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Energy Internet, the Future Electricity System: Overview, Concept, Model Structure, and Mechanism

Akhil Joseph [1,2,*] and Patil Balachandra [2]

1 Experimental Power Grid Centre, Energy Research Institute, Nanyang Technological University, Singapore 627 590, Singapore
2 Department of Management Studies, Indian Institute of Science, Bangalore 560012, India; patilb@IISc.ac.in
* Correspondence: akhil.joseph@ntu.edu.sg; Tel.: +65-6908 6546

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Abstract: Energy Internet, a futuristic evolution of electricity system, is conceptualized as an energy sharing network. Its features, such as plug-and-play mechanism, real-time bidirectional flow of energy, information, and money can lead to significant benefits and innovation in electricity production and utilization. Energy Internet integrates small-scale renewable energy systems, electric loads, storage devices, and electric vehicles for effective transaction of power backed by emerging technologies such as Internet of Things, vehicle-to-grid, and blockchain. At present, there is no scaled-up working model of Energy Internet, and literature is scarce, which makes the research in this domain significant, novel, and timely. Given this, an attempt is made to develop the conceptual model of an Energy Internet, elaborate its structure and components, and discuss its operational principles. First, a comprehensive overview of Energy Internet is presented along with its aptness as a future evolution of electricity system. Second, concepts, architectures, and features that underpin Energy Internet are outlined. Third, concept of 'Energy Intranet' is introduced to denote the scaled-down version of Energy Internet, which embodies energy prosumers and local energy markets to form a local energy cluster. Finally, discussion is presented on the network structure of Energy Internet, relevance of emerging technologies and innovative operational mechanisms.

Keywords: smart grid; energy internet; energy intranet; energy transition; energy blockchain; peer-to-peer energy trading

1. Introduction

Overdependence on fossil fuels to meet the growing energy demand has led to several negative outcomes, such as depletion of natural resources, increased pollution, imminent climate change, extreme weather conditions, human sufferings, and turbulent geopolitics. The consequences of such outcomes are in terms of increased cost of production and services leading to more deprivations and human sufferings. It is obvious that, we will not wait until the last day of the fossil fuel era to act. As one of the most significant solutions to address these challenges, almost all the countries have switched their focus on renewable energy sources and low carbon technologies to meet the current as well as future energy demands. The world is amid significant energy transition with renewable energy taking the main stage, especially in the case of electricity systems.

Solar and wind, which are considered as the most prominent renewable energy sources for power generation are uncertain, variable and intermittent [1]. Therefore, integration of such renewable energy source is extremely challenging for the real-time operation of the electricity system [1,2]. To smoothly manage the real-time operation of electricity systems with variable renewable energy sources coupled with dynamic energy demand, integration of energy storage systems are inevitable [3]. Batteries are well-known energy storage devices, which are also used in electric vehicles (EVs). In recent years, energy storage technology has become affordable and introduction of household storage systems, such as Tesla Power Wall, and large-scale battery storage systems, such as Hornsdale Power Reserve in Australia, have enabled convenient integration of local renewable energy generators, electric vehicles, household loads and storage devices. In addition, recent evolution of energy router as a prime single device solution for serving multiple purposes such as metering, communication, voltage regulation, and synchronization of local renewable energy generators is a significant way forward.

Emerging technologies, such as big-data analytics, cloud computing, Internet of Things (IoT), and blockchain have wide possibilities in facilitating synchronization of renewable energy systems with national grid as well as energy trade in distributed energy systems in an open platform. Big data analytics and cloud computing can support energy management, demand response and fault detection [4]. IoT is useful in electricity systems for several applications including automated metering infrastructure, and energy storage [5,6]. Blockchain technology has vivid applications in energy industry such as metering/billing, bill payments, grid management, green certificates, and carbon trading, and decentralized energy trading [7]. The availability of blockchain technology which works seamlessly with IoT and cloud computing can facilitate tracking of bidirectional flow of electricity between two prosumers [8]. Depending on their status (surplus or deficient), the consumers with local renewable energy generators (prosumers) can either sell or buy electricity anonymously. Bidirectional communication possibilities enable real-time information transfer between prosumers on energy supply and demand, price, storage, etc. Bidirectional money flow facilitates the possibility of instantaneous payment between the prosumers. Bi-directional payments can take place through various payment channels such as Unified Payment Interface (UPI). Therefore, it can be inferred that the technologies have evolved into a state at which electricity markets with bidirectional electricity, communication, and money flows can function seamlessly.

Persisting challenges, evolutions in energy technologies, and large penetration of information and communication technologies (ICTs) are influencing transformation in electricity systems. Integration of distributed renewable energy systems (RES) with traditional electricity system with the support of advanced electronic devices is an example of such transformation [9]. ICT can facilitate formation of local energy sharing networks coupled with RES known as microgrids, and its interconnected network structure to share electricity between microgrids. Energy consumers without RES are now enabled to hire their solar company [10] or license contractors to setup household RES through options like buy, lease, or loan. Policy frameworks such as open access to electricity distribution infrastructure provides platform for RES owners to participate in the local electricity markets. It is quite evident from the recent technological advancements and the literature that energy systems of the future would function more like an internet. Such a system can provide vast opportunities for energy end-consumers to produce, consume, sell, and store energy depending on their energy utilization practices. An energy system facilitating all such transactions would function like an Information Internet and is called an Energy Internet [11]. The Energy Internet is visualized as a system which can lead to complete transformation of the electricity system [12].

From an electricity system perspective, Energy Internet is a complex ecosystem that provides deep integration of advanced devices, and enables high penetration of renewable energy systems [13]. Transformation into this complex ecosystem system is constituted by three major factors, namely, energy systems, technology infrastructure, and business processes. In other words, Energy Internet integrates a wide spectrum of energy systems (large-scale, small-scale, variable, and base load power systems) with the support of advanced technology infrastructures. Such a system necessitates radical transformation in the business processes and service model [13].

The concept of Energy Internet is relatively new and its evolution into a functioning electricity system depends on integration of wide range of emerging technologies for communication, power flow, and money transactions [14]. Literature is just firming up, and it is still inadequate to systematically configure Energy Internet with its structure, features and functions especially in the context of transitioning electricity systems [15,16]. Literature so far is limited to exploring various technical and technological aspects of Energy Internet including energy markets. However, a clear direction on the implementation and operational aspects of Energy Internet remain a significant gap. Thus, there is a strong need for new research, and the objective of this study is to bridge this gap by conceptualizing a functioning Energy Internet for a transitioning electricity system. Specifically, it is proposed to explore Energy Internet's aptness as a future evolution of the electricity system, present its state-of-the-art, and its operational dynamics. This is the first study to propose an Energy Internet that is suitable for a transitioning electricity system with gradual adoption through replication and interconnection of small-scale energy sharing networks. Major contributions of this work are:

- an overview of Energy Internet, its current status, global context, and discussion on its aptness as a future electricity system;
- development of a conceptual model of Energy Internet and its features with a proposition for a novel seven-layer architecture model adapted from information internet;
- introduction of the concept of Energy Intranet to address the small-scale version of Energy Internet;
- conceptual description of relevant technologies and mechanisms of Energy Internet.

This paper systematically reviews the milestones in the evolution of Energy Internet and presents its conceptual model in the context of a transitioning electricity system. A novel model structure proposed in the study introduces the concept of 'Energy Intranet' and its relevance. In addition, a detailed discussion on the working and operational principles is presented in the paper. The rest of the paper is organized as follows. Section 2 presents the evolution of Energy Internet and its aptness as a future electricity system. In Section 3, the conceptual model of Energy Internet is discussed with various concepts, definitions and its features. Section 4 introduces the model structure of the Energy Internet. A detailed discussion on the mechanisms of Energy Internet is provided in Section 5. Discussions and way forward are presented in Section 6. Finally, conclusions are drawn in Section 7.

2. Energy Internet: The Beginning

2.1. Information Internet as the Cornerstone of Energy Internet

We believe that the transformation of legacy electricity system to an Energy Internet is expected to be like the evolution that took place in information internet. The evolution of internet started with ARPANET which was the private interconnection of computers used for military purposes [17]. Simultaneous evolution was witnessed in the computing technologies from centralized mainframe computers to personal computers (PCs) and to distributed computing systems like laptops and tablets. Distributed computing devices were interconnected through the internet to share information and resources [14]. Further, technology advancement had transformed to a fusion of parallel computing, grid computing, and distributed computing which was also known as 'cloud computing' to connect large scale storage devices and computing technologies [18]. Similarly, we expect Energy Internet to evolve through such kind of transformations where the traditional power system will be overhauled to adopt a new era of inter-connected storage devices, loads, and distributed generators with the support of ICTs. Thus, Energy Internet is a characterization of futuristic system of diversified prosumers, interconnection of multiple energy systems, electric vehicles and internet-based ICTs [13]. ICTs in Energy Internet support numerous renewable energy generators and electric vehicles, which require robust, flexible and decentralized energy management systems [19]. Albeit, Energy Internet is a mimic of information internet paradigm, its features like plug-and-play mechanism for fast integration of decentralized energy systems to the electricity transmission and distribution network, energy router for management of optimal power flow and communication, and grid intelligence for software coordination, distinguishes itself from the information internet [20]. Energy Internet is anticipated to work closely with the Energy 4.0 for the digital transformation in the energy value chain as an application of Industry 4.0 paradigm [21]. Projects such as Brooklyn Micro-grid [22], which works with blockchain technology for energy transaction, is a real-life example of how a close relationship with IoT and future Energy Internet is feasible. It can also be compared with the stock market or the consumer to consumer (C2C) business model [12] where energy is traded on a platform where sellers and buyers meet.

2.2. Energy Internet: Evolution, Current Status, and Global Context

The conceptual model of Energy Internet was systematically introduced by Rifkin [23]. Further, the model was reconceptualized by Huang et al. [24] through an in-depth discussion on the infrastructural aspects of Energy Internet architecture. The study presented a detailed discussion on the features of Energy Internet such as plug-and-play mechanism and energy routers. The possibility of developing an energy market using Energy Internet was explored at a later stage, which led to conceptualization of participants of the energy market such as energy cells, utility cells, and clearance house. Operational strategy of Energy Internet was proposed as a day-ahead energy market to facilitate interaction between energy cells [14,15]. Further, Si et al. [25] have proposed an Energy Internet model to optimally schedule energy flow between energy prosumers. They considered electricity and gas coupling model for residential and industrial prosumers participating in the energy market. Similarly, Hong et al. [19] have explored the possibilities of multi-energy micro-grid models for China. The model has been used to demonstrate potential of significant increase in revenue from Energy Internet based energy market over the traditional electricity business model. Next, an improved optimal control problem using deep reinforcement learning approach proposed by Hua et al. [26] is an example of applications of modern computing algorithms for Energy Internet.

Emergence of technologies such as smart grids, household storage devices, and vehicle-to-grid (V2G) has influenced the researchers to conceptualize Energy Internet to adapt to these transformations. Studies have explored the possibilities of optimal utilization of electric vehicles and its storage facility in an Energy Internet with micro-grid topology [19]. In addition, the development of blockchain technology and its capability to integrate into modern energy systems have been extensively studied in the recent literature [27,28]. The present study delves into the possibilities of blockchain technology facilitated Energy Internet to operationalize an energy market which makes use of electric vehicle batteries for energy storage.

The concept of Energy Internet is at its nascent stage and there are no working models of it at present anywhere in the world. Electricity system transitions observed in many countries are supported by smart grid infrastructure, which is a precursor to Energy Internet. Academicians across the globe are working towards proposing a tailor-made Energy Internet for their national electricity systems. Albeit, the word Energy Internet is widely used in United States and China, researchers around the world have recognized Energy Internet with similar characteristics but with different names. In Figure 1, we have shown countries actively researching in Energy Internet and the names they have assigned to the envisioned models.

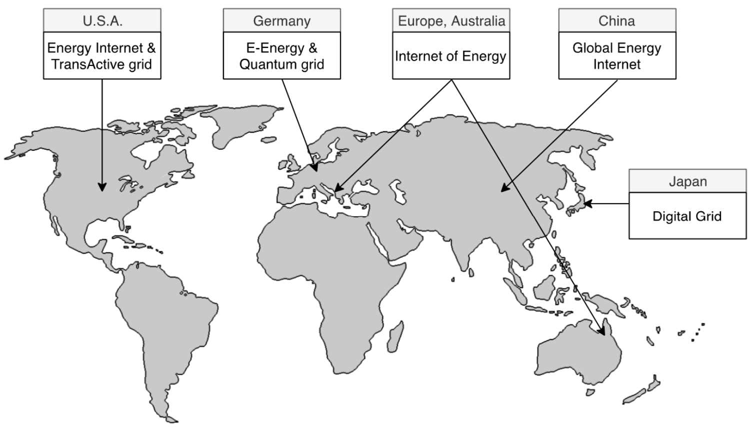

Figure 1. Energy Internet across the globe. Sources: [29–34].

Future Renewable Electric Energy Delivery and Management (FREEDM) systems center at North Carolina State University presented the key technologies required for Energy Internet architecture [24]. Later, the term TransActive energy systems came into existence with similar characteristics of Energy Internet [35,36]. Though the objective of Energy Internet and TransActive energy systems are to balance electricity demand and supply through energy trading in a renewable energy dominating system, the TransActive grid does not focus on internet like network infrastructure that witnessed in Energy Internet. In Germany, E-Energy is an initiative by the Federal Ministry for Economics and Technology (BMWi), and the Environment, Nature Conservation and Nuclear Safety [37]. The goal of E-Energy is to develop the existing smart grid system to integrate electric vehicles through ICTs and to optimize the energy system [38]. The Quantum Grid is an Energy Internet associated concept with a packet-based power transmission. The idea of Quantum Grid is like the transmission of data packets in internet. Here, power is transmitted as energy packets between the sink and the source in the chosen path determined by the routing algorithm controlled by Quantum Grid Routers [31,39]. Internet of Energy and Global Energy Internet are synonyms for Energy Internet. Researchers across the globe have identified that the Internet of Energy has similar characteristics as that of Energy Internet accepted by researchers in USA and China [40,41]. Global Energy Internet focuses on the worldwide network of Energy Internet which makes cross-border power trade possible [42]. Japanese version of Energy Internet is known as Digital Grid which envisions blockchain based energy market which is facilitated through Digital Grid Router [30].

Though Energy Internet is identified with different names across the world, the core idea of such system is the personalization, sharing, and interaction of electricity between consumers, generators, and prosumers [13]. Evolution of the Energy Internet is an ongoing process and every stage of evolution witnesses significant improvement from the past. The next anticipated stage of evolution is the provision of energy trading inside the Energy Intranet through a peer-to-peer energy trading mechanism.

2.3. Energy Internet: Aptness as A Future Electricity System

There are three types of interactive agents in an Energy Internet. They are; energy cells, utility cells, and clearance house. Individual residential consumers, small-scale commercial/industrial consumers or group of these entities are defined as energy cells. A typical energy cell can own local generation facilities, electric loads, storage devices, and electric vehicles. Tens of hundreds of such energy cells are connected to Energy Internet to trade-in energy, sell surplus energy to make profit or buy deficient energy. The physical connection in the Energy Internet is operated and maintained by the utility cell. Being a separate entity, utility cell provides ancillary services to maintain the stability of the electricity system. Clearance house gathers all the information regarding the demand, supply, and forecasts and performs market clearance algorithm to schedule the optimal dispatch order and to determine the market clearance price. Interactive agents in the Energy Internet are depicted in Figure 2.

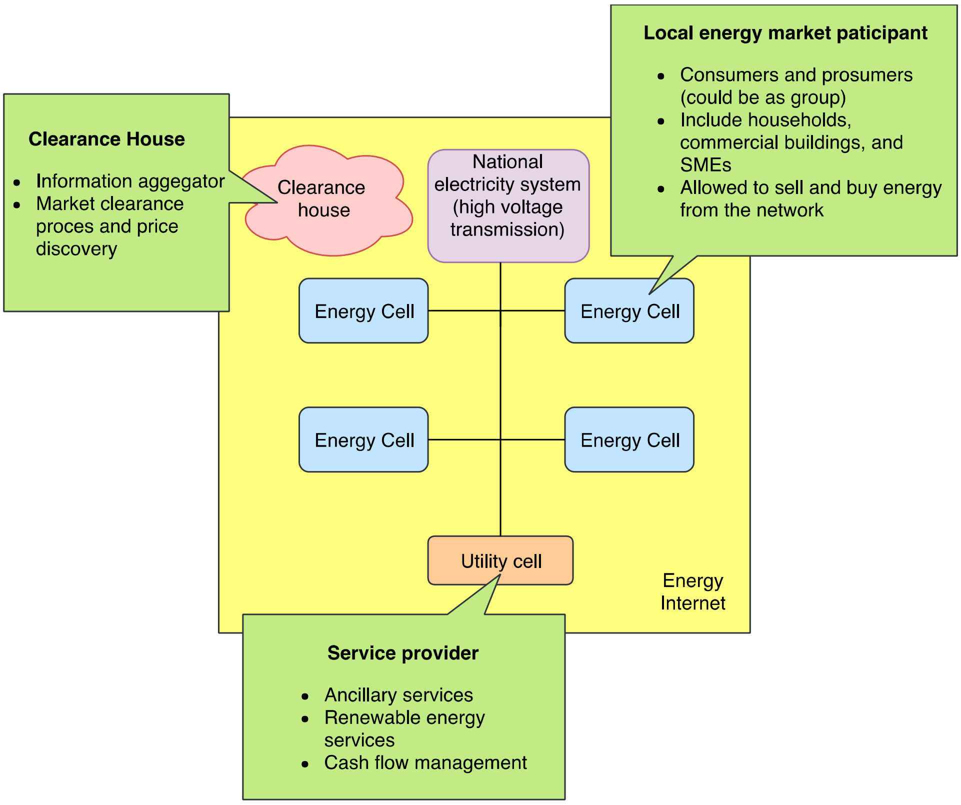

Figure 2. Interactive agents in Energy Internet architecture.

Energy Internet acts as a platform to sell and buy electricity for a prospective prosumer. It enables prosumers to sell surplus electricity generated from small-scale power generators (e.g., solar PV rooftop systems, small solar PV and wind generators) in a local energy market. All the participants (energy cells) in Energy Internet are rational entities, which act based on certain logic with conflicting interests in nature. Objective of the energy cells is to maximize their benefits subject to certain local and global constraints. Realization of such system would enable the consumers to improve their energy utilization patterns. Consumers would be aware of the methods to reduce energy consumption and to sell surplus energy to make income. Utility cells would be concerned only about operation and maintenance of the transmission and distribution infrastructure to enable reliable supply to the consumers through efficient technologies.

In this study, we have introduced a new concept called 'Energy Intranet'. The motivation behind introducing this concept is to bridge the gap in literature, which failed to address small-scale energy network systems, which have similar characteristics of Energy Internet. Introduction of this concept has taken a cue from the network of computers; we call them as internet and intranet. Internet is a global network of computers which provides various information and communication facilities through standardized communication protocols (TCP/IP) [43]. Similarly, intranet connects multiple computers for information and communication exchange, which is available only for the computers configured as a private network under TCP/IP or File Transfer Protocol (FTP). Intranets are used by organizations for secure exchange of information and communication without being exposed to the global internet.

While Energy Internet addresses nation-wide network of distributed renewable energy generators, loads, storage devices and electric vehicles, the small-scale networks with similar characteristics is introduced as Energy Intranet, and our proposition is to recognize Energy Internet as the network of Energy Intranets. We have depicted this concept in Figure 3.

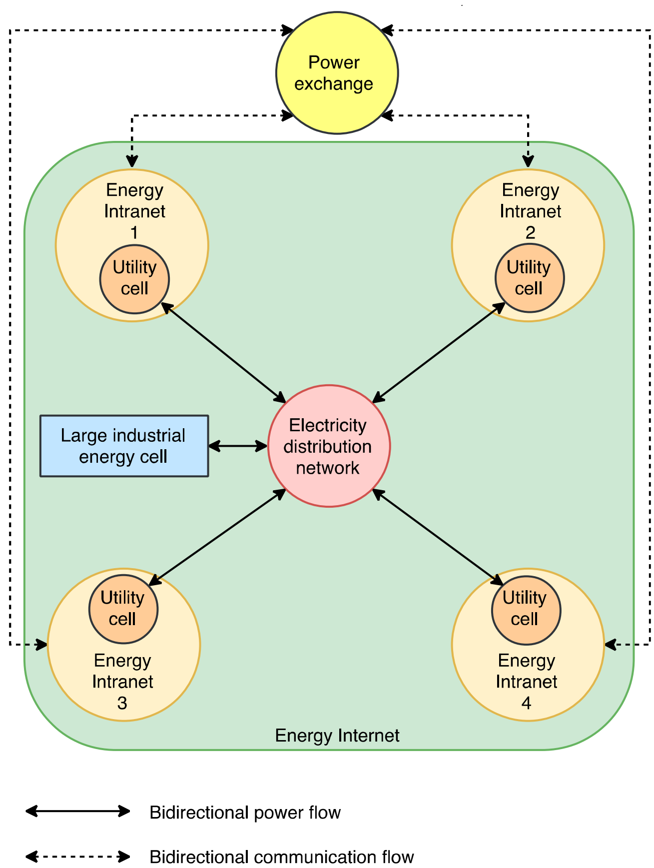

Figure 3. Energy Internet as the network of Energy Intranets.

This proposition for development of Energy Internet as a network of Energy Intranets is a decentralized way of technology adoption, which is anticipated to be faster than conventional centralized technology development projects. Design and development of easily deployable Do It Yourself (DIY) Energy Internet oriented devices will result in faster decentralized expansion of Energy Internet (e.g., Solar PV modules with built-in inverter).

3. Conceptual Model of Energy Internet

3.1. Concepts and Definitions

Evolution of computing and telecommunication technologies witnessed in the past three decades is the learning for the conceptualization of Energy Internet. The era of centralized computing infrastructure (mainframe) evolved into distributed computing technologies (PCs and cloud computing). Similarly, we believe that Energy Internet can be an outcome of a paradigm shift from the legacy electricity system and emerge as the future of electricity systems. The concept of Energy Internet has taken cues from the information internet, which is used by everyone for information exchange. Internet being a global network of computers which provides various information and communication facilities through standardized protocols such as TCP/IP [43] can become the backbone of Energy Internet. Energy Internet is much more than the information internet. Energy Internet integrates renewable energy systems, electric loads, storage devices, electric vehicles and transaction protocols through an internet like featured network structure to optimize the energy service delivery to the end-consumers [13,20,44]. The traditional legacy grid system is expected to undergo a network overhaul by the means of advanced technology devices to transform into a new era of interconnected energy systems.

Energy Internet has mimicked certain features of information internet such as plug-and-play mechanism, information routers, open source software platform, etc. [45]. However, Energy Internet distinguishes itself in terms of how the internet technology is applied for exchange of information, to facilitate bidirectional power flows and money flows. Figure 4 shows a comparison between features of internet network device and Energy Internet. Plug-and-play mechanism in the Energy Internet allows distributed renewable energy systems to couple and de-couple with the system without disturbing its energy balance. On the end-consumer side, energy router is equipped with solid-state transformer (SST) to cater to various energy needs of the consumer. Conversion of DC power generated by solar PV, and electric vehicle battery are performed by SST along with catering to various electrical loads connected to the system. Functioning of SST is like the Switch Mode Power Supply (SMPS) in a personal computer. SMPS supplies power to various components depending on the electrical specifications [24]. Software control of these are engineered to feature into a distributed grid intelligence system (DGI) which is an open source platform like Linux operating system (OS) in a PC. Various customizations are done by present day programmers on Linux like OS and can be replicated in DGI for better energy utilization and optimize operation of the system. Perfect example for open source software is Raspberry Pi which enables cost reduction of various devices in Renewable Energy Monitoring Systems [46]. Moreover, for hardware, the Arduino platform, which is used in SCADA systems [47] and electric vehicle charging stations [48], are considered as examples.

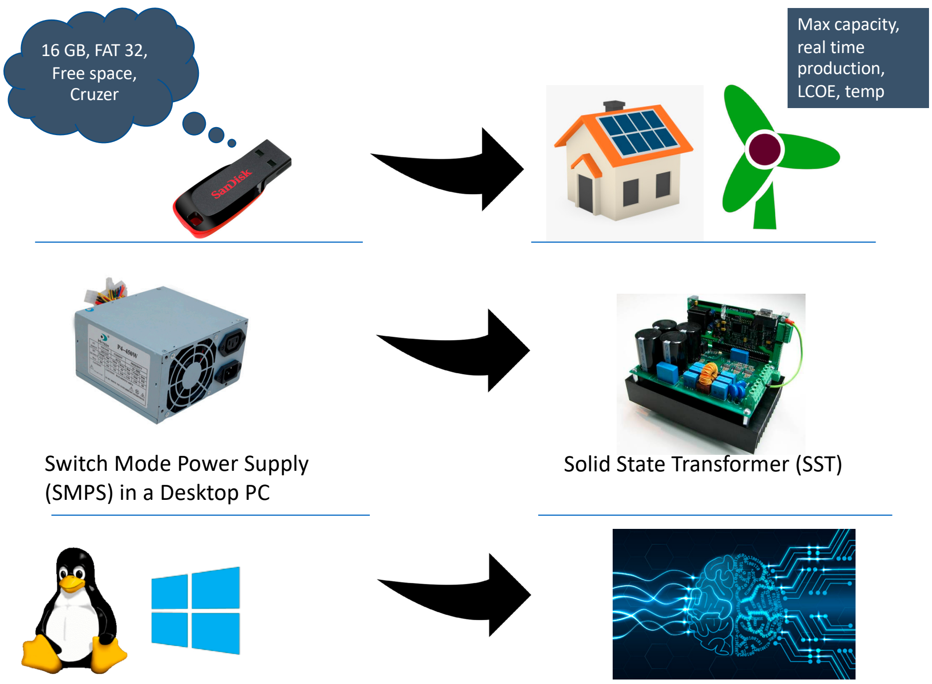

Figure 4. Feature comparison of internet devices and energy internet.

3.2. Energy Internet Architecture

Information internet is described using a seven layer architecture model known as Open Systems Interconnection model (OSI), a reference model developed by International Standards Organization (ISO) in 1978 [49]. OSI reference model is described as a set of series of layers with pre-allocated specific functions to the higher layers while shielding each layer from the details of services implemented in lower layers. The interface between the lower layers and higher layers defines the way the services are offered and accessed [49]. We have taken inspiration from the OSI model and structure of Energy Internet given in Zhou et al. [13] and Hong et al. [19] to define a new set of layers for Energy Internet architecture. These features of proposed Energy Internet architecture distinguish itself from that discussed in Zhou et al. [13] and Hong et al. [19]: (i) inclusion of microgrids which carry similar characteristics of Energy Internet and ability to trade energy. (ii) Peer-to-peer energy trading is introduced as a functional layer to trade energy among energy market participating prosumers.

(iii) Layers are connected hierarchically in terms of services. Further, set of all layers represents energy, information and money flows which other models fail to do.

Figure 5 shows the description of OSI reference model and our proposed Energy Internet model with seven-layer architecture. Each layer is connected in terms of services offered to higher layers.

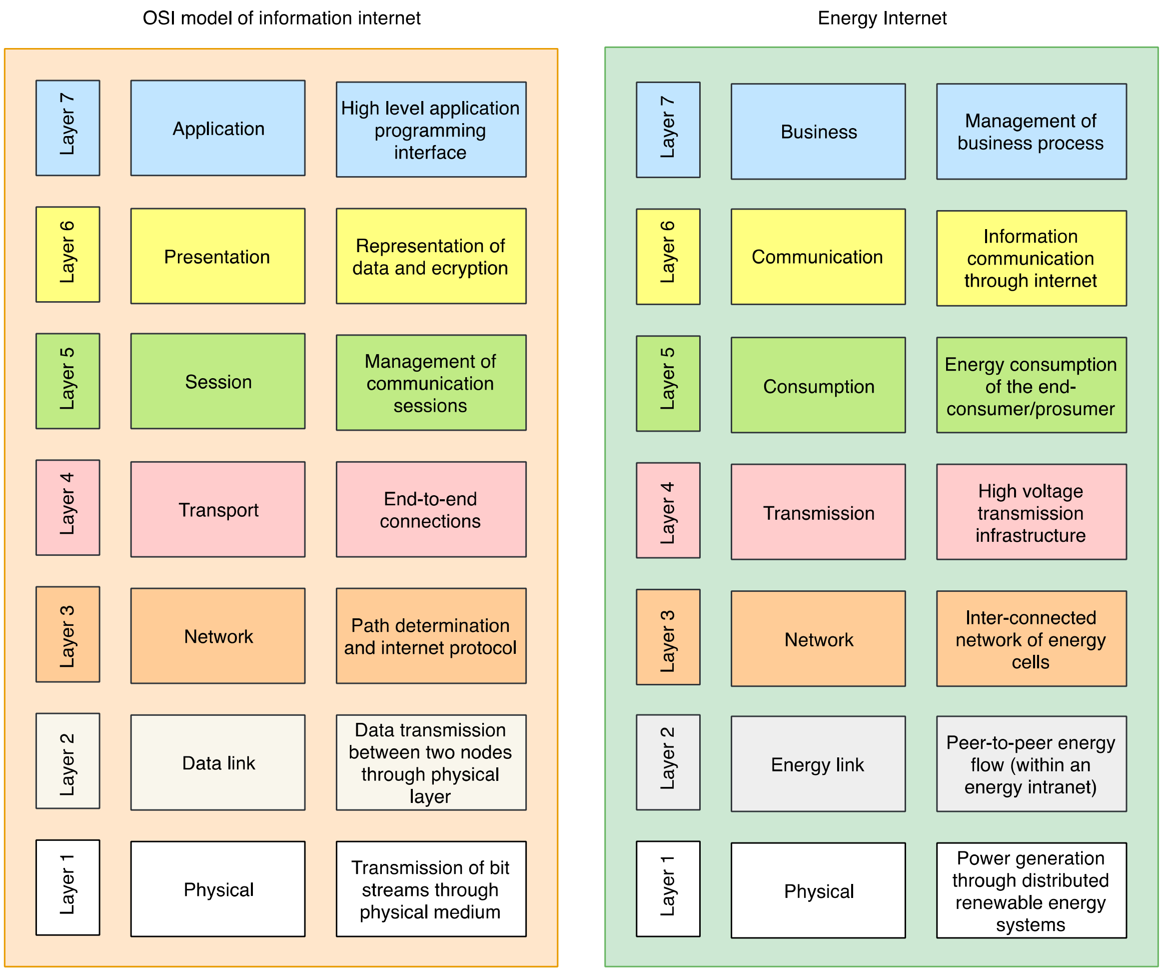

Figure 5. Open Systems Interconnection model (OSI) reference model and proposed seven-layer architecture. Source: OSI model [49] and Energy Internet Architecture (Authors' contribution).

The first layer is the Physical layer and it consists of electricity generators owned by energy cells. Both large-scale and small-scale electricity generators are part of Physical layer. Power generation from solar PV plants, standalone backyard wind electric turbines, fuel cells, etc., owned by energy cells are integrated into Energy Internet through the Physical layer, which is the base layer of Energy Internet architecture.

The second layer is the Energy link layer, which refers to the peer-to-peer energy-trading link between the energy cells in an Energy Intranet. This energy-trading framework is restricted to energy trade inside the Energy Intranet. The Energy link layer, which controls the peer-to-peer energy market, does not allow involvement of an aggregator, and whole trading process is controlled by the trading algorithm facilitated by the energy blockchain technology.

The third layer is the Network layer. Physical network of energy cells, to connect their renewable energy systems, storage devices, electric loads, and electric vehicles are addressed in this layer. Physical connections between the components are established using wires and power electronic devices. Energy router plays a crucial role in this layer to establish connections within the energy cell premises, and between the energy cells and utility cell.

The fourth layer is the Transmission layer, which consists of physical transmission network to transmit power between Energy Intranets in the Energy Internet. As Energy Internet is the network of Energy Intranets, and energy trade between Energy Intranets are permitted through high voltage transmission networks to transport power to remote networks. The transmission layer addresses the physical transmission infrastructure for such power transport.

The fifth layer is the consumption layer, which controls the energy consumption of energy cells. Energy cells consume power to operate their electric loads, and to charge storage devices, and electric vehicles.

The sixth layer is the Communication layer, which ensures communication between various entities, devices, and stakeholders in Energy Internet. Various communication protocols, such as internet (TCP/IP), Wi-Fi (IEEE 802.11 n/ac), Long Term Evolution (LTE), and upcoming 5G (IMT-2020), are part of this layer to provide communication channels between devices. Therefore, communication layer includes various sub-layers of internet (OSI model), and telecommunication and network architectures.

The seventh layer is a Business layer, which manages the business process of Energy Internet. Energy Internet consists of various stakeholders with the motivation to invest in technology infrastructures to generate power, to manage power flow through networks, to provide communication facilities, to address the customer grievances, and to manage financial services, such as instantaneous payments for the energy trade or option-based energy trade through counter. Interest of these stakeholders to invest in the business process is to make profits.

In summary, seven layers of Energy Internet can be grouped into three clusters. The first five layers control the bidirectional power flow in the Energy Internet. The sixth layer controls the bidirectional communication flow. The seventh layer controls the bidirectional money flow and other financial services from a business perspective.

The concept of the OSI layer has significantly contributed to the evolution of information internet (e.g., cybersecurity protocols). Similarly, the proposed seven-layer architecture is expected to serve as a framework to coordinate, design, and develop protocols for the Energy Internet. This would ensure the data security, standardization of software and hardware, and its interoperability. Unlike the OSI layer structure, which deals with transaction of data, Energy Internet architecture is a representation of energy transactions as a business process with bidirectional flows of energy, data, and money.

However, the major challenge in the context of the proposed architecture is the interaction of Energy Internet to the emerging technologies such as Internet of Things [50] and smart homes [51]. Physical components integrated with Energy Internet will be recognized with its unique identity and characteristics. Interaction of these integrated components may involve addition of new technologies to the Energy Internet. Such scenario can also lead to upgradation of existing features of Energy Internet as well. Thus, designing a unified architecture for the future needs is a challenge but, provisions for coexistence and interaction among other new architectures is certainly a possible solution [50].

3.3. Features of Energy Internet Adapted from Information Internet

3.3.1. Plug-and-Play Interface

The plug-and-play interface would be an open standard based interface for communication to recognize devices connected to the Energy Internet [52]. The plug-and-play mechanism is very similar to the instant detection and recognition of a USB device in a personal computer [20]. The set of processes that occurs after the insertion of a USB device in a personal computer will also take place in Energy Internet. Any device connected to the system, like loads, power generation facilities, and storage devices would be detected and recognized in the open standard algorithm.

The plug-and-play feature enables easy and fast coupling and decoupling of distributed generation systems, and storage devices. The presence of plug-and-play mechanism is crucial in an Energy Internet. Firstly, the plug-in process of distributed generator or storage device should take place automatically, and it should cause least disruption to the stability of the network system. Secondly, the unplugging of the distributed generator should stop its operation without affecting the stability of the network. Lastly, the system should recognize the module whenever it is re-plugged-in, as the converter topology differs for distributed generator and storage device, and it should connect with appropriate converter topology for smooth operation of the network [53,54]. Thus, to develop a perfect plug-and-play mechanism with associated converter topology to ensure the smooth operation of Energy Internet is an engineering challenge where research is ongoing [24]. In addition, recent research in IoT also lead to the concept of plug-and-produce which is an extension of the plug-and-play devices that are applied to industrial automation [55]. Energy Internet can have various automation systems with the plug-and-produce feature enabled for near-immediate implementation without any special tools or skilled expertise.

3.3.2. Energy Routers

Energy router is the Energy Internet counterpart of network router used in the information internet [56]. It does various tasks like status monitoring of connected devices, sending control reference command to various connected devices, voltage regulation, fault current limiting at the load side, restoration of voltage sag, and power factor correction [20,57].

Energy router separates various electrical parameters such as, voltage and frequency between the grid side and energy storage device or distributed energy system side. This is an important aspect of the Energy Internet system which provides improved stability to the system by decoupling the grid from low voltage side [58]. Energy routers are integrated with mechanisms to measure energy consumption, and other functions like remote load disconnection and load following [59].

Research and development on energy routers is very active but is at the nascent state. Research is going on to cover its architecture designs, functionality, and control strategies [60]. Most renowned version of energy router contains a solid state transformer (SST) for the conversion of electrical parameters [24]. Further, there are other prototype designs based on multilevel converters to provide flexibility in the grid operations at the active nodes [61,62]. Yet, the suitable design for cost effective commercial manufacturing of energy routers are not ready.

4. Model Structure of Energy Internet

4.1. Energy Intranet

'Energy Intranet' is a new concept introduced in this study. The term intranet is adopted from the intranet of computers, which is a private network of personal computers belonging to an organization, which is accessible only to the authorized users to prevent security breaches through global internet. Similarly, emergence of the term 'Intranet of Things' from 'Internet of Things' coined by Carlos Nizam of Airbus [63] is an example for corporate concern on data security and threats. The new term 'Intranet of Things' denoted the corporate assets accessible only within an organization of confined network boundary. The purpose of this new concept Energy Intranet is to address the small-scale networks, which have similar architecture of Energy Internet. The term 'Energy Internet' is used to denote the network of all Energy Intranets. Figure 6 represents the distinction between Energy Intranet and Energy Internet. The frontier of the term Energy Intranet is limited to a single network with a local energy market and energy cells as market participants. A micro-grid of household prosumers is an appropriate example for an Energy Intranet. In this case, all the energy cells could show similarity in energy demand and local energy generation potential. Flow of power and information by the energy cells is restricted within an Energy Intranet. This restriction is desirable while the energy trade is facilitated by a private blockchain.

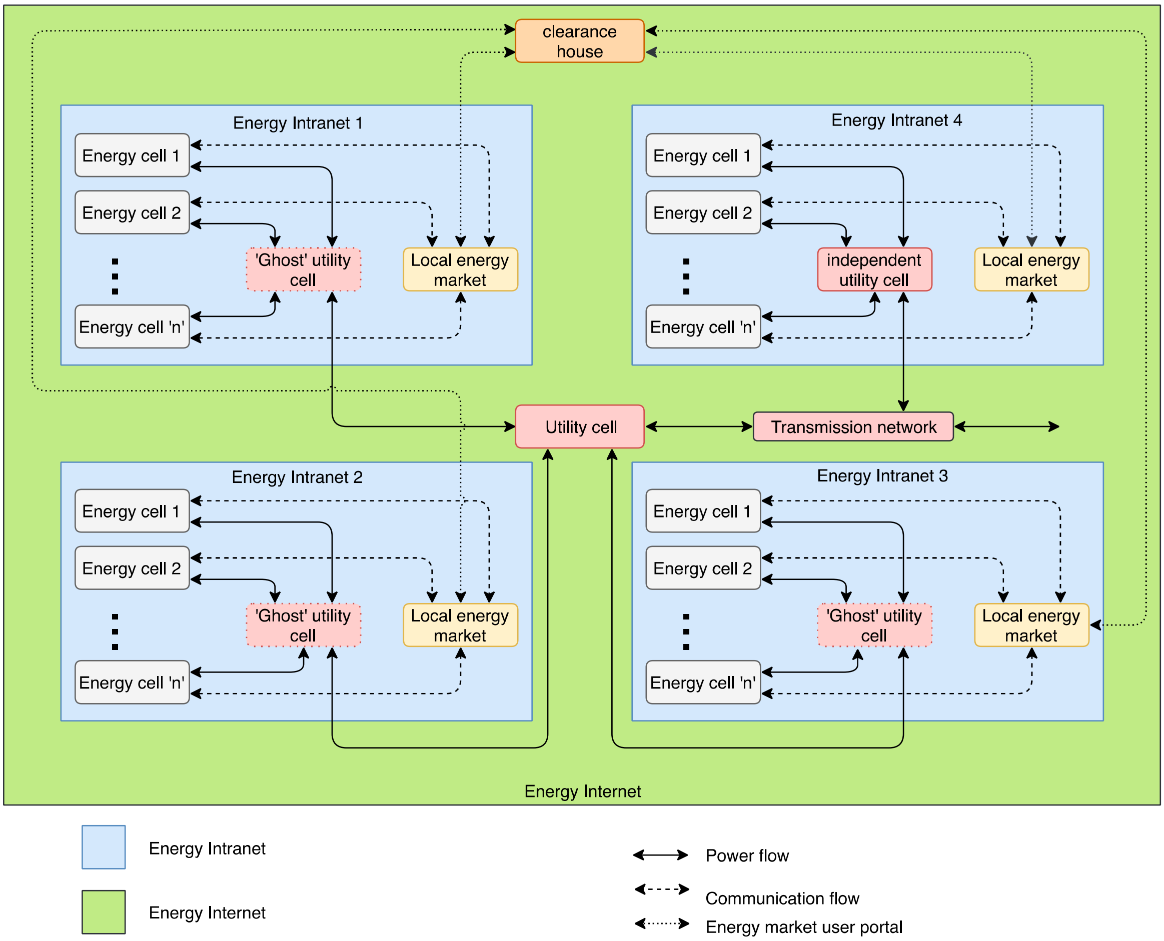

Figure 6. Structure of Energy Internet.

Energy Internet example shown in Figure 6 includes four Energy Intranets. Out of the four, three networks are managed by same utility cell and the fourth one is managed by an independent utility cell. Clearance house, which provides the computational infrastructure support for Energy Intranets through appropriate channels, preferably functions through internet.

Independent utility cell shown in Figure 6 represents a separate entity that manages the distribution network only for that Energy Intranet. In the case of 'ghost utility cell', the management of distribution network would be done by subsidiary utility cell owned by a parent company. This distinction is made depending on the ownership structure and network topology. This depiction is to represent the possible combination of Energy Intranets, which could be inter-connected in an Energy Internet. In that sense, an Energy Internet of a country may consist of millions of Energy Intranets.

4.2. Features and Modalities of Energy Intranet

The energy transactions in the proposed Energy Intranet consist of a day-ahead energy market and a real-time energy market. The day-ahead energy market operates to determine the optimal power dispatch schedule and market clearance price whereas the real-time energy market acts as a grid balancing mechanism formulated with a peer-to-peer trading market, which functions with the support of a private blockchain. Features and modalities of Energy Intranet are described as follows:

Local energy cluster as a self-sustaining network: Energy Intranet is a local energy cluster formed with similar structure of an Energy Internet. Unlike traditional grid, these local energy clusters can attract investments from its beneficiaries for the generation expansion and infrastructure development.

Such model of self-ownership for the self-consumption would improve the efficiency and effectiveness of the energy systems.

Power transfer between energy intranets are optional. That means, if an Energy Intranet is self-sufficient to meet its power demand with local generation at any given trading window then such Energy Intranets are self-sustaining which can operate without any power import or export from other Energy Intranets. Power transfer between an Energy Intranet and other networks in the Energy Internet is optional and dependent on the patterns of power generation and demand. The day-ahead energy market associated with the Energy Intranet is capable to set the generation and dispatch schedules, and to discover the optimal market clearance price, which makes an Energy Intranet to be self-sustainable.

Free entry and exit from the energy market: energy cells are entitled to participate in the energy market with a liberty of free entry and exit if they are not subjected to alteration in the optimal dispatch schedule. Energy cells equipped with local generation facility and storage may tend to utilize this facility. However, deviation from the day-ahead energy market dispatch schedule is not encouraged as it can affect the optimal dispatch plan. An energy cell shall opt-out from the energy market before the commencement of the trading window. In the real-time energy market, energy cell shall opt-out prior to the hourly market clearance process by notifying the absence of the participant. Such facility is utilizable by the self-sustainable energy cells with local generators and adequate storage capacity.

Large consumers as autonomous energy cells: Energy Intranet formed by the participation of small-scale consumers like household energy cells, and small commercial energy cells trade a fraction of power demand of large industries. In such cases, large consumers are excluded from the Energy Intranet of small-scale energy cells and such prosumers will be declared as autonomous prosumers to function as isolated energy cells. Large industrial and commercial prosumers with local generation facilities like captive generation or wind electricity turbine can function independent of Energy Intranet by directly connecting to Energy Internet as autonomous energy cells. Such energy cells can actively participate in the energy market by interacting with the Energy Internet.

Scalability: Energy Internet is scalable through interconnection of multiple Energy Intranets. Local Energy Intranets can be deployed over various geographical locations and interconnection between the Energy Intranets can be established to make a fully functional Energy Internet. Future expansion of the Energy Internet depends on the adoption and adaptation of Energy Intranets in the existing traditional power system.

Energy Internet, which consists of thousands of Energy Intranets, can address the variability issues associated with renewable energy sources. Multiple Energy Intranets spread over a large geographical location can address this issue effectively. Interconnected Energy Intranets can transfer power from surplus network to disrupted/deficit network. Thus, it can manage the variability, and intermittency issues by optimally managing the resources.

Bidirectional money-flow: energy cells as the participants in the energy market can utilize opportunity to generate profits by selling surplus energy generated by the local power generators. Such energy cells can even infuse more funds into the expansion of local generators to open a new source of income. Thus, whenever an energy cell imports power there would be a money out-flow and the power export will result in money in-flow. Money-flows in the day-ahead market are transacted through the clearance house, which performs the final bill settlement for the day-ahead market. Real-time market is a peer-to-peer trading market framework where the money-flow takes place directly between the seller and buyer. Peer-to-peer transactions eliminate the involvement of a third party for money transactions, which effectively reduces the price of the service. In the day-ahead energy market and real-time energy market, the bill settlement process is instantaneous. That means, as soon as the trading window is closed after power trading, the bill settlement for that particular trading window will be performed. In order to process this payment, internet based online payment platforms such as Unified Payment Interface (UPI), PayPal, and PayTM can be used. Users can set automatic payment options for hassle free instantaneous payment services.

Utilization of renewable energy resources and network assets: local micro-grids, which are part of Energy Internet, integrate the distributed generation (DG) systems owned by energy cells. Rooftop or stand-alone DG systems deployed in the backyard are compatible with the local micro-grids. Such bottom-up approach towards DG systems deferring the investments [64] results in maximized utilization of renewable energy resources [65,66]. Further, expansion of DG systems lessen the investments in centralized power plant based technologies such as nuclear and coal [67]. In addition, it reduces network maintenance investments [68]. However, in rural areas where the network infrastructure is weak, additional investment in transmission and distribution infrastructure would be necessary [69].

4.3. Network Structure of Energy Internet

As stated earlier, there are three major types of entities in the Energy Internet. They are, Energy Cells, Utility Cells, and the Clearance House [14,15]. In this section, we have conceptualized these entities in detail. Any attempt to categorize energy cells in this way has so far not been reported in the literature, but to capture all stakeholders of power sector we believe, this categorization is essential. Figure 7 shows the network structure of Energy Internet.

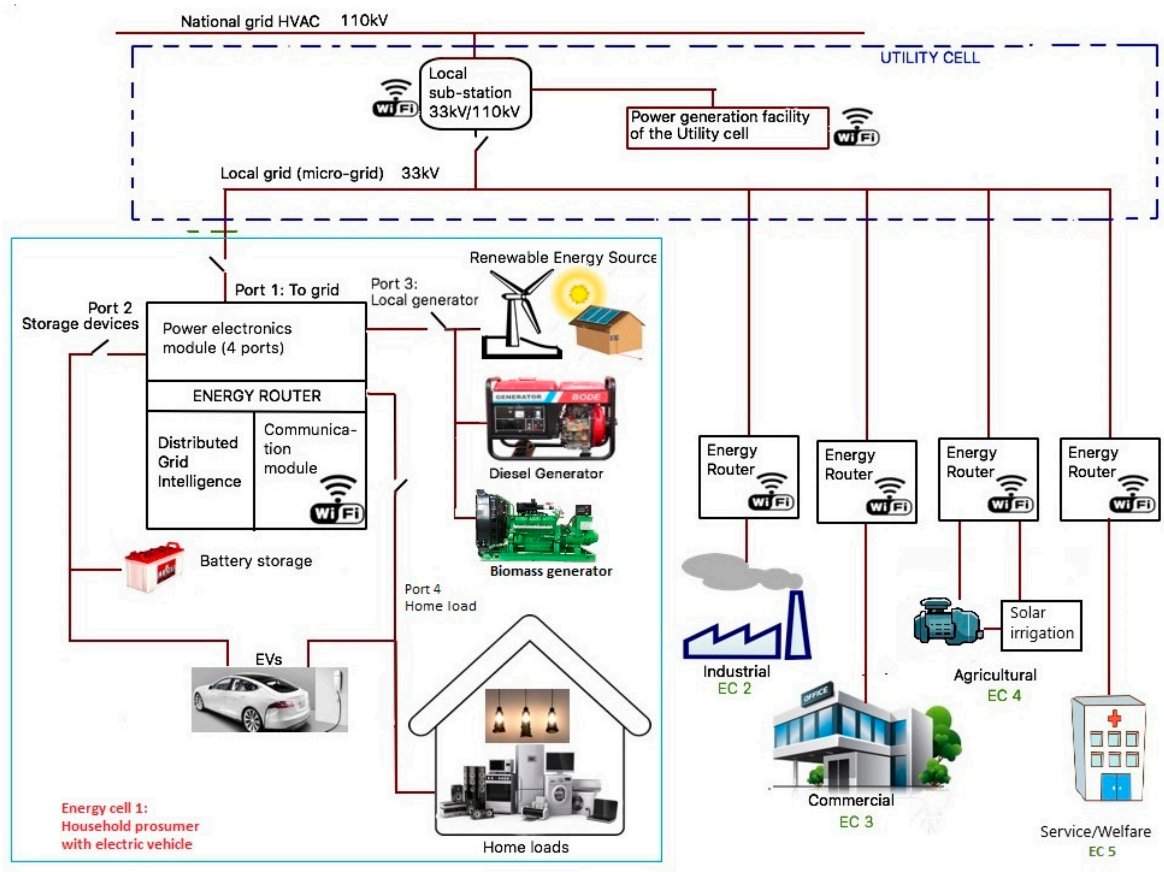

Figure 7. Energy Internet network structure.

4.3.1. Energy Cells

Energy cells are rational decision makers whose primary objective is to maximize their own benefits subject to various local and global constraints [15]. The local generation and load demands by the energy cells are predictable and forecastable [70]. There are four types of energy cells possible in the envisioned Energy Internet to represent all the types of prosumers, producers, and consumers in the power system. Depending on the nature of power generation and power consumption, the categorization has been done. It is assumed that, energy storage devices could be integrated with the energy cells based on the user preference. Energy cells are expected to take rational decisions regarding the utilization of storage devices. There are four types of energy cells conceptualized in this study.

Type I Energy Cell: Prosumers with Dominant Consumption

There could be energy consumers with local power generation facilities like solar rooftop systems, small wind electric generators (WEG), or biomass power plants, which could be used as major supply or backup supply along with the grid connection and storage devices. These types of consumers fall into Type I category, if they significantly consume power from grid apart from smaller contribution from local generation. The interest of the prosumers would be conflicting in nature. However, a rational consumer would try to minimize their own demand and will try to inject more power to the electricity system to make profit [12].

Type II Energy Cells: Producers with Minor Consumption

Like Type I energy cells, this type of energy cell consists of electric loads and local power generators. Type II energy cells try to capture the characteristic of a typical consumer whose local generation is more than their own electricity consumption. Industrial consumer with captive generation facility is an example of this type of energy cell. The objective of this type of energy cell is to consume power at the cheapest rate, and to sell maximum power from the local generation facility at peak rates. For an industrial consumer, if the cost of production is low, rather than keeping the plant idle and incurring monetary losses, injecting power to the electricity grid by participating in the energy market would be gainful.

Type III Energy Cell: Pure Consumers

Energy cells that only consume power available from the Energy Internet are categorized into type III energy cells. These energy cells will not own any local power generators. There could be two sub-categories to the type III energy cells, namely dispatchable loads, and non-dispatchable loads [12]. Dispatchable loads could be of residential consumers or certain industrial and commercial customers who can voluntarily shift their demand for a certain period. Non-dispatchable loads are critical loads where shift in power demand is impossible [12,14].

Type IV Energy Cell: Pure Producers

Energy Cells that consist of local generators, capable of generating and injecting power to the grid or Energy Internet, are categorized under type IV energy cells. The objective of type IV energy cells is to sell their power to make maximum profit.

Table 1 presents the summary of all the types of energy cells with their respective examples and objectives.

Table 1. Types of energy cells.

Type	Configuration	Example	Objective
I	Major consumption and minor production	Residential consumer with rooftop Solar Photovoltaic	Minimization of consumption cost
II	Minor consumption and major production	Captive power plants	Maximization of generation and serve the critical loads
III	Dispatchable load	Industries,	Minimization of cost by maintaining certain level of comfort
	Non-dispatchable load	hospitals	Maintain the service to critical loads
IV	Distributed generator with storage	WEG, SPV, storage devices	Additional income by surplus power sales. Maintenance of certain comfort level

4.3.2. Utility Cells

Utility cells facilitate electricity transaction between energy cells by providing physical infrastructure like wires, poles, and associated devices like transformers, smart energy meters, etc. Apart from this, utility cells also provide ancillary services like voltage regulation, load following, scheduling and dispatch, reactive power compensation, and loss compensation. It is assumed that utility cells can own and operate power plants, and they can participate in the power market [14,15]. However, utility cells are forbidden from possessing any market authority and regulations in the energy market. When utility cells participate in the energy market, it will be considered as a participant like any other energy cell. The primary mission of the utility cell is to maintain power balance in the network. That means, if the demand is more, and the supply from energy cells are not adequate, then utility cells shall inject power to the grid to maintain the stability. In addition, utility cells can generate revenue by renting out the distribution assets for the power distribution. The fee charged for this facility is the major income source for the utility [12].

4.3.3. Clearance House

Market clearance through preparation of dispatch schedules and price discovery are the major roles of the clearance house. The clearance house will gather information on forecasted demand and supply, and cost of electricity generation from various sources. By using an appropriate algorithm, the final market clearance price would be determined. The clearance house is a functional entity that acts independent from the influence of energy cells and utility cell [14]. In a national electricity system context, clearance house can be like energy exchanges.

4.3.4. Other Stakeholders and Institutions of Energy Internet

A national level electricity system is a composition of various stakeholders. These stakeholders play significant roles in supporting the electricity system as an important commodity service providers and business managers, which are essential for the growth of any country. Figure 8 is the depiction of various stakeholders which interact within the national level electricity system (Indian electricity system is used as an example).

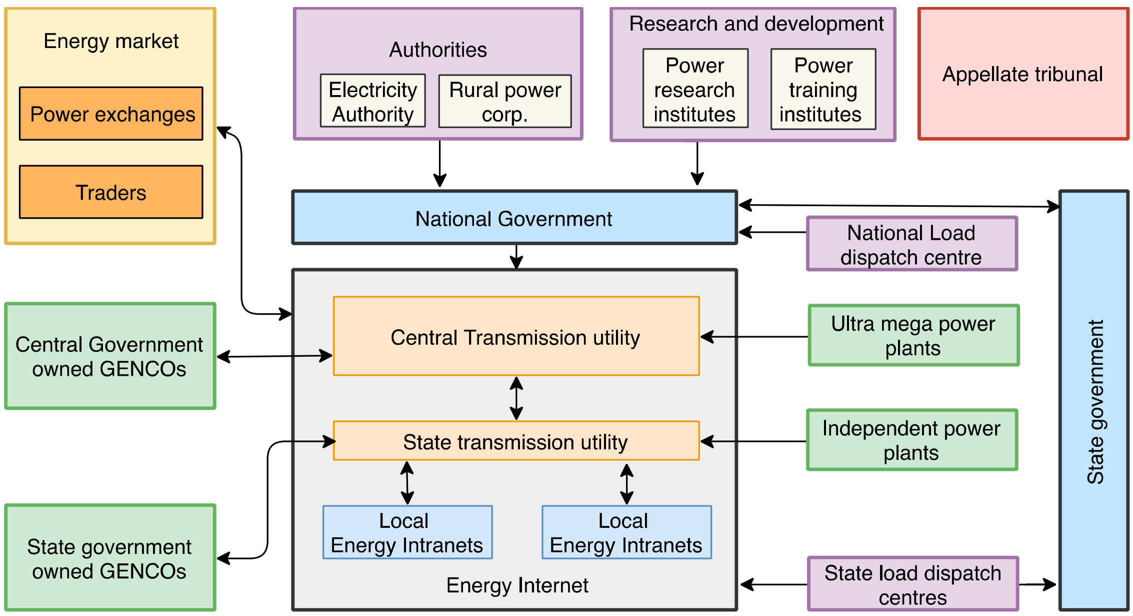

Figure 8. Proposed industry structure with Energy Internet.

Energy Internet infrastructure interacts with stakeholders who provide power, information, and financial services. In Figure 8, entities represented in green box represent the electricity generators outside the Energy Internet infrastructure, which transacts with the system by supplying electricity. These entities can be of publicly owned (national or state governments) or privately owned power plants. Entities in blue box (with black border) denote the government bodies that provide the legislative framework for smooth functioning of Energy Internet. Purple boxes represent agencies that provide policy and regulatory information to the electricity system. Purple box also represents the research and development agencies working with the electricity system. Energy market represented by the orange box consists of two entities namely, power exchanges and energy traders. Power exchanges are anticipated to provide the computational infrastructure for the functioning of energy market facilitated by Energy Internet. Apart from the exchange, there are power traders who support power trading activities such as short/medium/long time trading, cross boarder trading, and energy certificate trading [71]. Appellate tribunal for electricity is the entity which holds the authority to solve disputes between central/state regulatory commissions and consumers [72].

4.4. Relevant Technologies for Energy Internet

4.4.1. Electricity Generation and Storage Technologies

Energy Internet can foster the deployment of renewable energy sources to the electricity system by providing plug-and-play feature and a robust infrastructure which can address the variability and intermittency issues [14,24]. Small-scale consumers can take advantage of the plug-and-play feature to invest in renewable energy systems to connect their local power plants to the Energy Internet. By connecting to Energy Internet and participating in the energy market consumers as energy cells can generate revenue by selling surplus power to the consumers in need.

Prominent electricity generation technologies, which can be used by the participants of Energy Internet, are solar PV, wind electric turbines, and micro-hydro turbines. For rooftop applications, solar PV based on crystalline photovoltaic is highly recommended due to reduced cost, availability, and simplified technology. The Solar Rooftop project launched by Elon Musk at Tesla [73] is a perfect example for future innovations in rooftop technology. Musk's project focuses on providing efficient solar rooftop tiles, which can be installed at every slanting rooftops without affecting the aesthetics of the home thereby utilizing maximum space available. Similarly, small horizontal and vertical axis wind turbines with low noise are available in online e-commerce platforms (price of $150 onwards). Household consumers can procure the turbines and install it by themselves at their premises (DIY devices). An innovative turbine design by the start-up called Turbulent [74] has brought fish friendly low head (1.5 meter) low-pressure turbine (15–100 kW) which works based on the power of vortex created using canals. This system can be installed in cascade formation in a canal, or separately on the bank of the canal. Fuel cell is also an emerging small-scale renewable energy technology. Hybrid configuration of fuel cell with renewable energy technologies are widely acceptable model of small-scale energy production [75]. Further, application of solar water splitting in hydrogen storage and similar technologies have wide scope in Energy Internet [76].

Another important aspect is the storage technologies. Storage devices are integral part of any renewable energy dominated electricity systems to manage the variability and intermittency issues. The proposed Energy Internet can function without any static storage devices, and electric vehicle batteries are integrated into the system to substitute stationary storage devices. However, that may not be the case everywhere. In such cases, dependence on stationary storage devices such as lithium-ion or lead-acid batteries become inevitable. Recently, many well-known car manufacturers and equipment manufacturers started providing solar panels and batteries as a package for the customers. Tesla Powerwall, LG Chem Resu, xStorage by Nissan, etc., are available for easy installation (price of battery > $4500).

4.4.2. Information Communication Technologies

With the advent of 5G mobile communication technology, which targets at high data throughput, large number of devices connecting with reduced latency and energy consumption are expected to serve as the base communication channel for Energy Internet. The technology infrastructure of Energy Internet is based on energy router, which we have already discussed in Section 3.3.2.

The energy router communicates with other energy routers to aggregate information on electricity generation, demand, available storage capacity, etc., to optimize the power flow in the Energy Internet. Robust communication technologies such as 5G wireless communication can function with IoT infrastructure for low latency information transfer.

The real-time peer-to-peer energy market proposed in this study makes use of hourly data. This time resolution can improve further by taking 15-minute trading window or lesser. Increase in time resolution leads to multi-fold volume of data generation, which requires addition of computational infrastructure. On the other side, consumers will be provided with user-friendly applications to control the parameters and features of Energy Internet through their portable devices like smart phones and iPads.

4.4.3. Blockchain Based Energy Trading with Bidirectional Money-Flow

Energy market based on Energy Internet can provide instantaneous and bidirectional money-flow. This denotes the payment processed for energy consumed from buyer to seller, which takes place towards the end of a particular trading window. Direction of power flow can vary depending on the power sale position of the seller and buyer. Our study proposes integration of blockchain technology [77] to enable instantaneous money-flows. Blockchain technology provides decentralized record of transactions which are authenticated cryptographically [78]. In an energy blockchain, this decentralized record (ledger) would contain the transaction records of the peer-to-peer energy market [79]. This transaction record would represent both the price and quantum of energy trade. Such way of keeping the records through distributed ledger would eliminate the need for a third party to facilitate the transaction [80]. In addition, the transaction records are transparent, and any user can access them. However, privacy of every consumer is maintained by making the consumers anonymous [22]. Integration of modern payment technologies such as unified payment interface (UPI) and wallet services, such as PayPal and PayTM, can facilitate this instantaneous payment. Detailed working principle of blockchain based energy market has been discussed in upcoming section of this paper.

5. Mechanisms of Energy Internet

The mechanism of Energy Internet can be elaborated based on Figure 7. The energy router, which is a four-port device connected to the consumer, is the important device in an Energy Internet. It consists of communication module, power electronics module, and an open software intelligence module. Four ports are connected to the electricity grid network, electric loads, storage devices, and local energy generators. Energy router gathers information on the local power demand, generation, and available storage capacity and passes it to the clearance house for energy market clearance process. Based on the local energy generation, energy router acts to feed electricity to the network or to the storage devices. It can also isolate an energy cell from the Energy Internet whenever there is a need [24]. Depending on the price of electricity at the grid, the electric vehicle owner will make a decision, either to charge or discharge the electric vehicle to sell energy in the energy market. Throughout the energy market clearance process, the number of energy cells participating in the clearance process will remain same [14]. Each energy cell is a rational entity that tries to maximize its own profit by economically managing its local generators, electric loads, and storage devices including electric vehicles. Thus, decision of each energy cell affects the market clearance price of the energy markets [14]. Energy cells are allowed to form coalitions by sharing their private information regarding the energy demand and local electricity generation [15]. However, study of such coalition formation is not under the scope of this research.

Further, discussion about the mechanism of energy internet is presented in terms of working principles and operational principles. Working principles discuss how exactly the energy internet works in a national level electricity system. Whereas, operational principles discuss the operational strategies which stakeholders are bound to follow.

5.1. Working Principles

Energy Internet conceptualized in this study consists of two types of energy markets. First, is a day-ahead energy market and second is a real-time energy market. In a day-ahead energy market, based on the forecasted demand and supply of electricity, market clearance price and quantum of power trade are computed. In order to forecast the electricity demand and supply, the information aggregator will gather data on electricity demand of energy cells and electricity supply from local renewable energy sources, and utility cell owned power plants. The energy market clearance algorithm will make use of this data to determine energy market clearance price and the optimal quantum of energy, which will be traded by energy cells. Dispatch schedule of the generators will be decided based on the day-ahead market clearance algorithm. Any deviations in the actual day of consumption from day-ahead market forecasts will be balanced using a real-time energy market.

Real-time energy market mentioned in this study is a peer-to-peer energy market, which operates based on energy stored in electric vehicles connected to the Energy Internet. A threshold price of electricity fixed by the consumers is set as a benchmark for deciding whether to charge or discharge the electric vehicle. The tendency of an energy cell to sell electricity while it is expensive and consume while it is cheaper is captured by providing necessary freedom to the consumer to set a threshold price. Considering this willingness to charge and discharge, electric vehicle battery would be the criteria for selection of buyers and sellers in the peer-to-peer energy market. By providing such kind of platform—for the electric vehicle owners to sell electricity by discharging the electric vehicle battery through a vehicle-to-grid program—it will reduce investments and expenses on static storage devices.

The real-time peer-to-peer energy market clearance algorithm will determine the optimal dispatch order and market clearance price for each trade. This transaction detail can be plugged-into a private energy blockchain to facilitate instantaneous payments. Modern mobile payment technologies such as mobile wallets and unified payment interface can perform instantaneous payments at the end of each trading windows. In addition, the blockchain based peer-to-peer energy market does not need any third party as an entity to facilitate the trade.

Figure 9 represents the four-step process of real-time energy market clearance between a seller and a buyer. In the first step, buyer will send a request to the seller to invoke the smart contract to sell power. Seller would respond to this request by confirming the power sale agreement in the second step. In the third step, power flow will take place between the seller and buyer throughout the duration of the trading window. In the fourth step, the trading window will be closed and payment from the buyer to the seller will be executed. This transaction record will be added as a permanent block of an energy blockchain.

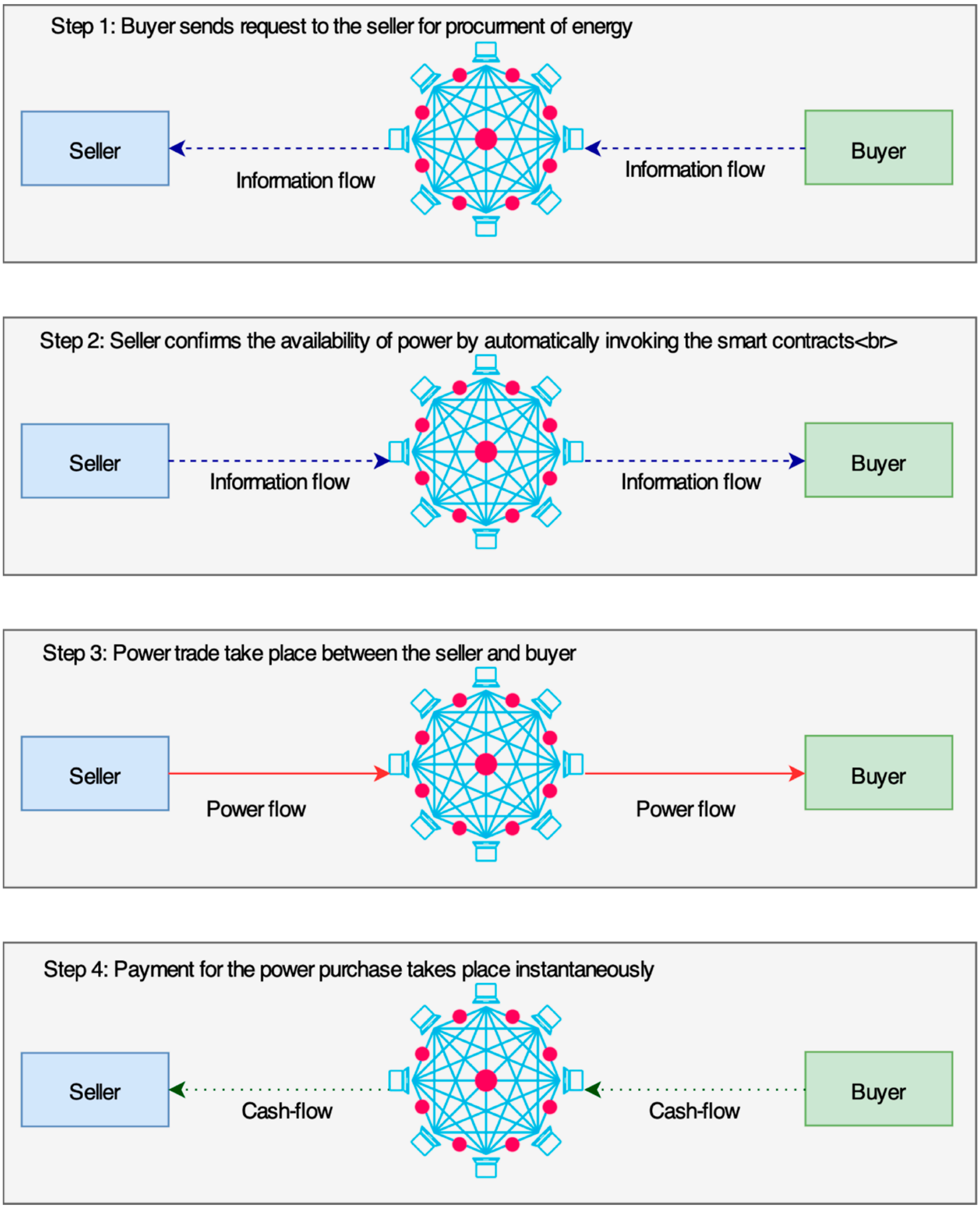

Figure 9. Step-by-step clearance of real-time blockchain based energy market.

5.2. Operational Principles

As we have discussed earlier, Energy Internet is a network of Energy Intranets. Prosumers in the Energy Intranet can meet their power demand by local generation facility. However, export of surplus energy generated or import of additional energy to meet the demand can be performed only through the energy market framework formulated for Energy Intranet, which the respective energy cell is connected to. That means, participation in the Energy Intranet prohibits an energy cell from a bilateral trade with another energy cell by bypassing the market framework. In addition, the capability to export or import energy by an energy cell in the Energy Intranet is limited to the confined boundary of network specified by the utility cell.

The boundary of the Energy Intranet and size of an energy cell are decided by considering various factors such as; topology of the network, peak load of each consumers, ownership status of the distribution infrastructure, local generation capacity, etc. However, an energy cell does not hold the privilege to sell electricity to any other energy cell or Energy Intranet by bypassing the market framework of the incumbent Energy Intranet.

Size of an energy cell can vary from a single household prosumer/consumer to a coalition of multiple number prosumers/consumers. For example, an Energy Intranet established in a hybrid apartment and a villa complex can have multiple energy cells. Household consumers in a multi-story apartment building can form a single energy cell. Whereas, villas with rooftop solar PV can be individual energy cells. In addition, if a set of inhabitants has contributed for the construction of a wind electric turbine, then the turbine can be another energy cell. In this case, erection, operation, and maintenance of the distribution infrastructure is done by the project developer and the only stakeholders are the residents in the housing project. In such cases, utility cell is a separate entity. Energy Intranets in an Energy Internet can trade power between the networks. It allows the large-scale entities to remain as autonomous energy cells to integrate directly with the national level energy internet rather than connecting to a low voltage energy intranet.

Another aspect of the operational principle to be noted here is regarding the time of computational exercise of day-ahead market and real-time market. Figure 10 represents the operational timing of the energy markets. The day-ahead energy market computational algorithm is done one hour before the mid-night of the actual day of energy consumption (day zero). This computation is solely based on the forecasted demand, and supply values. The algorithm will publish the dispatch schedule and market clearance price before 12:00 a.m. of the actual day of the consumption and information will be broadcasted to all energy routers and, thereby, to all energy cells. On the actual day of consumption, the real-time balancing energy market will operate on every trading window (hourly trading window in this study). That means, the energy market clearance process will repeat itself to balance the deviations from the forecasted demand and supply (orange blocks in Figure 10) throughout the day.

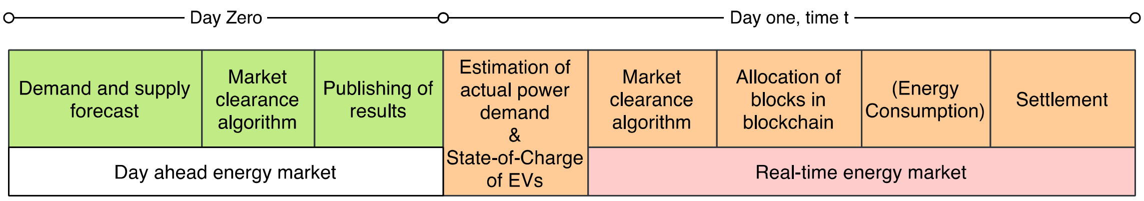

Figure 10. Example of processing a Day-ahead energy market and Real-time energy market.

6. Discussions and Way Forward

Evolution of Energy Internet as an energy-sharing network of distributed energy systems coupled to the local energy grids, and is like the evolution witnessed in the computing infrastructure. Energy Internet as conceptualized here is a scalable model, which can be integrated into an existing national electricity system. However, considering the size and complexity of a typical national electricity system, it is arduous to predict success in terms of complete and momentary integration. Therefore, the ideal proposition is the co-existence of Energy Internet and legacy system at least in the medium-term. Based on the learnings from the integration process, gradual changes in the integration planning can be made. Future research can explore the possibilities of transformation from current utility-based business perspectives to commercial association of numerous microgrids interconnected Energy Internet. Such research may attain multidimensional pathways. For example, techno-economic pathway for enhancement of economic operations and engineering & development pathway for production of commercially viable Energy Internet oriented devices.

In addition, there must be stimulations in the energy industry in terms of innovations in the business models. These stimulations can be in the form of allocation of spaces for entrepreneurial activities, optimization of financial channels, and emergence of novel financial-energy products [81]. It is desirable to minimize governments' role and control in this space. However, governments must provide the policy frameworks to support such futuristic energy innovations.

Identification of prospective action agents and their roles are necessary to effectively enable transition to Energy Internet from legacy electricity system. Major action agents that have stakes are—conventional power plants, distribution networks, electric vehicle manufacturers, and consumers. Conventional power plants need to prepare their short-term and long-term action plans to trade in energy market. This may include processes like revocation of existing power purchase agreements or implementation of efficiency improvement programs. Next, distribution networks and their business model need structural changes to embrace the 'utility cell' concept. Legacy power distribution networks are required to bifurcate into two entities, namely, carriage (infrastructure) and content (injection of power) businesses. In such a scenario, the present distribution business owners will have to formulate strategies for treatment of existing power purchase agreements, electricity losses, financial labilities, etc. Further, electric vehicle manufacturers are expected to provide essential features in electric vehicles to enable vehicle-to-grid mechanism, which integrates electric vehicles to Energy Internet. Few of the essential features are: (i) on-board vehicle-to-grid control system with embedded energy meter, (ii) devices to communicate vehicle battery status with the information aggregator, and (iii) charging device that can facilitate bidirectional power flow. Further, urban and rural energy consumers need to overcome the apprehension over the new technology infrastructure and pricing mechanism. In order to effectively involve these action agents, management of regulatory and technological transformations is the key action measure. Regulatory body oriented and human judgement-based regulation process have to give way to internet- and big data-based artificial intelligence-oriented supervision and regulation system. This indeed requires a technological transformation which in turn need addition of multidisciplinary complex talents [13]. Finally, communication protocols between heterogeneous devices and software integrated in the Energy Internet play a crucial role in data and information sharing [82]. In order to ease this challenge of standardization and interoperability, coordination between various agencies across the globe is an essential function.

7. Conclusions

The future of Energy Internet is bright because of integrability of emerging technologies, increasing focus on distributed renewable energy systems and its applications in energy sharing networks. In this is paper, we have presented the Energy Internet as a future evolution of a transitioning electricity system through in-depth discussions on conceptual model, model structure through introduction of new concept called Energy Intranet, and mechanisms of Energy Internet. We foresee that, given the presence of vast opportunities, there will be appropriate revisions in policies and regulations to enable transformation of legacy grid-based electricity systems into Energy Internet. The current initiatives suggest there will policy impetus for promoting electric mobility, energy storage devices, electronic payments, and emerging technologies such as blockchains and vehicle-to-grid. Findings from this paper emphasize on coexistence of Energy Internet and legacy grid in the initial stages and then gradual scaling-up of the Energy Internet at a national level leading to disruption in the whole electricity industry. All these can lead to a radical shift in the way electricity is produced, transported, and consumed.

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