A smart grid offers two-way energy and communication flow, incorporates consumers'

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decisions, and provides a platform to integrate distributed and automated systems that manage the energy flow [9]–[11].

Despite the considerable promise of the smart grid and its many attractive features, current research has indicated that it also has many shortcomings, e.g., inadequate utilization of energy forms like biomass, chemical and heat systems, a dependency on existing structures, which results in inefficient routing or scheduling, and security weaknesses [12]–[14]. Following the trend of smart grids and in view of the significant technological progress of the (data) internet, the concept of an energy internet (EI) has been advanced. A preliminary conceptual example of the EI was discussed by the prestigious magazine *The Economist* in 2004 [15], where an intelligent grid—called the "EI"—anticipates two-way flow of (various forms of) energy and information using internet-oriented technologies that leverage real-time data, improved power line qualities, and various sensors and micro-power sources. More systematic research with the EI as its core started in the late 2000s. For example, Tsoukalas and Gao [16], [17] presented the basic assumptions, architectural requirements, and prototype implementation for building an internet-type of "energy network". In [16], the basic assumptions of an EI are summarized as: virtual storage, dynamic pricing capabilities, and architectural requirements, including smart metering infrastructure, load and price forecasting, etc. The work also examined resemblances between the internet and electric networks. However, the authors did not undertake analyses of the technological aspects and key equipment required, such as energy routers having the plug-and-play services needed to implement the technology.

Around the same time, E-Energy (Internet of Energy) was initiated by the Federal Ministry of Economics and Technology, Germany. The E-Energy model mainly focuses on sustainable energy systems that are digitally connected throughout the entire power system—from generation to transmission, distribution, and consumption—using information and communication technologies (ICTs) (see Table 1 for a complete list of acronyms.) [18]. In 2010, in the US, the future renewable electric energy delivery and management (FREEDM) system center proposed an initial implementation plan to construct an EI. The FREEDM system aimed to incorporate numerous pivotal technologies as essential features of the EI, e.g., plug and play interfaces, large-scale distributed generation and storage units, and information and power electronics technologies [19]. Later, in 2011 and 2013, preliminary researches were conducted in China to develop a future electric power grid with the integration of new technologies in an EI [20], [21] (respectively). And shortly afterward, in 2015, a Chinese organization, the "Global Energy Interconnection Development and Cooperation Organization" (GEIDCO), founded the first dedicated organization to promote and encourage the sustainable development of a global EI [22].

In previous researches and scientific literature, the conceptual basis and implementation requirements of an EI have been investigated by considering features and sub-components, such as the architectural design, large-scale integration of ICTs, and the key components and design

TABLE 1. Nomenclature.

Abbreviation	Meaning
AMI	Advanced metering infrastructure
ADMM	Alternating direction method of multipliers
BEMS	Building energy management system
CPS	Cyber-physical system
CSR	Core server
DSM	Demand side management
DR	Demand Response
DERs	Distributed energy resources
DGI	distributed grid intelligence
DoS	Denial-of-service
EI	Energy internet
ER	Energy router
EH	Energy hub
EIAE	Energy internet access equipment
EMP	Energy management problem
E-Energy	Internet of energy
FREEDM	Future renewable electric energy delivery and management
GGL	Global grid level
GHG	Green house gases
GEIDCO	Global energy interconnection development & cooperation organization
HEMS	Home energy management systems
ICTs	Information and communication technologies
ICN	Information communication network
IEDS	Integrated energy distribution system
IoE	Internet of energy
IoT	Internet of Things
IEM	Intelligent energy management
KMS	Key management system
MESs	Multiple energy systems
MTC	Machine type communication
MPC	Multi-port converter
MILP	Mix integer Linear programming
MGs	Micro grids
PEM	Packetized energy management
PLC	Power line communication
PSU	Power sharing unit
PID	Proportional integral derivative
QGR	Quantum grid routers
QR	Quantum grid
RERs	Renewable energy resources
SERs	Sub energy routers
SST	Solid state transformer
SCADA	Supervisory control and data acquisition
SDN	Software-defined network
SDNEI	Software-defined energy internet
TDM	Time-division multiplexing
TCL	Thermostatically controlled load

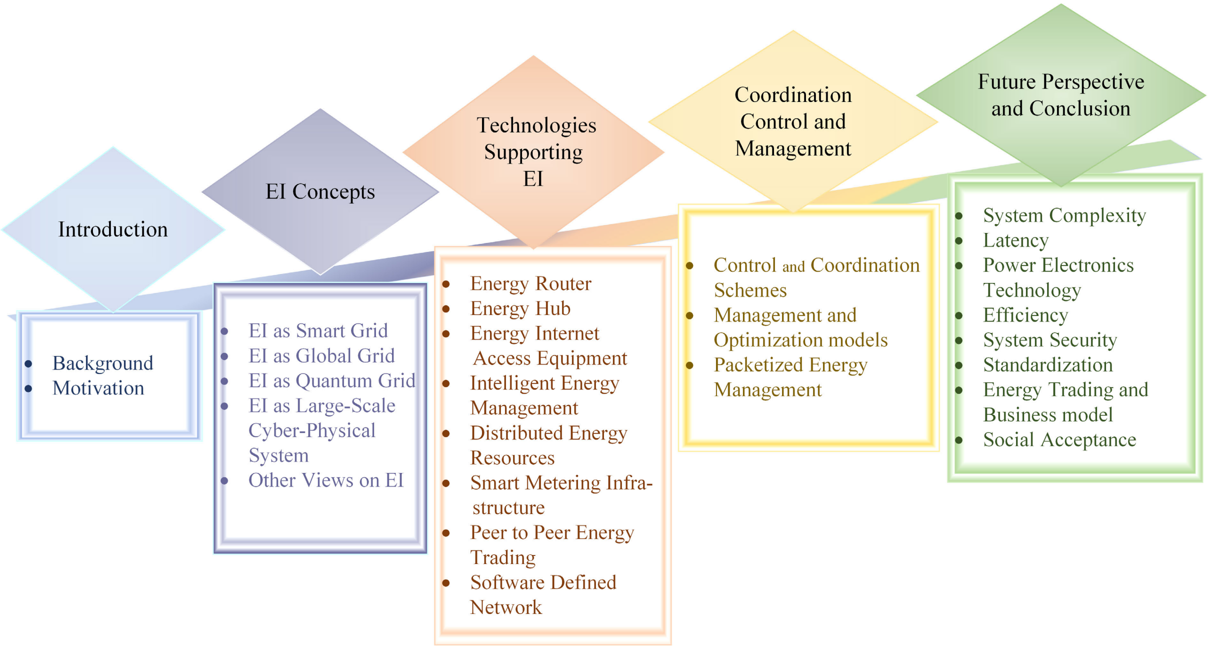

FIGURE 1. Overview of the structure of the paper and the technological challenges reviewed.

challenges [23]–[26]. Initially, some of the early researchers, such as Cowan and Daim [24], viewed the EI in terms of a smart grid; however, as the EI concept developed, more recent researchers have started to approach the EI as an independent paradigm different from the smart grid and the *EI is now described as an enabler of the smart grid*. Some works, for example, [25], [26], have explicitly highlighted the key differences between the smart grid and the EI. In [25], the authors identified the communication challenges and standards required to build an EI framework. The same group of researchers in [26] outlined the architecture of an EI based on the FREEDM system, along with a description of the design of EI components—particularly energy routers—and presented key challenges to the EI. These works examined the EI framework, but the management of EI resources and the controlling methods required remained unaddressed. In another work, [27], the EI concept is considered with a focus on smart grid applications integrated with the Internet of Things (IoT). Other researches, such as [28], have focused on the communications devices and architectures within the EI and have examined specific components of the EI, for example, the energy router architecture.

Today, the EI has become a topic of extensive ongoing research. Nevertheless, no coherent and comprehensive definition of the EI exists, and consequently, many different interpretations and conceptualizations of the EI can be found in the literature. In this paper, we try to systematize the existing literature to map the differences and similarities of existing contributions to the definition of the EI. As shown in Fig. 1, we first examine the many different meanings and definitions of the EI concept as a ‘‘smart grid’’, ‘‘global grid’’, ‘‘quantum grid’’, and other miscellaneous viewpoints. We present our comprehensive universal definition of the EI as a ‘‘cyber-physical system,’’ and elaborate on this conceptual basis of the EI, its main characteristics, the core technologies needed to construct the EI framework. In consideration of coordination and management of EI resources, we briefly describe different control schemes, management strategies and optimization models. Additionally, we highlight the key requirements and challenges facing the EI with the aim of exploring further development of the EI concept.

The remainder of the paper is structured as follows. Section II provides a classification of different contributions concerning IE. In Section III, we comprehensively describe the technical features and key technologies of the EI. Section IV introduces the control methods and coordination schemes needed for the optimal use of EI resources, and the concluding section, Section V, highlights the requirement and challenges in EI infrastructure. Finally, Section VI concludes this article.

II. EI CONCEPTS

As noted in Section I, no consensus exists on a definition of what constitutes an EI, and researchers have examined the EI idea using different definitions, interpretations, and perspectives. In this section, we will discuss the most common definitions of the EI.

A. EI AS A SMART GRID

In the past decade, most research efforts have explained the EI in terms of a smart grid. For example, [24], [41]–[46] refer explicitly to the EI as a smart grid or consider the EI an essential feature of a smart grid, and some papers interpret the EI as a web-based smart grid [47]–[52]. Tsoukalas and Gao [16] described the EI as follows: ‘‘An implementation of smart grids is EI where energy flows from suppliers to

TABLE 2. Distinguishing features of smart grid and the energy internet (EI).

Features	Smart grid	Energy internet	Remarks
Transmission	Two-way flow of information and communication	Multi-way flow of information, communication, and energy	The EI enables the multi-way flow of information, communication, and energy whereas smart grid has information and communication flow only [25], [29].
Technology	Dominated by ICTs	Dominated by ICTs, Internet, or web technologies	The dominant technology in the EI is internet-based communication with ICTs and features like plug and play services and others while smart grid relies mainly, or solely, on ICT's [19], [26], [30].
Metering and routing equipment	Smart meters, sensors, home energy management systems	Energy routers, smart meters, intelligent energy management softwares, residential energy routers, etc.	The energy router together with smart meters is a unique feature of the EI; it not only measures and manages the data but also enables other features, such as converting the voltage level, communicating with other ER, and combining renewable energy resources (RERs) [31]–[33].
Network topology	Mainly centralized with the involvement of renewable energy sources	Decentralized with large-scale involvement of distributed renewable energy resources	The EI paradigm is highly reliant on power networks, distributed RER networks, storage networks, etc., while the smart grid is based on a centralized approach with some involvement of renewable generation [34].
Functionality	Grid monitoring, management, and data processing	Processing and analyzing of data and energy, grid management	The EI is based on multi-agent and intelligent systems that processes and analyzes the data and energy simultaneously, whereas the smart grid mainly focuses on data management and monitoring [28]
Available standards	International standards are available. e.g., DNP3, CEN-TC294, and IEC 61850	A few communication protocols are being established, such as ISO/IEC/IEEE/1880	In the smart grid, some international standard communication protocols are available and others are being developed, e.g., DNP3, CEN TC294, and IEC 61850 [35], [36]. On the other hand, the EI communication protocols IOT-G230MHZ and TD-LTE230 are beig discussed in [37], [38], but more standardized communication protocols are required.

customers like data packets do in the Internet." In their work, they investigate the assumptions underlying the EI, the prerequisites to restructure the delivery of energy, and the infrastructure needed to construct an internet-type energy network. Similarly, the EI is viewed in [53] as an advanced form of smart grid and the analogy between internet networks and energy networks is highlighted, as can be seen in (Fig. 2).

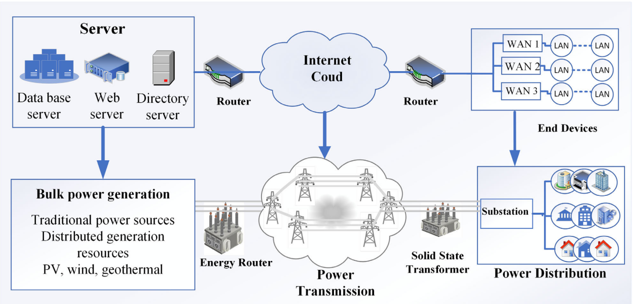

FIGURE 2. Comparison of energy flows in internet and power system networks [53].

However, interpreting the EI as a smart grid is not the only approach to its definition. In [26], for example, the EI is described in terms of how its characteristics differ from a smart grid. The EI system is considered to have three main components [25]—energy subsystem, network subsystem, and information subsystem—that are interconnected with ICTs. The work explores various technologies and core components of the EI in comparison to the smart grid. Among them is the energy router, which is a fundamental component not only responsible for connecting subsystems in real-time but also for enabling two-way communication and energy flow, as shown in Fig. 3. Wang *et al.* [54] similarly expounded the physical structure of the EI and categorized it into three levels, in this case; trans-regional, regional, and user level. A key difference with the smart grid mentioned in the work is the consolidation of various forms of energy, such as electricity, heat, peat, and gas at a regional and user level through an intelligent component known as an integrated energy distribution system (IEDS). In addition, the other key differences discussed in two articles ([25], [54]) and in [24], [27], [28] are summarized in Table 2.

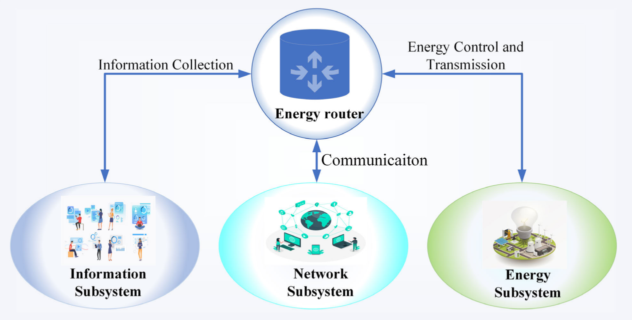

FIGURE 3. Overview of the subsystems of an EI defined in [25].

B. EI AS A GLOBAL EI

A promising idea explored by Liu *et al.* in [55] is the EI as a global energy internet (GEI) and a "strong" smart grid on a much larger scale. The GEI would interconnect RERs globally (including solar, wind, hydro, and geothermal), assure optimal management and coordination of these resources, and consequently ensure a clean, sustainable, and secure energy network across the globe. The authors put forward three aspects requiring further research: the system dynamics model, simulation methods, and multiagent game theory. The construction of a GEI is, however, a major undertaking and requires investigation of many areas, e.g., investment planning, investment decision making, coordination and/or interaction between countries and technical considerations.

Accordingly, in [56], the authors investigated the technological aspects of GEI and proposed an economic dispatch framework that is practically verified in South Asian countries. The framework focused on technical problems related to a GEI and explored reinforcement of the share of RERs while simultaneously handling uncertainty constraints and power regulations. The work additionally proposed an algorithm, the alternating direction method of multipliers (ADMM), to protect sensitive information of the countries involved and to enable reliable exchange of energy and communications.

C. EI AS A QUANTUM GRID

A unique approach to describing the EI is presented in [57] where the EI is viewed in the context of a quantum grid (QR). The so-called quantum grid integrates internet revolutionized communication and resembles the electrical power grid in certain aspects. For example, power transmission is attributed as energy packets similar to data packets, and power transmission lines and nodes are allocated addresses just like the internet network (IP addresses). In addition, the power nodes are referred to as quantum grid routers (QGR) and their functions are: (i) to optimize and control the energy generation resources, such as distributed energy resources, bulk power generation, and consumption; and (ii) to achieve quick restoration and self-healing. The basic layers of the QR network comprise a power plan, routing and control plan, and business plan. These plans are fully connected by leveraging the ICT, which thereby enables the QGR to exchange information in various layers by means of energy packets based on routing and control plans.

Other concepts similar to the QR include packetized energy management [58], the digital power grid [59], the physical energy packet transmission [60], and the local area packetized network [61]. The relationship between the different forms of packetized energy management and the EI is considered in [62] and deeply explained in IV-C.

D. OTHER MISCELLANEOUS VIEWS ON EI

Some research studies have elaborated the EI in a different way. For example, Energy + Internet is studied in [63], which compared the challenges inherent in the business model and management of integrated energy resources, services, and policies in a traditional energy system and a new Energy+Internet system.

In [64], Feng and Xiaoli explored the EI as "people oriented" that anticipated the wellbeing of the users by establishing communication channels between the users and energy systems. They argued that an economical and environment-friendly "best energy service" is the ultimate demand of the users. Seen from the technology point of view, the communication, information, and processing technologies used must connect the energy production systems with the consumer/prosumer and provide intelligent management and optimization of energy resources.

E. EI AS A LARGE-SCALE CYBER-PHYSICAL SYSTEM

After examining the various interpretations of the EI, it can be seen that the EI is a broad concept merging numerous energy-based networks (heat, gas, electricity, etc.) to provide a unified platform for better coordination and sharing of the energy resources. Consequently, development of the EI architecture is complex and multidisciplinary. In this article, we investigate the EI framework from the perspective of energy delivery and transactions in the electricity network and analyze complementary technologies.

Our proposal is a natural extension of the idea of the EI as a quantum-like grid enabled by packetized energy management, detailed in Section II-C. We argue that the EI is most accurately and universally represented as a software-defined "energy network of networks," such as power generation networks, storage networks, data management networks, and distributed generation networks, as shown in Fig. 4. Each network is interconnected through three layers, i.e., energy, communication, and information. The core component responsible for organizing the three layers at the local level are the sub energy routers (SERs). Further, we argue that the EI can be most clearly approached using the idea of "discrete or packetized energy," as emphasized in [62], [65]. The SERs communicate with each other through (discrete) energy packets that are akin to the data packets in the internet network. The SERs also exchange the obtained information with the core server (CSR). The CSR is the heart of the whole system and it performs the following functions: (i) accumulation of all information resources; (ii) control and coordination of the SERs; and (ii) packetized energy management (PEM) by leveraging information from SERs and making real-time optimal decisions for the distribution of resources.

Seen in the way described above, the EI can thus be viewed as a cyber-physical system (CPS), since it it comprises the features of physical systems and cyber systems simultaneously. Physical systems like electricity generation resources must be controlled and managed according to the instructions received from the cyber-systems, i.e., the SERs, CER, smart meters, sensors, and embedded systems. Thus, we define the EI as follows: ***a cyber-physical system in which physical energy infrastructures and physical distributed RERs are interconnected and managed via a software-defined cyber energy network using packetized energy management techniques***. Such a comprehensive definition and architecture cannot be designed without the integration of cutting-edge technologies including real-time communication technologies, control systems, information processing, smart metering infrastructure, and software-defined network. Moreover, it is also essential to organically deploy such technologies with management and planning strategies while taking into account EI requirements and challenges.

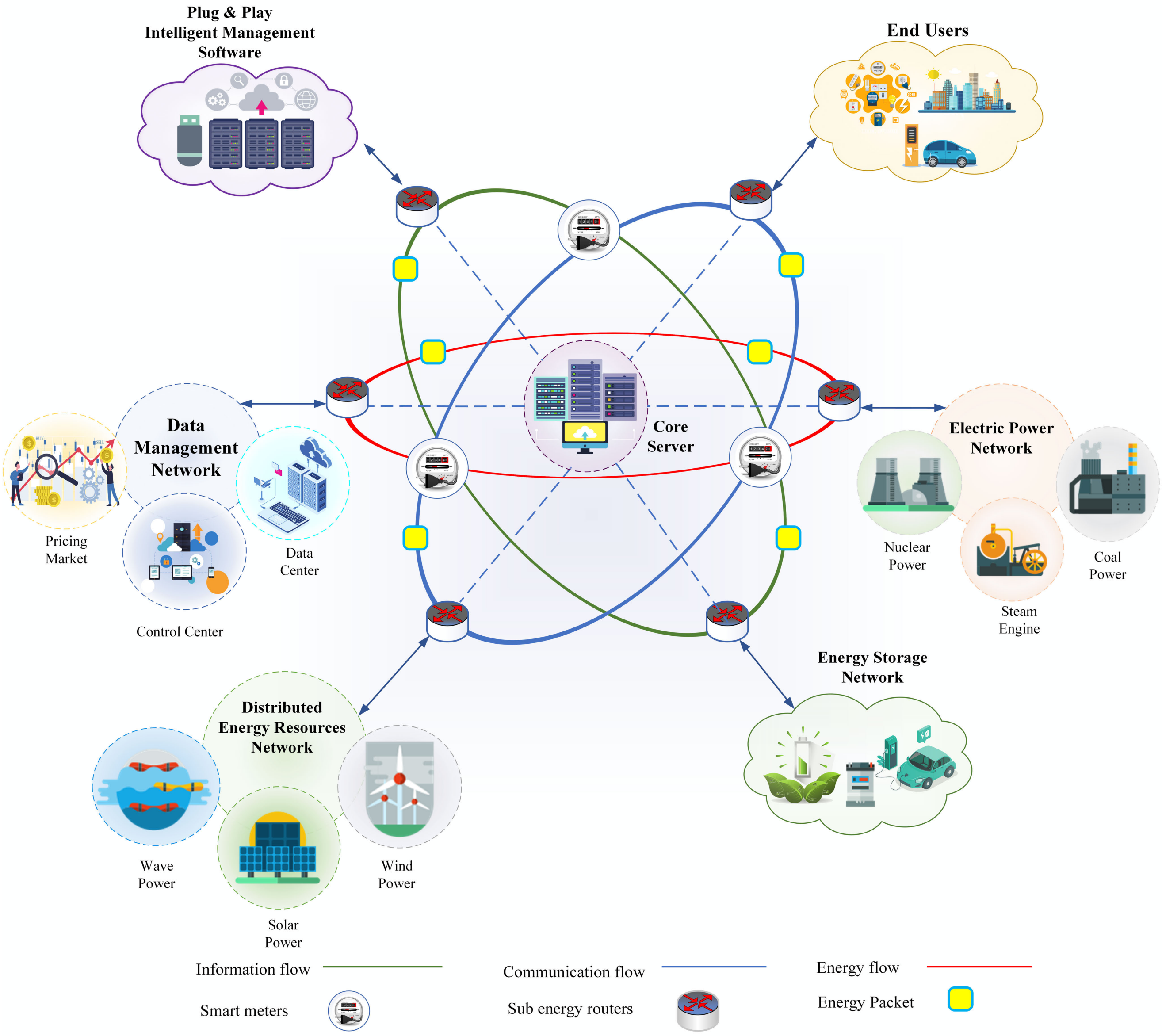

FIGURE 4. Basic structure of an EI comprising multiple networks, such as a distributive energy resources network, energy storage network, data management network, and internet and communication networks with features, like Plug and play, intelligent soft ware, sub energy routers, and smart meters.

F. SUMMARY

The overall concept of an EI was discussed based on definitions and uses that have been presented in the literature. The main studies on the topic are summarized in Table 3, where their reasoning is indicated. It is worth mentioning that none of the surveys consider the EI as a large-scale CPS enabled by a PEM system. Such a definition is, however, of importance for the technologies used. In the next section, we will present the key technological enablers of the EI.

III. SUPPORTING TECHNOLOGIES FOR EI

In this section, we discuss pivotal technologies that can contribute to the implementation of the EI.

A. ENERGY ROUTER

The energy router (ER) is essential equipment for realizing a functioning EI infrastructure. The ER concept was first proposed by FREEDM [19] and included features such as conversions of forms of energy and voltage levels, high power quality, and plug and play interfaces. The former two services provide flexible and optimal utilization of energy and ensure reliability of the system, and the latter ensures ease of operation. The ER proposed in FREEEDM was based on a solid-state transformer (SST), and its architecture comprised three layers: physical control (power and energy), distributed grid intelligence (DGI), and communication layer.

The first layer is designed to provide flexibility in the physical system and to manage conversion, for example,

TABLE 3. Summary of the relevant research work.

Focus of the study	Survey (s)	Publication year (s)	Remarks
EI sustainability in terms of communication design, requirements, and standards	Kun et al. [25]	2017	The survey compares the EI with smart grid technologies and explains the EI architecture based on FREEDM including communication framework and standard protocols. Open challenges with proposed requirements are also described.
EI architecture in terms of four key features with complementary technologies including challenges and requirements	Kun et al. [26]	2018	Authors in [26] extend their previous work [25] and describe the communication infrastructure with potential key technologies in the EI. In addition, the article also presents an overview of the EI components including FREEDM system, etc. However, the control methods and management of key resources remain unidentified.
IoT applications explored in the smart grid, smart cities, and the EI	Yasin et al. [27]	2019	The work views the EI and smart grid as the same concept and mostly focuses on IoT applications in the smart grid, without considering the key communication technologies (e.g., the ER) of the EI.
EI treated as a part of smart grid with some key equipment including benefits and hindrance	Suhail et al. [28]	2019	The basic architecture of the EI (based on FREEDM) is discussed including the ER and its types, benefits, hindrances, and requirements. However, technical solutions for the management of various EI resources are not analyzed.
Internet of energy (IoE) described as a potential solution to address the energy management in buildings	Mahammad et al. [39]	2018	The work focuses on IoE applications in building energy management systems (BEMS). The principal aim is to improve the energy efficiency in building or offices while incorporating renewable resources and considering implementation challenges.
A tool proposed to leverage EI applications including both hardware and software implementations and challenges	Leeng et al. [40]	2019	The study comprehensively investigates the hardware equipment in the EI and proposes novel concept of EIAE, its design, technical features, and implementations at the user level.
Various concepts of the EI presented and a universal definition proposed; key supporting technologies, coordination, and management schemes discussed	Our Survey	-	Our survey examines various concepts of the EI and proposes a universal definition. Based on the definition, key supporting technologies are described, considering control and coordination methods. Potential bottlenecks including important requirements are explained to implement the EI in the future.

from high voltage alternating current (AC) to direct current (DC) as rectification, DC to DC (different voltage levels) as a chopper, and DC to AC as inversion, and also to provide low-level voltage for the AC bus. The second layer is the communication layer, which regulates the bidirectional flow of information and communication and uses technologies such as Ethernet, wireless LAN, and fiber optics. Lastly, the DGI layer utilizes information from the communication layer and coordinates other SSTs to enable optimal decision making and improve energy efficiency and utilization. Critical features of the SSTs are plug-and-play services, flexible power control and optimal energy flow [68].

Three types of ER based on SST, multiport converters (MPC), and power line communication (PLC) are described in [31], [66], [67]. The authors expounded a similar functionality of SST as proposed by FREEDM, i.e., the transformation of various forms of energy and regulation of voltage and current levels using power electronics devices. The MPC is specifically designed for the low-level voltage distribution network, i.e., for homes and buildings, and it manages the subsystems, including generation resources and storage systems, to maintain and balance the energy supply.

The PLC layer is a key layer in an ER and responsible for the simultaneous flow of energy and information by leveraging time division and multi-path transmissions. It is noteworthy that PLC is economical as it uses the same power line for energy and communication flow; however, it has shortcomings as regards bandwidth requirements, low data rates, and signal attenuation. Many researches have tried to address these shortcomings and improve the efficiency and reliability of PLC. For instance, the authors in [67], [69], [70] considered the electrical network similar to a data network; the energy is split into energy packets like data packets in the internet network. The energy packets are transmitted using transmission techniques such as time-division multiplexing (TDM). In TDM, the energy packets are tagged with header (source of generation) and footer (source of consumption) information and multiplexed over the transmission network. When these packets arrive at the load side, the ER distributes the packets to the final destination address. To improve energy efficiency of the transmission network, it is also important to utilize interference mitigation techniques. The architecture of the three types of ER is presented in Fig. 5.

B. ENERGY HUB

Energy hub (EH) was an important concept in the project Vision of Future Energy Networks [71]. The EH is a system that combines various energy networks, including electricity, heat, and gas to meet the demand of the end users. The EH offers two key features: flexibility and reliability; that is, it has the flexibility to utilize energy from different energy networks, and thus, it is not dependent on a specific energy source. This, in turn, increases the reliability of the system, particularly from the consumers' perspective. In addition,

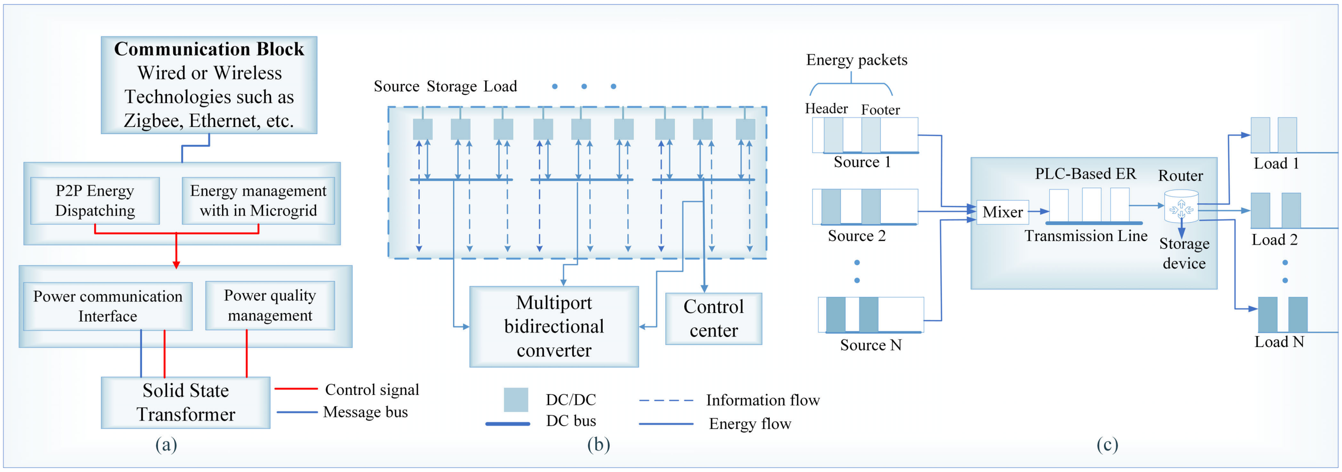

FIGURE 5. **Types of energy router: (a) Solid-state-based energy router, (b) Multi-port converter-based energy router, and (c) Power-line-communication-based energy router adopted from [31], [66], [67].**

the authors explored the feasibility of the combined transmission of different energy forms and proposed a device known as an energy interconnector. Combined transmission of different energy forms improves the system efficiency. A simple example would be that any heat losses in the electrical system could be used for regulating the temperature in the heat or gas network, which ultimately reduces the overall system losses. However, studies have shown that in such a combined network, common mode failures could result in a catastrophic collapse [72].

EH concepts are described more comprehensively in [73] that compares four key components of an EH—(variety of) energy inputs, storage systems, converters, and optimal output of EH models. Drawbacks in existing EH models are also discussed and methods are suggested for the management of EHs; features that would improve the sustainability of future energy systems are also proposed. Using a similar approach, Parisio *et al.* [74] described the EH model in a control-oriented manner and optimized the energy scheduling problems using mixed-integer linear (MIL) formulation. Wang *et al.* [75] applied MIL programming using a graph theory approach for the optimal planning of multiple energy systems (MESs) in EH.

C. ENERGY INTERNET ACCESS EQUIPMENT

In the EI infrastructure, the various energy generation networks, energy storage networks, and distributed energy resources (DERs) are connected to provide fully and flexible energy supply. In addition, the electricity market facilitates energy trading with the energy suppliers or between prosumers by adopting effective demand response strategies. To enable these services, energy internet access equipment (EIAE) is proposed in [40] as a way to connect and monitor energy usage and energy supply in real-time. Three prominent features of such EIAE are the following: (i) EIAE as end users' cyber-physical terminal media act as interfaces and measure, observe, and control all DER-using devices; (ii) EIAE enables interactions between end users and energy generation and supplies components in the EI using measurements, observations, and controlling methods; and (iii) EIAE is possibly the final execution component/device in the EI that provides all the aforementioned services. The authors highlight the differences between ER and EIAE to emphasize the novel features of EIAE. These novel features are succinctly summarized as follows: "EIAE should have cascading capabilities that enable bidirectional circulation of information flow and energy flow as well as aggregation and re-transmission." The other technical features of EIAE are perceptibility, controllability, autonomy, unified access, and cyber-physical capability. The key differences among ER, EH, and EIAE are presented in Table 4.

D. INTELLIGENT ENERGY MANAGEMENT

The EI infrastructure relies on fast and reliable information, leveraging smart and intelligent energy management systems. In this context, FREEDM [19] proposed an intelligent energy management (IEM) software that interacts with DERs, storage systems, and end users and enables plug and play features. Unlike a supervisory control and data acquisition (SCADA) system, the IEM has a distributed and flat architecture that makes it scalable and sustainable. IEM provides optimal utilization of RERs and cooperates with the storage system under contingencies or when grid power is not available. In essence, IEM performs multi-objective tasks and adapts the load demand curve, minimizes the operational costs and circuit losses (in SST), and regulates the voltage. In order to achieve these objectives, IEM requires recognition and incorporation of renewable distributed resources, on-time energy and power dispatch, and most importantly, a robust algorithm to control and distribute tasks efficiently.

E. DISTRIBUTED ENERGY RESOURCES

The envisioned EI has to be highly flexible to accommodate DERs while maintaining sustainability and availability of power generation. The EI encompasses numerous DERs that, along with other complementary technologies

TABLE 4. Distinguishing features of the energy router (ER), energy hub (EH), and energy internet access equipment (EIAE).

Features	ER	EH	EIAE
Aim and function	Acts as a core component in the EI and aims to combine MESs using conversion technologies, ICTs, and internet technologies	Acts as a part in the EI and aims to combine MESs and storage systems with mainly conversion technologies and ICTs	Acts as a key component in EI and aims to control and optimize energy usage (from various resources) at end users
Transmission	PLC-based ER used for the energy and information flow	Energy and information flow with a specific device such as an interconnector	Not intended for transmission; however, acts as a medium to access DERs and other resources
Information & communication process	Collects information directly from MESs and enables bidirectional communication	No bidirectional flow of communication and information	Allows bidirectional flow of communication and information
Control system means	Responsible for control of energy, information, and communication simultaneously through distributed grid intelligence	Responsible for control and management of energy resources of MESs in the EI	Responsible for control of energy scheduling of MESs at end users' level
Main focus	Mainly accumulates energy and information from MESs and organizes the optimal resource allocation in the EI	Mainly accumulates MESs to improve reliability and availability in the EH	Mainly facilitates the economics and comfort of end users

such as storage systems, play an important role to optimize energy management. However, the controllability and management of DERs and storage systems face numerous challenges and sustainability issues, including high computational burden, frequency design requirements, communication topologies, etc. Yazdanian and Mehrizi-Sani, [76] reviewed distributed control and management techniques that can potentially improve computational capabilities and cooperation between growing numbers of DERs, power grids, and end users. In the same vein, Ding *et al.* [77] discussed a novel strategy—"event-triggered communication"—for optimal control between communication devices in DERs. Their proposed strategy considered the communication complexity and attempted to enhance coordination between DERs, which, in turn, improves the reliability and flexibility of the energy management. The authors also described trade-offs between communication resources and control performance. Choi *et al.* [78] designed a hierarchical distributed architecture and agent-based smart management that facilitates cooperation between homes and energy generation resources. The designed hierarchical architecture acts as a cloud and provides information and processing, data acquisition, and communication while the edge network makes autonomous decisions through an intelligent agent. Other research works have employed a fractional order proportional integral derivative (PID) controller with robustness [79]; explored test-beds for two levels of energy management and control systems [80]; and examined agent-based controlling techniques [81].

F. SMART METERING INFRASTRUCTURE

Smart and intelligent sensing devices are of great importance in the EI. Smart devices such as smart meters provide accurate data measurement, control, and predictions. As an essential component of advanced metering infrastructure (AMI), smart meters collect real-time information of energy generated from various sources and the energy consumed by the end users. Based on this information, smart meters together with demand-side management (DSM) and demand response (DR) offer potential benefits to end users and energy suppliers. For instance, from the end users' point of view, smart meters allow the end users to know about their electricity consumption, pricing tariffs, and real-time updates through a user interface often known as "home energy management system (HEMS)." This information helps consumers to manage energy usage and to achieve reductions in their electricity bills. Seen from the point of view of the utility companies, the peak load can be curtailed, shifted, or predicted by implementing DR programs, thereby improving the energy efficiency of the system [82].

Alahakoon and Yu [83] studied smart meters, their framework, and potential applications. They found that the information received by smart meters such as power generation, consumption, and power quality can be used to enhance system stability and reliability. Their proposed framework identified prospective features of smart meters in terms of data analytics capability, technological perspectives, and stakeholder applications, and the work also detailed the limitations of existing smart metering infrastructure. However, future requirements and challenges such as communication latency, bandwidth, real-time processing, security, and privacy need to be addressed effectively. To focus on the communication aspects of smart meters, Fan *et al.* [84] examined the smart meter communication framework, the current challenges, technological solutions, and areas requiring further research, e.g., scalable inter-networking, interoperability, self-organization, and DR applications. In addition, the authors emphasized the need for the standardization of information and communication strategies for the deployment of smart meters and other devices to enable efficient and reliable energy transactions in smart grids.

Recently, the security concerns of AMI and smart meters are much more demanding and researchers have given serious attention to this topic. For example, Ghosal and Conti [85] investigated the key management system (KMS) of the AMI and discussed the role of defensive approaches to provide a secure communication and management system. The security challenges in AMI systems are, for example, consumer privacy preservation, potential cyberattacks against system resiliency, and electricity theft. Similarly, the authors in [86] proposed an information-centric network and key management scheme to ensure data integrity, confidentiality, and authentication of widespread smart meters. To tackle these threats and enable an efficient KMS, it is essential to deploy standardized ICTs, intelligent softwares, and potential solutions such as key graph technique, authentication (based) technique, and hybrid approaches [85], [87].

G. PEER-TO-PEER ENERGY TRADING

The EI is an interconnected, open, smart, and user-centric system that makes secure and reliable peer-to-peer (P2P) energy transactions and delivery feasible. As such, P2P allows prosumers to take part in the electricity market by selling their excess energy [88] or reducing their energy demand [89]. By doing so, the prosumers can make full use of DERs and consequently reduce electricity costs. P2P energy trading has many potential benefits, such as reducing peak (demand), lowering overall operational and investment costs, lowering reserve capacity requirements, and improving energy efficiency and power system reliability [90]–[92]. It is, therefore, important to investigate the technical and energy market requirements of P2P energy trading and an effective way to encourage customers to take part in the trading.

The architecture of P2P energy transactions is explored in [93], which investigates both the physical layer responsible for the transmission of electricity and the virtual layer providing secure transmission communication for energy trading between prosumers. The work examined the challenges faced by both layers including security concerns, dynamic pricing market, and cost reduction. To address these challenges, relevant technical approaches, such as constrained optimization, game theory, auction theory, and blockchain are essential to designing P2P architecture. In the same fashion, Zhang *et al.* [94] designed a four-layer model for low voltage (LV) microgrid through the "Elecbay" platform leveraging the game theory approach. Alam *et al.* [95] developed a P2P energy trading approach at the microgrid level among smart homes. Their objective was to incorporate storage systems and microgrid trading and distribute the energy cost equitably ensuring Pareto optimality.

H. SOFTWARE-DEFINED NETWORK

To meet the diverse communication demands and utilize the interconnected technologies efficiently, the adoption of a software-defined network (SDN) has emerged as an innovative networking approach. The SDN aims to improve routing strategies by establishing resources programmable software networks. The SDN and EI have been studied in [96]–[98]. Zhong *et al.* [96] investigated software defined EI (SDEI) architecture from three perspectives: energy flow plane (EP), data plane (DP), and control plane (CP). These planes function independently and incorporate new technologies to upgrade their infrastructure. The EP is responsible for the physical flow and control of energy. The DP collects and analyzes the information from various energy sources and services, including generation data from DERs and consumption data from households. The CP is the key layer and is responsible for dynamically controlling and configuring the DP and EP layers by enabling flexible cooperation between them; maintaining a balance between demand and supply; and programming ER optimally. The ER, on the other hand, supports P2P communication and energy flow and is classified into three categories: the ER at transmission (ER-T), the ER at distribution (ER-D), and the ER at consumption (ER-C). The authors discuss the interesting example of EVs to demonstrate the application of an SDEI in a mobility management system and to illustrate the potential challenges facing energy service providers. A similar approach for an SDN was developed in [97], where the SDN architecture was split into three layers. The infrastructure layer accommodates various energy networks, including network equipment such as the ER and switches. The middle layer, or the control layer, controls the data obtained from the infrastructure layer and is interlinked with the top layer known as the application layer. Additionally, the authors highlighted the concept of an intelligent energy controller (similar to the IEM in FREEDM) that receives data from multiple energy sources and sorts the data before sending it to the control or data center. Another interesting study [98] explores an SDN for the communication architecture of the EI at two levels, microgrid level (ML) and global grid level (GGL). In the study, the proposed communication architecture is evaluated based on the reliability, security, and latency features. Test bed cases of the proposed framework for the ML and GGL were presented, and it verified low latency and improved reliability results.

I. SUMMARY

This section introduced the main technological enablers of the EI identified in the literature. Table 5 lists the technologies, their main features and existing challenges, and presents some observations about the technologies. In the following section, we will discuss how these different elements can be used to coordinate and manage the distributed resources that lay the foundation for an EI.

IV. COORDINATION CONTROL AND MANAGEMENT

In an EI, various generation resources, storage components, consumption devices, and other elements must interact to maintain the stability and sustainability of the electricity infrastructure. Consequently, a robust and effective coordination and control scheme is necessary to ensure seamless operation of the EI. In this section, we will discuss coordination control and management strategies in the EI.

TABLE 5. A summary of the key technologies in EI.

Technologies	Reference(s)	Features	Challenges	Remarks
ER and EH	[68], [31], [69], [71], [73]	– Plug and play interfaces – Bidirectional flow of communication – Real time scheduling and management – Quick fault-detection restoration	– Real time control and protection – Management of MESs – Standard communication and information protocols	To enable EI and EH features, a standard network infrastructure, modeling of MESs, and multidisciplinary cooperation is essential
IEM	[19], [26]	– Optimal energy management – Addresses the load demand curve – Cooperation among MESs	– Tight coupling of EI components – Intelligent energy management software security and management	To control energy flow and enhance the efficiency of power system, power, voltage, and frequency control methods should be incorporated extensively.
DERs	[76]–[81]	– Improves the flexibility and reliability of the EI – Environment friendly	– Complexity in load management and forecasting problems – Intermittent nature – Reliable communication and power conversion requirements	To counter intermittency of DERs, storage network and management strategies need to be devised while monitoring the power quality factor.
Smart meters & EIAE	[82]–[85]	– Real time exchange of information – Assistance to manage energy utilization with DSM and DR	– Communication media – Real time processing, latency, and bandwidth – Security and privacy requirements	To establish reliable and flexible communication among end users and system operators, it is important to ensure data integrity, confidentiality, and authentication of widespread smart devices
P2P energy trading	[88], [93]–[95]	– Reduces stress on the power system – Improves the economic efficiency	– Network topology and optimal cost distribution – Voltage and capacity constraints	To facilitate active participation in P2P energy trading, new business and trading models should be included in the energy infrastructure; prosumers should be encouraged to sell their excess energy
SDN	[96]–[98]	– Provides efficient routing strategies – Programmable resources – Enhances energy control and communication efficiency	– Real time information processing and energy control with low latency – Computing capacity and efficient protocols for fast communication among ERs	To achieve the advantages of SDN technology, coordination among other SDNs and scalability are key problems to be identified and understood.

A. CONTROL AND COORDINATION SCHEMES

As we have seen, the EI structure is anticipated to be decentralized with the dominant integration of DERs accompanied by (AC or DC) microgrids (MGs) and microgrid clusters. Both AC and DC MGs are the essential units of the future EI, providing prominent benefits, such as improved reliability and stability of power grids, enhanced energy usage efficiency, and others listed in [99], [100]. However, MGs face many challenges including proportion power sharing and voltage regulation [101]. A great amount of research has been reported to control power-sharing proportion through multi-agent theory [101]–[103] and voltage (frequency) regulation through secondary control schemes [104]–[106]. Correspondingly, the authors in [107] have demonstrated a coordination and controlling scheme that provided insight on energy sharing among MGs incorporating energy, storage networks, and DERs, and maintaining a stable operation of the power system simultaneously. To accomplish better coordination, Sun [108] *et al.* analyzed a hybrid strategy and proposed a power-sharing unit (PSU) aiming to make full use of DERs in MGs with the help of a modified droop control approach using single-phase back-to-back converters. However, it is pertinent to note that droop-control schemes have shortcomings in terms of voltage synchronization, power sharing tradeoffs, and dependencies of load frequency and voltage [108], [109]. Therefore, the authors in [110] came up with an interesting multi-agent-based consensus algorithm to enhance the coordination and controllability of the DERs in the EI. The useful results of the researches can be summarized as follows:

- The synchronization of the voltages of various DERs, storage networks, and other EI elements with the main grid enables the EI to operate as a *spinning reserve system*;
- Coordinated control of the EI elements decreases energy costs; and
- Using MA systems, the EI infrastructure can flexibly achieve the desired power sharing among DERs.

The authors in [111], [112] described improved droop controlled schemes, while centralized control schemes and a multi-agent-based system are described in [113] and [114], respectively. Furthermore, communication among MGs and other generation resources is another important issue that needs the development of comprehensive ICT infrastructure along with control methods. The methods investigated in [115]–[118] are event-based control and predictive control. Table 6 gives a brief summary of the controlling methods.

TABLE 6. **A brief summary of the controlling methods.**

Control and Coordination schemes	Reference(s)
Droop based control methods	For improving voltage or frequency restoration in microgrids: [111]–[113], [119], [120]
Multi agent based methods	For improving power sharing and keeping voltage synchronized: [99], [100], [110], [114]

B. MANAGEMENT AND OPTIMIZATION MODEL

Thus far, research has tended to focus on the EI infrastructure/architecture [16], [19], [26], [28], ER [66], [68], [70], and frequency or voltage control [121], [122]. However, an important aspect of the power system is the energy management problem (EMP) in which an energy management system should be setup to achieve the goals of the EI. Typically, an EMP is designed as an optimization problem and solved using different approaches such as centralized, decentralized, or distributed methods. The centralized approaches provide global or near-optimal solutions. However, with the fast growth in DERs, many of these approaches do not always converge to an optimal point, while at the same time imposing strict conditions on the system, such as considerable computational complexity, and strict communication requirements. Distributed approaches, on the other hand, are robust, and enable fast computations and communication, and they are, thus, more popular.

The EMP for microgrids or smart grids has been explored widely in the literature [123]–[125]. The EMP with DSM has been analyzed for minimization of the cost of the system [126], [127] and the electricity bill of the consumer in the residential sector with a HEMS [128]–[131]. Subsequently, the problem has been approached using meta-heuristics, such as PSO [132], GA [133], HSA [134], and others [135]–[137], with the objective of optimally scheduling energy consumption and improving the reliability and stability of the power grid.

The EMP for an EI differs somewhat from the aforementioned methods because the EI is envisaged as an extensive collection of numerous energy generation networks, DERs networks, storage networks, etc., with large numbers of prosumers. Designing the EMP for the EI remains a major challenge because many of the previously studied smart-grid-based methods do not scale adequately. Nevertheless, some researches have attempted to tackle the EMP problem in the EI. For example, Sun *et al.* in [122] discussed EI features and proposed an innovative framework for energy management. Their model is complicated and incorporates other networks, including heating and gas. Therefore, the authors introduced a distributed-consensus-ADMM algorithm to solve the EMP problem. The proposed algorithm optimally manages the energy demand/output, taking into account customers' participation in the energy market. In the same context, other works [70], [138], [139] have attempted to manage and optimally allocate multi-energy sources such as PV, wind, and storage using intelligent ERs. Guo *et al.* [70] explored the hierarchical optimization method for the EH and ER in an EI to preserve privacy and information. The authors' approach comprised two levels: a lower level and an upper level. In the lower level, the optimal dispatch of energy is accomplished by providing the operation plans and integrating DERs in EH. In the upper level, on the other hand, the ER is employed to ensure secure and effective communication among other EHs and ERs. Chen *et al.* [138] designed a novel ER that enables bidirectional power flow, optimizes energy reallocation, and integrates other energy generation resources such as PV, wind, and storage. The proposed ER solution is easily scalable, capable of providing plug and play services, and improves the power quality by addressing the load-energy fluctuations. Gao *et al.* [139] modeled the ER based on probabilistic approaches aiming for energy trading and energy scheduling using a cloud computing tool.

C. PACKETIZED ENERGY MANAGEMENT

PEM is an interesting approach toward energy management and coordination of energy generation. The PEM concept is analogous to data transmission in a communication network; just like data is broken into packets, energy can also be broken into discrete packets. In this sense, energy packets or chunks represent a fixed power for a certain time duration, e.g., 1 kW in 1 minute (i.e., 0.0166 kWh of energy). Using PEM, the energy demand and supply can be aligned with the dynamic generation and consumption resources. Moreover, PEM brings benefits such as flexible decision-making, fairness, responsiveness, and scalability [58].

Recently, efforts have been made to implement PEM using physical [58] or virtual energy packets [61]. Takahashi *et al.* [60] claim that power distribution through discrete or PEM can be a game-changing approach toward energy management, energy control, and energy wastage reduction. In their work, they designed the ER such that it dispatched power packets with a destination address attached to each packet. Moreover, the power packets from distinct sources are distributed and transmitted through routers and delivered to the end users as per the attached address. The power packets-based distribution network also integrates storage capability and is a feasible solution for PEM. However, packet congestion is still problematic and requires economical solutions.

Zhang and Baillieul [140] developed a packetized direct load current solution for a thermostatically controlled load (TCL). They employed queuing theory to provide effective control of TCL, reduce power peaks, and smooth energy consumption oscillation. The authors extended their earlier work in [141] where they presented a model based on energy packet requests and withdrawals, which considers the total waiting time and mean waiting time of appliances. To achieve maximum utilization of power packets and meet urgency requirements, Ma *et al.* [142] adopted a deferred acceptance technique with heuristics algorithms to solve the scheduling problem. More recently, Zhang *et al.* proposed a protocol for P2P energy packets dispatched in a "local area packetized power network " using the branch-and-bound (BB) method with dynamic programming [143]. In [144], the authors demonstrated a PEM for DERs and proposed a macro model that considers the Markov chain and deferrable loads like electric vehicles and imposes the criteria of accepting and rejecting active energy packets during the state of charging and discharging. They analyzed the quality of service (QoS) guarantee and the accuracy of the model.

At the same line, Nardelli *et al.* [62] examined the implementation of the EI concept through PEM for residential sector loads. Their work considers a cyber-physical domain where flexible loads request energy as virtual energy packets from servers or a common inventory. The inventory is then responsible for the optimization and management of resource allocation based on prioritization, etc. To achieve QoS, the authors emphasized the role of massive machine-type communication (MTC) with ultra-reliable low latency. Nardelli and his group further extended their work in [145] and proposed PEM for flexible loads in the residential sector. Their work considers a cyber-physical system in which three types of loads send requests as virtual energy packets to the energy server through a residential energy router. The energy server can accept or reject the requests based on the energy available and prioritization rule/algorithm used. The proposed management algorithm addresses the peak load consumption and coordinates energy demand efficiently.

V. FUTURE PERSPECTIVES

Although the EI combines many promising features and versatile technologies, it requires co-ordination and co-operation between numerous energy, information and communication networks, which raises a number of challenges, such as system complexity, system security, efficiency, standardization issues, social acceptance, and energy trading and business models. We will now discuss the challenges (Fig. 6) that should be addressed in future researches.

- **System complexity:** An EI structure is built on multiple systems, which makes design, control, and optimization of the entire multi-level system comprising communication, information, and energy infrastructure very complex. On the one hand, the EI potentially offers exciting features based on latest technologies in communication and information but, on the other hand, reliability, efficiency, and robustness remain key issues hampering its implementation. Gungor *et al.* [146] used a three-layer division to discuss the communication requirements of potential smart grid applications to ensure flexible utilization of energy sources with advanced technologies: the application layer, power layer, and communication layer. A wide range of technologies is analyzed and the work also investigates the management of communication and information processing independently for each layer. Another interesting work [147] has investigated an energy-efficient infrastructure for communication and information for three cases: home area networks, neighborhood area networks, and wide-area networks.
- **Latency:** Latency is defined in [148] as "the time between when the state occurred and when it was acted upon by an application." To enable plug and play services and fully utilize the energy at all times, latency requirements have to be very strict. For example, in an electric substation, the communication latency for protection information is 8–12 ms, and for controlling and monitoring purposes is 16 ms [98]. These requirements could be even stricter in the case of MTC, as discussed in [149], and in the EI.
- **Power electronics technologies:** With the unprecedented integration of energy resources into the existing power system, EI components such as the ER, EH, and EIAE must provide robust conversion of energy resources as well as desired frequencies and voltages. In AC/DC MGs, power electronics-based devices are the leading technologies for power sharing and voltage restoration, as mentioned in IV-A. Achieving high-quality power supply in terms of efficiency and reliability is another challenge that needs to be overcome by leveraging efficient power electronics technologies (e.g., wide band-gap power semiconductors) and conversion systems.
- **Efficiency:** A core objective of the EI is to achieve improved efficiency compared to traditional power grids and smart grid. However, this is not easy because the aim of EI is to incorporate massive utilization of RERs. Indeed, it is important to manage, control, and optimize all RERs efficiently. The multiple energy vectors in an EI provide flexibility to accomodate and optimize the energy flow in an efficient manner to some extent. Furthermore, the two main drivers for improving efficiency in the EI are; the scheduling or management methodology in the physical energy delivery infrastructure, and in the ICT system. Both of them are briefly discussed below.
- **Energy scheduling and management:** To maintain flexible demand and supply, special attention should be given to the EMP due to the multi-layer architecture of the EI. Thus far, a few researches have discussed some control and management schemes, particularly centralized and distributed management. However, better and smarter energy management strategies must be employed for the optimal scheduling of energy resources. This also has the knock-on effect of

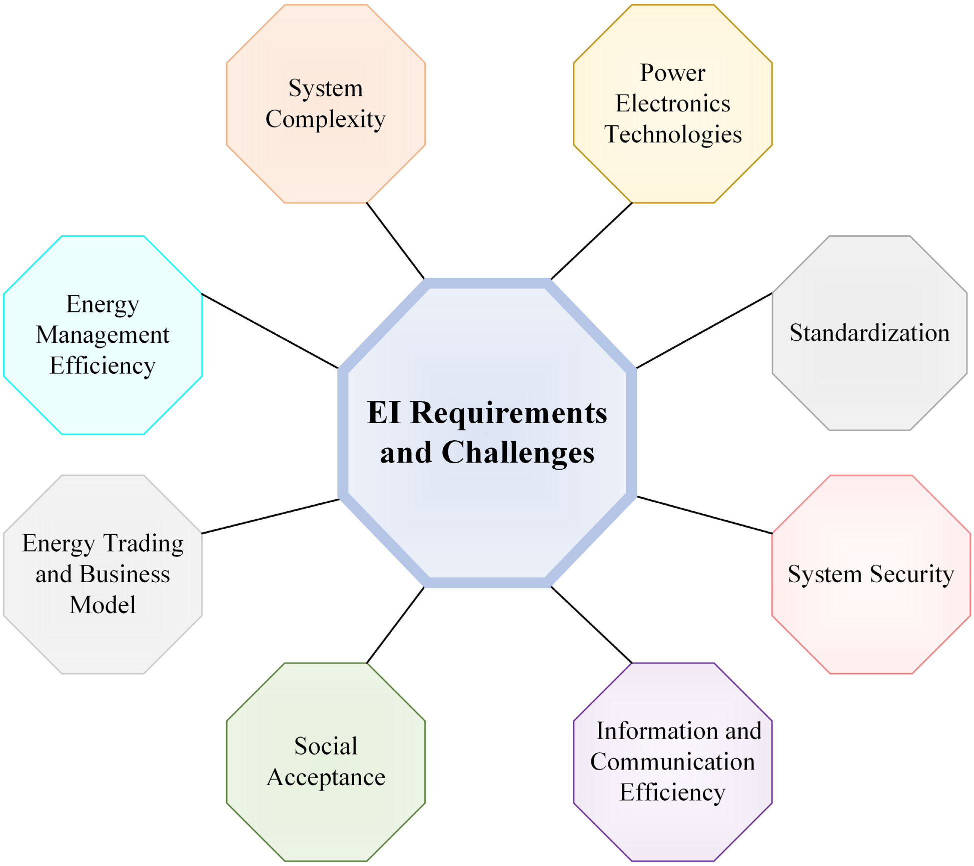

FIGURE 6. Challenges and requirements for advancing the energy internet (EI) technologies; future researches can focus on addressing these challenges.

encouraging prosumers to take part in the energy transactions using DR and DSM. Moreover, the efficient management of the storage network could also benefit both consumers and suppliers and lead to an overall economic and stable power grid.

- **Information and communication network:** The information and communication network (ICN) layer is the key for realizing a high-functioning EI. A fast and robust ICN network allows quick and seamless co-ordination and control of the complex EI network. However, it is still challenging to efficiently process and quickly communicate big data from different RERs and to improve the system performance. Some studies such as [150], [151] have discussed the information layer and its transmission in the EI. Another work [98] proposed an SDEI as an advanced approach to meet the demands and requirements of ICN. However, this is still an emerging research area that requires standard and efficient protocols for ICN. As discussed in [62], the development of the fifth generation of mobile systems (5G) and other solutions, such as edge computing for vertical applications, point toward a promising pathway to realize the EI in a more cost-effective manner.
- **System security:** In the EI, the multiway flow of information and communication is monitored and controlled by widespread and heterogeneous devices including the ER, smart meters, etc. These ubiquitous devices bring many security concerns for the ICN and energy network [152]. The issue of system security deserves great attention because inadequate security can pose a severe threat to system reliability, stability, and efficiency. Generally, the EI architecture relies strongly on the ICN to control, predict, manage, combine, and coordinate the energy resources. However, ICNs are vulnerable to cyberattacks that can jeopardize EI operations. Cyberattacks that could threaten system stability include denial-of-service (DoS) attacks, malware injection, and fake energy pricing [153]. To secure the stability and safety of the entire infrastructure, appropriate control system approaches and security detection techniques should be utilized.
- **Standardization:** To promote and implement the EI in a comprehensive manner, a set of well-defined standards should be established with global-level collaborations among governments, regulatory authorities, and industries [154]. Since the EI represents a comprehensive

multi-layer system that combines power generation, transmission, and consumption with ICN and internet technology, standard protocols and standardization are necessary to fast-track worldwide implementations using best practices. Many interoperability and communication standard protocols are already available for the smart grid, such as IEEE P2030, IEEE P2030.1, and IEC 60870 [146], [155], and a few of them are applicable to the EI, e.g., ISO/IEC /IEEE1880, IOT-G230MHZ, and TD-LTE230. Nevertheless, there is a great need to establish further standard protocols [25], [38].

- **Energy trading and business models:** To support and strengthen the EI applications, new policies for energy trading and innovative business frameworks are an urgent and critical requirement. The business potential of EI-enabled smart grids should be investigated as a way to engage energy users to perform trading and decision making. Governments and policymakers have an important role in facilitating energy market participation. Zhou *et al.* [156] considered a three-layer business management module for the EI. The module is associated with big data analytics from MESs and numerous services and applications to perform business management operations and tasks. To be able to develop an effective business model for the EI, stakeholders such as energy providers, regulators, operators, and prosumers must deepen their collaboration and facilitate cooperation on a larger scale.
- **Social acceptance:** The EI can only be realized by involving energy users fully and by making the best possible use of advanced technologies. Social awareness should be promoted extensively through the following steps: (i) improving or changing users' perceptions of modern technologies; (ii) promoting or publicizing the EI concept; and (iii) involving users in decision making. Recently, the social acceptance of various renewable technologies, such as PV or wind energy, has achieved considerable attention [157], and there is a similar need for tailored policies, business models, and open interactions to advance EI development.

VI. CONCLUSION

In this paper, we have reviewed the current definitions and conceptual basis of the EI given in the scientific literature; analyzed and categorized the scientific literature into broad categories; and proposed a modern universal definition that broadly captures the concept of the EI and its scope of applications. Further, we have also reviewed the technologies underpinning the EI paradigm and its implementations. We have presented the requirements that need to be fulfilled before our envisioned EI is implemented to its fullest extent and definition. And finally, we have explained the challenges that need to be overcome for the EI to be a successful technology in the future.

The EI is a technological paradigm whose promise is based on the ongoing remarkable advances in ICTs, power electronics technologies, and artificial intelligence methods. However, as indicated in this review, several challenges need to be addressed before the EI becomes a reality. These challenges can be broadly summarized into three categories as follows:

- Technological challenges related to the technological maturity and efficiency of the distributed devices in the network, ICT infrastructure, cyber-security and privacy, management algorithms, etc.
- Policy challenges such as the need for standardization, modernized constructive regulation, and incentivization of private- or public-sector participation.
- Social challenges such as the need for public acceptance, improving societal welfare, etc.

Currently, tremendous progress is being made to overcome these bottlenecks, and some versions of the EI have been practically implemented, for example, by using packetized energy concepts [158]. The EI has steadily grown to gain acceptance and become a popular research topic with significant practical benefits. Thus, the EI clearly has tremendous potential to radically transform the energy distribution technology and business, especially in the electricity sector. Indeed, the EI concept promises to make the electricity grid a truly intelligent grid.

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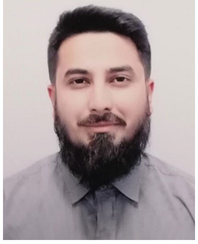

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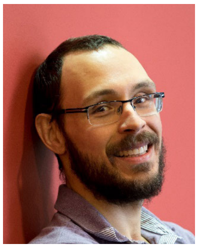

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