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

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ABSTRACT The climate change crises, exacerbated by the global dependency of fossil fuels, have brought significant challenges. Extensive renewable-energy-based electrification in the mid- to long-term is considered to be the most promising development pathway to solve 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 (data) information and telecommunication network architectures. Recently, many measures have been taken to practically implement the EI as well. Although the different EI models share many ideas, a definitive universal definition of the EI is currently unavailable. Moreover, some studies have proposed protocols and architectures, but a generalized technological overview is still missing. Such 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 the EI across the world. In this paper, we first examine and analyze the typical popular definitions of the EI in scientific literature. Based on their definitions, assumptions, scope, and application areas, the papers are 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. We conclude this survey by highlighting the main open challenges and requirements in terms of system complexity, security, standardization, energy trading and business models, and social acceptance in order to have an EI-based energy system in the future.

INDEX TERMS Energy internet, energy management, smart grid, internet of things, communication

I. INTRODUCTION

Over the last few years, the depletion of traditional fossil fuels and the growing concerns about environmental repercussions have resulted in serious research attention being focused on developing alternative energy resources for electricity generation. Traditionally, electricity generation sources have heavily relied on fossil fuels that have continuously deteriorated the environmental condition [1], [2]. In addition, the traditional power grid faces a string of grave issues, e.g., (i) centralized structure with one-directional power flow, (ii) inadequate participation of consumers, (iii) weak market mechanisms, and (iv) other sustainability and economic challenges, etc. [3]–[5]. To deal with these issues, the concept of a smart grid has become a popular and highly researched paradigm [6]–[8]. Smart grid offers two-way energy and communication flow, entails consumers' decisions, and provides a platform to integrate distributed and automated systems that manage the energy flow [9]–[11].

Despite the promise and continuous development of the smart grid and its attractive features, current research has shown that it still has many shortcomings, e.g., inadequate utilization of various energy forms and systems like biomass,

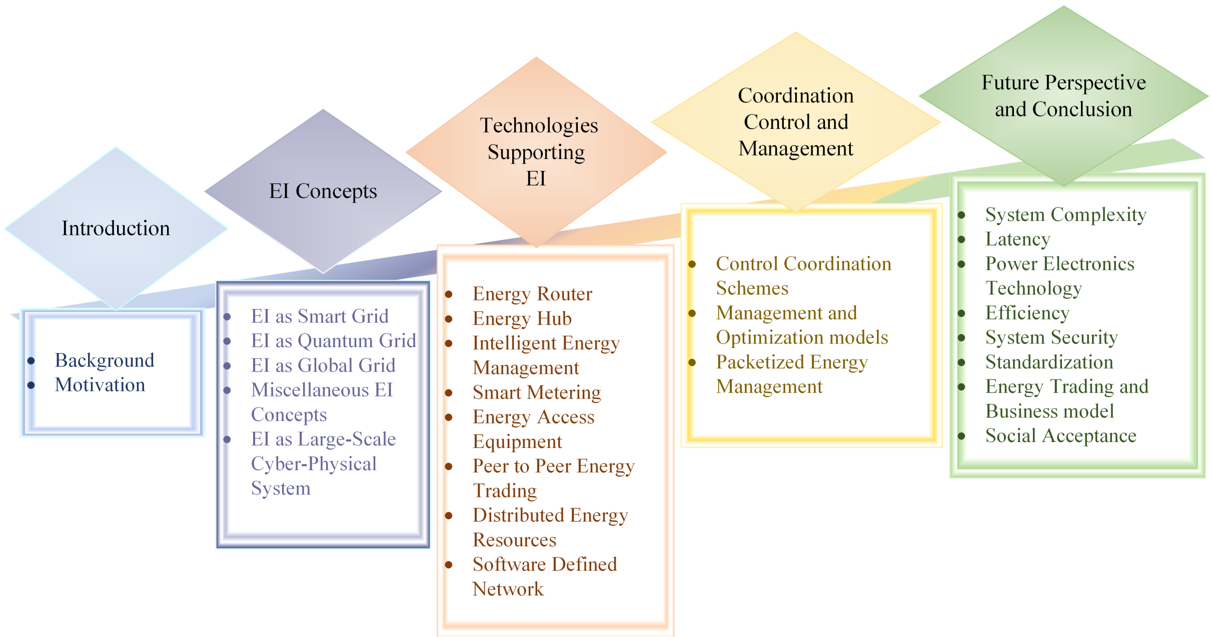

FIGURE 1: Technological challenges of the energy internet (EI) that are reviewed in this paper (From background, concept, supportive technologies, coordination and management, to future barriers and requirements).

chemical, and heat systems, dependencies on existing structures that result in inefficient routing or scheduling of the energy, and security weaknesses [12]–[14]. Following the trend of smart grids together with the technological boom of the (data) internet, the idea of the energy internet (EI) has been introduced. A preliminary conceptual example of the EI was discussed by the prestigious *The Economist* back in 2004 [15], where an intelligent grid—called the "Energy Internet"—anticipates a two-way flow of (various forms of) energy and information with internet-oriented technologies that leverage real-time data, improved power line qualities, various sensors, and micro-power sources.

Despite the above proposal, more systematic research activities using the EI as its core started only in the late 2000s. For example, Tsoukalas and R. Gao revealed the basic assumptions, architectural requirements, and prototype implementations of building an internet type "energy network" in 2008 [16], [17]. Especially in [16], the basic components of the EI were assumed to be as follows: virtual storage, dynamic pricing capabilities, and architectural requirements, including smart metering infrastructure, load, price forecasting, etc. In addition, the authors examined the resemblances between the internet and electricity network. However, they did not analyze the technological aspects and required key equipment, such as energy routers (and its desired important features), plug and play services, etc., to implement the technology.

Around the same time, the project E-Energy (internet of energy) was initiated by the Federal Ministry of Economics and Technology, Germany. The E-Energy model mainly focused on sustainable energy supply systems that digitally connect the entire power system—from generation to transmission, distribution, and consumption—based on information and communication technologies (ICTs) [18] (a complete list of acronyms is presented in Table 1). Meanwhile, 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 proposed FREEDM system aimed to incorporate numerous pivotal technologies as an essential feature of the EI, such as plug and play interfaces, large scale distributed generations and storage units, and information and power electronics technologies [19]. Successively in 2011 and 2013, preliminary research studies were conducted in China to develop the future electric power grid with the integration of new technologies in the EI [20], [21]. Shortly afterward, in 2015, a vibrant organization in China called 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 implementations of the EI have been investigated by considering various features and sub-components such as architectural design, large-scale integration of ICTs, key components, and design challenges (often separately) [23]–[26]. Initially, some of the early researchers, such as Cowan *et al.* [24], viewed the EI in terms of the smart grid. However, as the EI concept began to be viewed more seriously, researchers started approaching the EI as an independent paradigm different from the smart grid, especially in the last few years: *EI is now described as an enabler of the smart grid.*

For example, the authors in [25], [26] explicitly high-

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
EIACE	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
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
SER	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

lighted the key differences between the smart grid and the EI. In [25], the authors identified the communication challenges and standards for building an EI framework, whereas the same group of researchers in [26] delineated the architecture of the EI based on the FREEDM system, along with the design of EI components—particularly energy routers—and the key challenges for the EI. In these two research works, the authors surveyed the EI framework, but without analyzing the management of EI resources with the essential controlling methods. Furthermore, in some other works, [27], the EI concept focused on smart grid applications integrated with the internet of things concept. Some authors such as [28] also focused on the communications devices and architectures within the EI; they examined the components of EI, paying special attention to the energy router architecture.

Today, it is clear that the EI has become a popular topic with extensive ongoing researches. Nevertheless, no coherent universal definition of the EI exists, and many different interpretations abound in the literature. In this paper, we try to systematize the existing literature to map the differences and similarities of the existing contributions under the name of the EI. As shown in Fig. 1, we first review the different meanings and definitions of the EI concept considering the existing and current research trends. We discuss the way the EI has been approached as a "smart grid", "global grid", "quantum grid", and other miscellaneous viewpoints. We then present our comprehensive universal definition of the EI as a "cyber-physical system," and elaborate on this conceptual basis of the EI and its main characteristics.

The EI concept needs to be supported by emergent and emerging technologies; in fact, these technologies offer the strongest hope and potential for successful EI implementations. Hence, we describe the core technologies that are needed to construct the EI framework, for example, energy routers, energy hubs, energy access equipment, etc. Coordination and management methods are required to connect disparate energy technologies powering the future EI. Because of its importance, we strongly focus on the topic of the coordination and management of EI resources; here, we briefly describe the different control schemes, management strategies, and optimization models. Finally, we highlight the key requirements and challenges of the EI, with the aim of motivating further developments in EI techniques, technologies, and implementations.

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.

II. EI CONCEPTS

Researchers across the globe have studied the EI with different meanings, interpretations, and perspectives. In this section, we will discuss the following main definitions of the EI.

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 enables 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 mainly rely on ICT's. [19], [26], [30]
Metering and routing equipment	Smart meters, sensors, home energy management systems	Energy routers, smart meters, intelligent energy management soft-wares, 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 conversion of voltage level, communication with other ER, and integration of 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 analysis of data and energy, grid management	The EI is based on multi-agent and intelligent systems that process and analyze the data and energy simultaneously whereas 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 etc. [35], [36]. On the other hand, in the EI, the EI communication protocols IOT-G230MHZ and TD-LTE230 are beig discussed in [37], [38], but, more standardized communication protocols are required.

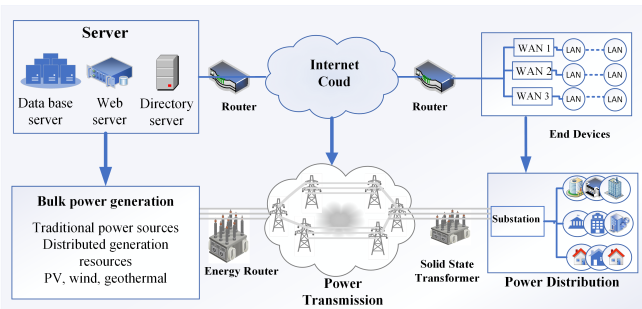

FIGURE 2: Comparison of energy flow in internet and power system network [53].

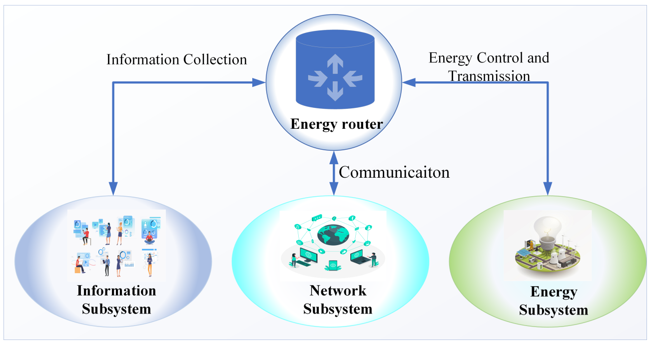

FIGURE 3: An overview of the subsystems of an EI defined in [25].

A. EI AS A SMART GRID

In the past decade, most research efforts have explicated the EI in terms of smart grid. For example, [24], [41]–[46] either referred to the EI as a smart grid or considered the EI as an essential feature of the smart grid, with a few papers interpreting the EI as a web-based smart grid [47]–[52]. Tsoukalas and R. Gao explained the EI as follows: "An implementation of smart grids is EI where energy flows from suppliers to customers like data packets do in the Internet" [16]. They also investigated the assumptions and requirements to restructure the delivery of energy infrastructure and to construct an internet type of energy network. Similarly, the authors in [53] viewed the EI as an advanced form of the smart grid and highlighted the analogy between internet networks and energy networks (Fig. 2).

On the other hand, the authors in [26] described the EI in terms of its differing characteristics from the smart grid. They considered the EI system to have three main components [25]—energy subsystem, network subsystem, and information subsystem—that are interconnected with ICTs. They explored 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 enabling the two ways of communication and energy flow, as shown in Fig. 3. Likewise, Dan Wang *et al.* in [54] expounded the physical structure of the EI and categorized it into three levels; trans-regional, regional, and user level. A key difference that the authors mentioned in their work is the consolidation of various forms of energy, such as electricity, heat, clod, and gas in a regional level and user level through an intelligent component known as an integrated energy distribution system (IEDS). In addition, the other key differences discussed in these two articles and others [24],

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 compared the EI with smart grid technologies and explicated 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] extended their previous work [25] and described the communication infrastructure with potential key technologies in the EI. In addition, the article also presented an overview of the EI components including FREEDM system etc. However, the control methods and management of key resources remained unidentified.
Internet of things applications explored in the smart grid, smart cities, and EI	Yasin et al. [27]	2019	The work viewed the EI and smart grid as the same concept and mostly focused on IoT applications in the smart grid; importantly, key communication technologies (e.g., the ER) of the EI were taken into account.
The EI treated as part of smart grid with some key equipment including benefits and hindrance	Suhail et al. [28]	2019	Authors discussed the basic architecture of the EI (based on FREEDM) including the ER and its types, benefits, hindrance, and requirements. However, technical solutions for the management of various EI resources were 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 focused on IoE applications in building energy management systems (BEMS). The principal aim was 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 investigated the hardware equipment in the EI and proposed 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 presents and examines various concept of the EI and proposes a universal definition. Key supporting technologies are described, including control and coordination methods. Potential bottlenecks, with the important requirements to implement EI in the future, are also explained.

[27], [28] are summarized in Table 2.

B. EI AS A GLOBAL EI

In another promising idea explored by Jichun Liu *et al.* in [55], the EI is described as global energy internet (GEI), i.e., as a "strong" smart grid having a much larger scale. In this context, GEI interconnects renewable energy sources (RES) globally (including solar, wind, hydro, and geothermal) and employs optimal management and coordination of these resources, thereby ensuring a clean, sustainable, secure energy network across the globe. Moreover, the authors put forward three research pathways to achieve the benefits of GEI—system dynamics model, simulation methods, and multiagent game theory. However to construct the GEI, a few topics still need to be investigated e.g., investment plannings, investment decisions, coordination or interaction among countries, and technical problems, etc.

To model the technological aspects of GEI, the authors in [56] proposed an economic dispatch framework that is practically verified in South Asian countries. Their framework particularly focused on the technical problems of GEI and explored the reinforcement of RES shares in the electrical power system while coping with the uncertainty constraints and power regulations. Furthermore, they came up with an algorithm—alternating direction method of multipliers (ADMM)—to protect the sensitive information of the countries and to enable a reliable exchange of energy and communication.

C. EI AS A QUANTUM GRID

The authors in [57] came up with a unique idea to describe the EI in the context of a quantum grid. The so-called quantum grid (QR) 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 the addresses just like the internet network (internet protocol address, IP address). In addition, the power nodes are referred to as quantum grid routers (QGR) and their functions are to (i) optimize and control the energy generation resources, such as distributed energy resources, bulk power generations, and consumption, and to (ii) achieve quick restoration and self-healing. The basic layers of the QR network is comprised of a power plan, routing & control plan, and business plan. By leveraging ICTs to fully connect the various components, the QGR is able to exchange the information in various layers by means of energy packets considering routing & control plans.

Other similar concepts 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 relation between PEM and the

EI is given in [62].

D. OTHER MISCELLANEOUS VIEWS ON EI

Some research studies have elaborated the EI in a different way. For example, [63] studied Energy + Internet and compared the challenges of the business model and management of integrated energy resources, services, and polices in traditional energy and new Energy + Internet systems. In [64], Feng and Xiaoli explored the EI as a "people oriented" system that examines the well being of the people by establishing communication channels between people and energy systems. They argued that an economical and environment friendly "best energy service" is the ultimate demand of the people. Seen from the technology point of view, the communication, information, and processing technologies 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 broader concept that aims to merge numerous energy-based networks (heat, gas, electricity, etc.) and to provide a unified platform for better coordination and sharing of the energy resources. The development of such a large EI architecture is complex and requires attention from many disciplines. Unfortunately, this also makes it onerous to come up with a simple all-encompassing definition. In this article, we approach the EI framework from the viewpoint of energy networks and their interactions, such as transactions in the electricity network, and their 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 is 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]. SERs communicate with each other through (discrete) energy packets that are similar to the data packets in the internet network. 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 the 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.

In this picture, the EI is viewed as a cyber-physical system (CPS) since it consolidates the features of physical systems and cyber systems simultaneously. Physical systems like electricity generation resources are controlled and managed according to the instructions achieved through cyber-systems, e.g., 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 EI definition and architecture requires the integration of cutting edge technologies including real-time communication technologies, control systems, information processing, smart metering infrastructure, software-defined network, etc. Besides, it is also essential to organically deploy such technologies with management and planning strategies while taking into account EI requirements, and challenges.

F. SUMMARY

The broad concept of the EI was discussed in this section following different definitions and applications that have been presented in the literature. The main surveys of the topic are also summarized in Table 3, along with their perspectives and ideas. It is worth mentioning that none of the existing surveys consider the EI as a large-scale CPS enabled by PEM.

In the next section, we will present the key technological enablers of the EI.

III. SUPPORTING TECHNOLOGIES FOR EI

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

A. ENERGY ROUTER

The energy router (ER) is an essential technology/device for building the EI infrastructure. The idea of the ER was first detailed by FREEDM [19] with major features including the conversion of various 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 reliability of the system. The proposed ER was based on a solid state transformer with an architecture comprising three layers: physical control (power and energy), distributed grid intelligence (DGI), and communication layer.

The first layer was designed to provide flexibility to the physical system and to accomplish the conversion of various energy technologies, such as from high voltage alternating current (AC) to direct current (DC) as a rectification, DC to DC (different voltage levels) as a chopper, and DC to AC as an inversion, and also to provide low-level voltage for the AC bus. The second layer was the communication layer that adopts the bidirectional flow of information and communication and uses technologies like Ethernet, wireless LAN, and fiber optics. Lastly, the DGI layer utilizes the information from the communication layer and coordinates among other SSTs to enable optimal decision-making and improve energy efficiency and utilization. The promising

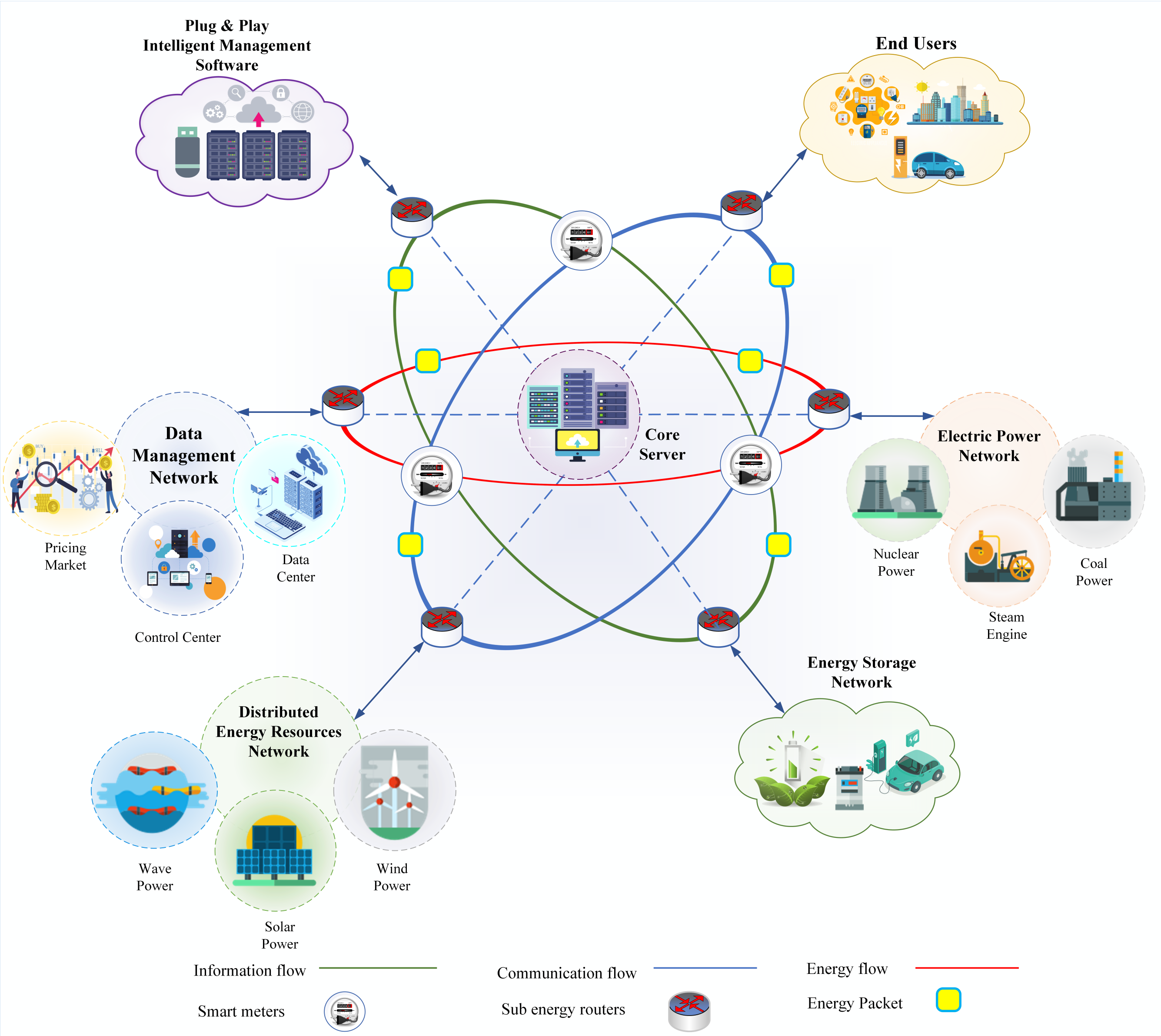

FIGURE 4: A basic structure of the EI representing multiple networks, such as distributive energy resources network, energy storage network, data management network, internet and communication networks with myriad features, like Plug and play, intelligent soft wares, energy router, and smart meters etc.

features of SSTs are plug and play services, flexible power control, and optimal energy flow [68].

Furthermore, in [31], [66], [67], three types of ERs based on solid state transformer (SST), multi-port converter (MCP), and power line communication (PLC), were described, respectively. The authors expounded a similar functionality of SST as proposed by FREEDM, i.e., the transformation of various forms of energy and regulating voltage and current levels using power electronics devices. The MCP is particularly designed for the low-level voltage distribution network, i.e., for homes and buildings, which manages the subsystems including generation resources and storage systems to maintain and balance the energy supply.

On the other hand, the PLC is the key layer in ER and responsible for the flow of energy and information simultaneously 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 to deal with the bandwidth requirements, low data rates, and signal attenuation. Many researches have tried to tackle these shortcomings and improve the efficiency and reliability of PLC. For instance, the authors in [67], [69], [70] considered the electrical network to be similar to a data network and split the energy into energy packets , similar to data packets in the internet network. They used transmission techniques such as time-division multiplexing (TDM). Under TDM, the energy packets are tagged with header (source of generation) and footer (con-

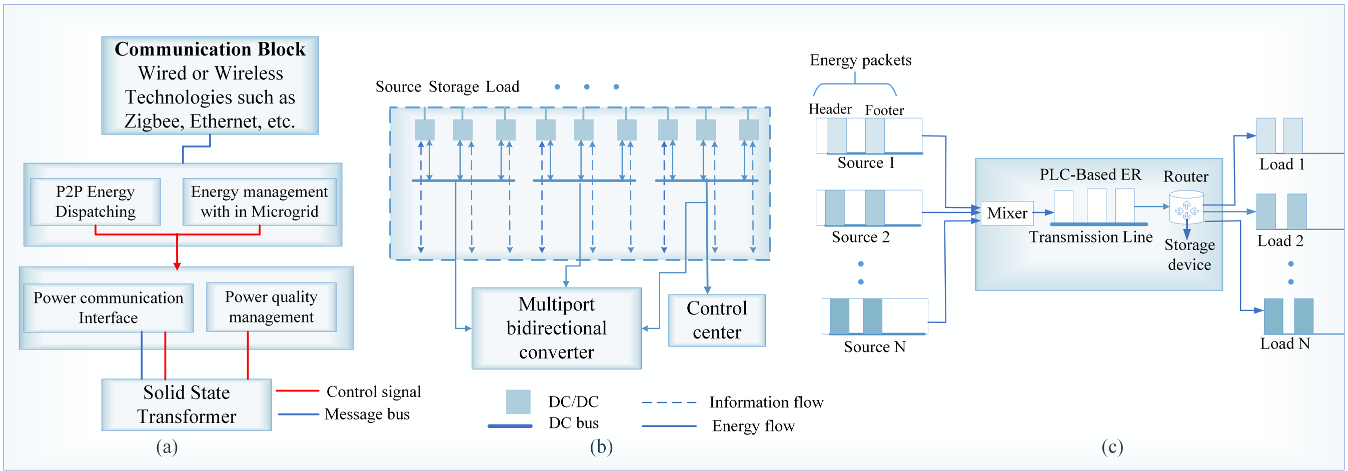

FIGURE 5: Energy router types: (a) Solid state based energy router (b) Multi-port converter based energy router , and (c) Power line communication based energy router adopted from [31], [66], [67]

sumer) 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. Figure 5 presents the architecture of the three types of the ER.

B. ENERGY HUB

Energy hub (EH) is another important concept discussed in a project Vision of Future Energy Networks [71]. EH is a system that combines various energy networks including electricity, heat, and gas and converts energy to fulfill the required demand and facilitate the end users. EH possesses two key features: flexibility and reliability. EH enables flexible utilization of energy from different energy networks without depending on a specific energy source, which, in turn, increases the reliability of the system, particularly from the consumer's perspective. In addition, the authors explored the feasibility of the combined transmission of different energy forms and proposed a device known as an energy interconnector. The proposed energy interconnector enables combined transmission and improves the system efficiency. For example, 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 coould result in a catastrophic collapse [72].

Recently, the work in [73] comprehensively described the EH concepts and compared its four key components—(variety of) energy inputs, storage systems, converters, and optimal output of EH models. Moreover, the authors discussed the drawbacks in the existing EH models and suggested efficient methods for the management of EH as well as additional features to improve the sustainability of the future energy system. Similarly, the authors in [74] designed the EH model in a control-oriented manner and optimized the energy scheduling problems using mixed-integer linear (MIL) formulation. Further, Yi 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), networks, etc., are connected to provide full and flexible energy supply to the end users. In addition, the electricity market facilitates energy trading with the energy suppliers or among prosumers with effective DR strategies. Thus, to connect and observe the energy usage and energy supply in real time, the authors in [40] proposed energy internet access equipment (EIAE). The authors summarized three prominent features of the EIAE: (i) EIAE as end users' cyber-physical terminal media creates an interfaces that then measures, observes, and controls all types of devices using DERs; (ii) EIAE enables interactions among the end users and energy generation and supply 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 necessary services. Furthermore, the authors highlighted the differences between ER and EIAE and presented some novel features of EIAE. These novel features were 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 particularly relies on fast and reliable information, leveraging smart and intelligent energy manage-

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 the core component in the EI and couples multiple energy systems (MESs), conversion technologies, and transmission of information and communication through internet technologies	Acts as a component in the EI and combines MESs with conversion technologies and storage systems mainly	Acts as a key component and is particularly designed 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, but it acts as a medium to access DERs and other resources
Information & communication process	Collects the 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 controlling energy, information, and communication simultaneously through distributed grid intelligence	Responsible for controlling and managing the energy resources of MESs in the EI	Responsible for controlling the 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

ment systems. In this context, FREEMD [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 the 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 more importantly, a robust algorithm to control and distribute tasks efficiently.

E. DISTRIBUTED ENERGY RESOURCES

A feature of the envisioned EI is that it is highly flexible to accommodate DERs and maintain sustainability and availability of the power generation. The EI encompasses numerous DERs that, along with other complementary technologies such as storage systems, play an important role to optimize energy management. However, the controllability and management of DERs and storage system are still facing numerous challenges and sustainability issues such as high computational burden, frequency design requirements, communication topologies, etc. To tackle these, Mehrdad *et al.*, [76] reviewed distributed control and management techniques to improve the computational capabilities and cooperation among the growing number of DERs, power grids, and end-user side. Similarly, the work in [77] discussed a novel strategy—"event-triggered communication"—for optimal control among the communication devices in DERs. Their proposed strategy considered the communication complexity and attempted to enhance the coordination among DERs, which, in turn, improves the reliability and flexibility of the management. The authors also described trade-offs between communication resources and control performance. Jink [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 cloud and provides information and processing, data acquisition, and communication while the edge network makes autonomous decisions through an intelligent agent. Another research work, [79], employed a fractional order proportional integral derivative (PID) controller with robustness; [80] explored test-beds for two levels of energy management and control systems; and agent-based controlling techniques were examined in [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 the information, smart meters control energy usage and demand. Smart meters together with demand-side management (DSM) and demand response (DR) enable potential benefits to end users and energy suppliers. For example, 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, etc., through a user interface, often known as "in-home display". This facilitates the consumers to manage their energy usage and achieve reductions in the electricity bill. From a utility point of view, the peak load can be curtailed, shifted, or predicted by implementing DR programs, thereby improving the energy efficiency of the system [82].

Damminda Alahakoon *et al.* [83] studied smart meters, their framework, and potential applications. They revealed that the information received by smart meters, such as power generation, consumption, and power quality can be used to enhance the system stability and reliability. Also, the proposed framework identifies potential features of smart meters in terms of data analytic, technological perspectives, and stakeholder applications overseeing the limitations in the existing infrastructure. However, the potential requirements or challenges, such as communication latency, bandwidth, real-time processing, security, and privacy need to be addressed appropriately. Reference [84] examined the smart meter communication framework, the current challenges, technological solutions, and open research directions, e.g, scalable inter-networking, interoperability, self-organizing, DR, etc. In addition, the authors emphasized the standardization of information and communication strategies for the deployment of smart meters and other devices to realize 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 in [85] authors 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 the AMI systems are; consumer privacy preservation, 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 security issues, it is essential to deploy standardized ICTs, design efficient KMS, intelligent soft wares, and potential solutions such as key graph technique, authentication (based) technique, and hybrid technique [85], [87].

G. PEER TO PEER ENERGY TRADING

The EI is interconnected, open, smart, and user-centric, which enables feasible, secure, and reliable peer to peer (P2P) energy transactions and delivery. As such, P2P enables prosumers to take part in the electricity market and sell excess energy [88] or to reduce their energy demand [89]. By doing so, the prosumers can make full use of DERs and consequently reduce their electricity costs. P2P energy trading empowers the power grid to obtain conspicuous benefits, such as reduced peak (demand), lower overall operational and investment costs, lower reserve requirements, and improved energy efficiency and power system reliability [90]–[92]. It is, therefore, still an important issue to investigate the requirements of P2P energy trading and encourage the customers to take part in the trading within the EI framework.

In [93], the authors explored the architecture of P2P energy transactions including the physical layer that is responsible for the transmission of electricity and the virtual layer that provides secure transmission and communication for energy trading among prosumers. Moreover, the authors explored the challenges faced by both layers and discussed the relevant technological approaches such as constrained optimization, game theory, auction theory, and blockchain in order to identify and address the impact of these challenges. In the same fashion, the work in [94] designed a four-layer model for low voltage (LV) microgrid through the "Elecbay" platform leveraging the game theory approach. Muhammad Raisul 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 to optimally distribute the energy cost ensuring Pareto optimality.

H. SOFTWARE-DEFINED NETWORK

To meet the diverse communication demands and efficiently utilize the interconnected technologies, software-defined network (SDN) has emerged as an innovative networking approach. The SDN intends to improve routing strategies by establishing the programmable resources and software networks. The SDN and EI have been studied in [96]–[98]. Zhong *et al.* [96] investigated software-defined the 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. Among the three planes, the EP is responsible for dealing with the physical flow and control of energy, and DP collects and analyzes the information from various energy sources and services, including generation data from DERs and consumption data from household. 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). Finally, the authors discussed an EV example to demonstrate the application of the SDEI in the mobility management system and energy service provider with potential challenges.

A similar approach for the 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 in [98] explored the SDN for the communication architecture of the EI at two levels, microgrid level (ML) and global grid level (GGL). The proposed communication architecture was evaluated based on the reliability, security, and latency features. The test bed cases of the proposed framework for

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 multiple energy systems (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 – Requires reliable communication and power conversions	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 demand-side managment (DSM) and demand response (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 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 – Enhancing 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 understand.

the ML and GGL were presented, and it verified low latency and improved reliability results.

I. SUMMARY

In this section we have covered the main technological enablers of the EI in the literature. Table 5 lists the technologies together with their main features, the existing challenges, and our remarks about them. In the following section, we will discuss how these different elements can be used to coordinate and manage the distributed resources that form the basis of the EI.

IV. COORDINATION CONTROL AND MANAGEMENT

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

A. CONTROL AND COORDINATION SCHEMES

As we have seen that 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, etc. [99], [100]. However, the MGs face many challenges such as 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 under load condition, while maintaining a stable operation of power system. In the same fashion, Qiuye [108] *et al.* analyzed a hybrid strategy and proposed a power-sharing unit (PSU) intending to make full use of DERs in MGs with the help of a modified droop control approach such as using single-phase back-to-back converters. It is pertinent to note that the conventional droop-control schemes have shortcomings in terms of voltage synchronization and power sharing tradeoffs, dependencies of load frequency and voltage, etc. [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 these 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 were 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 such as event-based control and predictive control etc., [115]–[118]. 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

So far, we have focused on the EI infrastructure/architecture [16], [19], [26], [28], ER [66], [68], [70], and frequency or voltage control [121], [122]. However, an important aspects of the power system is the energy management problem (EMP) in which an energy management system should should be setup to achieve the goals of the EI. Typically, the EMP is designed as an optimization problem and solved using different approaches such as centralized, decentralized, or distributed approaches. Centralized approaches provide global or near-optimal solutions. However, with the fast proliferation of DERs, many of these approaches do not always converge to an optimal point and often, at the same time, pose strict conditions on the system, such as computation complexity, communication requirements, etc. On the other hand, the distributed approaches are robust, fast in computation, and communication, and thus, more popular.

In the literature, the EMP has been explored widely for microgrids and smart grids [123]–[125]. The EMP with DSM is analyzed to minimize the cost of the system [126], [127] and the electricity bill of the consumer in the residential sector with a home energy management system (HEMS) [128]–[131]. Subsequently, the problem is solved using meta-heuristic optimization algorithms, such as the PSO [132], GA [133], HSA [134], and others [135]–[137], with the objective of optimal scheduling energy consumption and improving the reliability and stability of the power grid.

However, for the EI, the EMP is somewhat different from the aforementioned methods because the EI is envisaged as a bigger collection of numerous energy generation networks, DERs networks, storage networks, etc., with wide proliferation of prosumers. Therefore, designing a robust and efficient EMP for the EI is still a major challenge because many of the aforementioned smart-grid-based methods do not scale adequately. What is more, still some work have attempted to tackle the EMP problem in the EI. For example, authors in [122] comprehensively discussed the features of EI and proposed an innovative framework for energy management. Their designed model incorporates various forms of energy systems like heating and gas and then the EMP problem was solved with the distributed-consensus-ADMM algorithm. The proposed algorithm optimally manages the energy demand/output and takes into the account the 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, etc. using intelligent ERs. Guo [70] *et al.* explored the hierarchical optimization method for the EH and ER in the 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. On the other hand, in the upper level, the ER is employed to ensure secure and effective communication among other EHs and ERs. Lei 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

Packetized energy management (PEM) is one of the core methods to implement the EI. PEM is an interesting approach toward energy management and coordination of various energy generations in the EI. The concept of PEM 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). Under PEM, the energy demand and supply can be aligned with the dynamic generation and consumption resources. Moreover, PEM has several benefits such as flexible decision-making, fairness, responsiveness, and scalability [58].

Recently, efforts have been made to implement PEM using either physical [58] or virtual energy packets [140]. Takahashi *et al.* [141] suggested that power distribution through discrete or PEM can be a game-changing approach toward energy management, controlling, and reducing energy wastage. In their work, they designed the ER for dispatching power packets with the 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.

In [142], the authors 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 previous work [143] and designed a model based on energy packets' requests and withdrawals considering the appliances' total waiting time and mean waiting time. To achieve the maximum utilization of power packets and urgency requirements, another study [144] deferred acceptance technique with heuristics algorithms and solved 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 [145]. In [146], the authors demonstrated PEM for DERs and proposed a macro model that considers the Markov chain and deferrable loads such as electric vehicles. Their model imposes the criteria of accepting, rejecting, and activating energy packets during the state of charging and discharging. They analyzed the quality of service (QoS) guarantee and the accuracy of the model.

In the same line of work, Nardelli *et al.* [62] pointed out the implementation of the EI concept through PEM for residential sector loads. According to the authors, a cyber-physical domain is considered where flexible loads request energy as virtual energy packets to the 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 use of massive machine-type communication (MTC) with ultra-reliable low latency. Further, new governance model are important to construct and implement the EI. Nardelli and his group further extended their work in [147] 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 available energy and prioritization rule/algorithm. The proposed management algorithm addresses the peak load consumption and coordinates energy demand efficiently.

V. FUTURE PERSPECTIVES

The EI amalgamates and provides many promising features and versatile technologies to closely couple numerous energy, information, and communication networks and enable efficient energy delivery. However, this also leads to a complex system that that faces several challenges such as system complexity, system security, efficiency, standardization, regulatory barriers, social acceptance, energy trading glitches, and good business model. We will now elaborate some of these challenges (Fig. 6) that should be addressed in future researches.

- **System complexity:** The EI structure is built on multiple systems. This makes it very complex to design, control, and optimize the entire multi-level system comprising communication, information, and energy infrastructure. On the one hand, the EI provides exciting features based on the latest technologies such as real-time communications, 5G communications, edge computing, and smart metering technologies. On the other hand, reliability, efficiency, and robustness have remained key issues hampering its implementations and opening the door for emerging researches. In [148], the authors discussed the communication requirements of potential smart grid applications to ensure the flexible utilization of energy resources with advanced technologies in three layers: application layer, power layer, and communication layer. For each layer, a wide range of technologies has been analyzed to independently manage the communication and information processing. Another interesting work [149] has investigated the energy-efficient infrastructure for communication and information in three cases: home area networks, neighborhood area networks, and wide-area networks. However, there are still many open issues and challenges that need to be addressed to establish the envisioned EI.
- **Latency:** Latency is defined in [150] 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 MT communication, as discussed in [151], and particularly in the EI.
- **Power electronics technologies:** With the unprecedented integration of energy resources into the existing power system, the 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:** One of the core objectives of the EI is to achieve improved efficiency compared to the traditional power grid and smart grid. However, this is not easy because the EI incorporates massive utilization of renewable energy. Indeed, it is important to manage all RERs efficiently. The multiple energy vectors in an EI also provide flexibility to optimize and manage the energy flow in an efficient manner to some extent. Furthermore, the main drivers for improving efficiency in the EI are to improve it in the scheduling or management methodology, in the physical energy delivery infrastructure, and in the ICT system.
- **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 such as 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 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 [152], [153] have discussed the information layer and its transmission in the EI. In [98], the authors have proposed an SDN EI 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, points to 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 pervasive devices bring many security concerns for the ICN and energy network [154]. Such issues deserve high attention because they impose a severe threat to system reliability, stability, and efficiency. The EI architecture strongly relies on ICN to control, predict, manage, cooperate, and coordinate the energy resources. However, ICNs are vulnerable to cyberattacks that can jeopardize the operation of the EI. Some cyberattacks that could threaten the system stability are denial-of-service (DoS), malware injection, fake energy pricing, etc. [155]. To secure the stability and safety of the entire infrastructure, control system approaches should incorporate security detection techniques.
- **Standardization:** To promote and implement the EI in a comprehensive manner, a set of well-defined standards should be established with global-level collaborations between governments, regulatory authorities, and industries [156]. 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 implementation 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 [148], [157], and a few of them are applicable in the EI, e.g., ISO/IEC /IEEE1880, IOT-G230MHZ, and TD-LTE230. Nevertheless, there is a great need for establishing standard protocols for the EI [25], [38].
- **Energy trading and business models:** To support and strengthen the applications of the EI, 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 to engage energy users to perform trading and decision making. Governments and policymaker should help to facilitate and reinforce the active participation of energy users. Ref. [158] has elucidated a three-layer business management module for the EI. These modules are associated with each corresponding layer to perform business management operations and tasks. To develop a business model for the EI, stakeholders such as energy providers, regulators, operators, and prosumers must deepen their collaboration and cooperation on a larger scale.
- **Social acceptance:** The concept of the EI can be realized only by fully involving the participation or cooperation of energy users and 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 [159]. There is a similar need for tailored policies, business models, and open interactions to simulate social awareness among energy users.

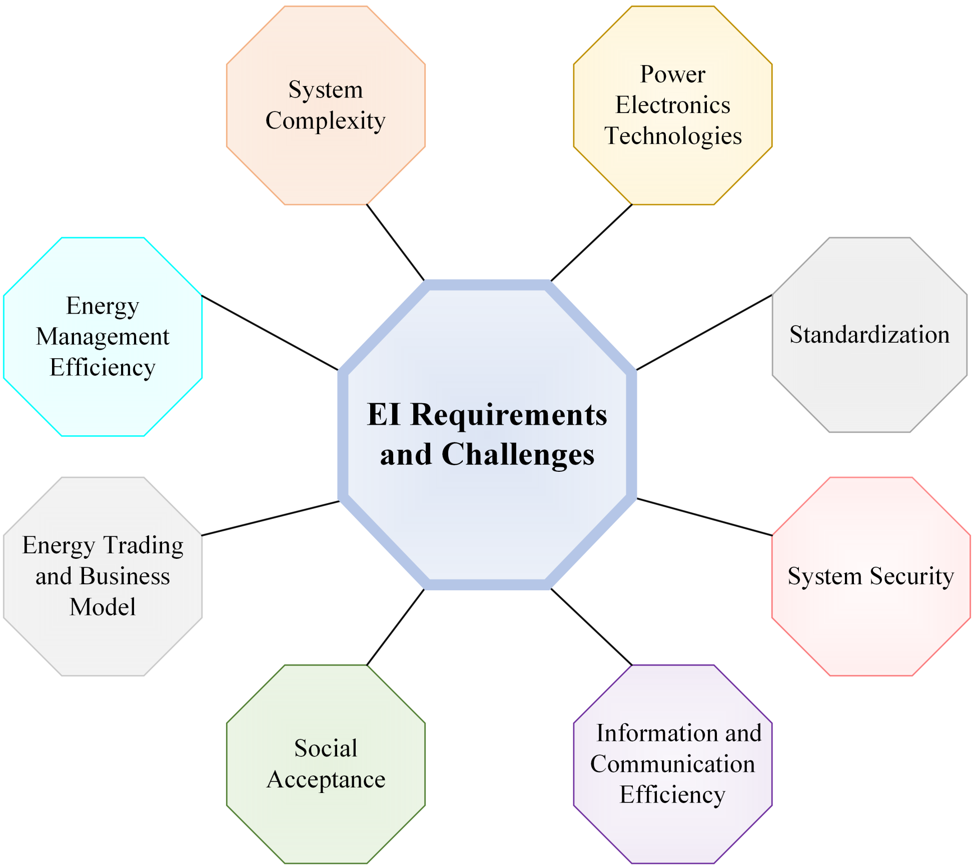

FIGURE 6: Challenges and requirements for advancing the energy internet (EI) technologies, which can be the future research prospects.

VI. CONCLUSIONS

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 application scope. 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 the 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, ICTs 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 [160]. 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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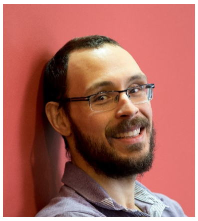

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