IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 5, 2020, accepted November 21, 2020, date of publication November 27, 2020, date of current version December 11, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3041031

Smart Grid to Energy Internet: A Systematic Review of Transitioning Electricity Systems

AKHIL JOSEPH[1,2] AND PATIL BALACHANDRA[2]
[1]Experimental Power Grid Centre, Energy Research Institute @ NTU, Nanyang Technological University, Singapore 627590
[2]Department of Management Studies, Indian Institute of Science, Bengaluru 560012, India

Corresponding author: Akhil Joseph (akhil.joseph@ntu.edu.sg)

ABSTRACT The concept of Energy Internet has emerged from the limitless possibilities of energy sharing networks formed by interconnection of electricity producers cum consumers (prosumers) with renewable energy sources/systems, electric loads, and storage devices. Energy Internet represents a radical transformation of traditional electricity system by orchestrating real-time bidirectional power, communication, and money flows. This transformation is expected to be resultant of ongoing renewable energy transitions and evolution in the energy technologies such as smart grids, storage devices, vehicle-to-grid, etc. Energy Internet will rely on wide spectrum of Information and Communication Technologies such as Internet of Things, Artificial Intelligence, Blockchains, Payment Interfaces, etc. These technologies have achieved a state of evolution to facilitate seamless bidirectional flows in the Energy Internet. This paper has attempted to study the aptness of Energy Internet for a transitioning electricity system by focusing on national electricity systems across the globe. Firstly, study delves into discussion on studies related to smart grids since it is the precursor of Energy Internet, and various other studies which discuss the developments that likely to enable smooth transition of present electricity system to Energy Internet. Secondly, a systematic review of literature related to state-of-the-art of Energy Internet is performed to outline its structure, operational features and energy market mechanisms. We find that while system infrastructures, technologies, and operational principles across globe are adequately ready for the transition to Energy Internet, hindrances put forth by the policies, regulations, government agencies and institutions need to be addressed to realize a nation-wide Energy Internet.

INDEX TERMS Blockchain, energy Internet, energy transition, peer-to-peer energy trading, smart grid.

I. INTRODUCTION

National electricity systems are going through transitions worldwide which are driven by renewable energy systems and low carbon technologies. Shift in investment focus from large-scale conventional fossil-fuel based power generation systems to large number of small-scale distributed renewable energy systems is the preferred choice. Planning and managing an electricity system with large number of producers as well as consumers where the transactions are dynamic and real-time are complex and challenging for a legacy grid system. Thus, there is a sheer need for a transition towards a futuristic energy system that has all the capabilities to address such challenges. Bi-directional communication among the producers, consumers, and the utility play an important role in management of such futuristic electricity systems. This communication channel can be further developed into an energy trading mechanism, where the price of electricity can be derived in such a way that all participants are benefited.

The concept of Energy Internet has evolved from this thought process, where consumers (including residential prosumers) and generators (including industries with captive generators) with varying power consumption and generation levels are facilitated to participate actively in the power transaction mechanism. Energy Internet integrates millions of heterogeneous prosumers to the network. Participants of this transaction mechanism are called Energy Cells. The priorities of such energy cells are varied according to the patterns of their energy consumption, local electricity generation potential, storage capacity, and availability of the dispatchable loads. In addition, there are technical and resource constraints. These have made Energy Internet a highly desirable but very complex system to operate. At present, there is no working model of Energy Internet under operation across the

The associate editor coordinating the review of this manuscript and approving it for publication was Jiayong Li.

globe and the literature is scarce, making the research in this area significant, novel, and timely.

Concept of Energy Internet is relatively new, and studies by Tsoukalas [1], [2] and Rifkin [3], [4] are known to be the earliest attempts to study the Energy Internet. These studies inspired development of the concept of Energy Internet as an energy sharing network model for small-scale energy prosumers like households with solar rooftop. Rifkin presented Energy Internet as third industrial revolution, whereas Tsoukalas proposed Energy Internet as a successor to smart grid. Huang [5] developed the framework of Energy Internet by conceptualizing energy cells, and utility cells. Su and Huang [6] further developed the concept by introducing possibility of a day-ahead energy market for the residential prosumers. This energy market framework is formulated using non-cooperative game-theoretic algorithms. Further, Zhang *et al.* [7] extended the work of Su and Huang [6] by modelling coalitional scenarios of energy cells using n-person cooperative game. These studies developed a day-ahead energy market for Energy Internet and tested the model with IEEE test 13 node data to analyze the performance. However, a model of Energy Internet is not yet studied with real-world data.

An important aspect missed out in the literature is the absence of real-time electricity grid balancing mechanism for the Energy Internet. Though, Dabbagh and Sheikh-El-Eslami *et al.* [8] presented a study on day-ahead energy market and balancing energy market which is apt for a micro-grid. Modern grid technologies such as vehicle-to-grid (V2G), and peer-to-peer trading platform using storage devices are integrated into the electricity system, but the peer-to-peer market is not designed to fit into a blockchain. Having said that, one of the first study which conceptually elaborated a smart grid based peer-to-peer energy market based on energy blockchain was by Mengelkamp *et al.* [9] in the context of Brooklyn micro-grid. Further, Joseph and Balachandra [10] systematically reviewed the milestones and evolution of Energy Internet and presented its conceptual model in the context of transitioning electricity system. Findings of the study suggests for policy impetus for promoting technologies such as e-payments, blockchain, and vehicle-to-grid. Present study is an extension of Joseph and Balachandra [10] to evaluate the practical implementation aspects of Energy Internet by developing from existing smart grid infrastructure which can be scalable to a nation-wide electricity system.

The present dearth of literature in the domain of Energy Internet is an opportunity to formulate the research in multiple directions and to take an early mover advantage. There are gaps in the literature which required a scientific study to understand the energy transitions and readiness of national electricity systems to embrace Energy Internet. Studies so far presented the Energy Internet as a system which is strenuous to implement in real world. In addition, an Energy Internet is not presented as a technology which is scalable and apt for a national electricity system. The present study is positioned to fill these gaps and to seek answers to two major questions. What are the enablers of Energy Internet? What is the status of development of Energy Internet from a national electricity system perspective?

Consequently, the specific research objectives of this study are as follows: (i) to provide a comprehensive discussion on smart grid which is considered as a precursor of Energy Internet. The focus is on the state-of-the art of smart grid, features of smart grids which enables Energy Internet, and related issues and challenges; (ii) to have an in-depth systematic review of relevant literature to present an overview of futuristic Energy Internet. An elaborate discussion on the structure of Energy Internet and various energy market mechanism are presented. Major contributions of this paper are – (i) Review of literature to understand the role of smart grid and its state-of-the-art in the Energy Internet perspective; (ii) Review of a number of notable studies on Smart Grids which are considered as the enablers of transition to futuristic Energy Internet. An evaluation of readiness of enablers of transition to Energy Internet is presented. (iii) Critical analysis of present issues and challenges for smart grid implementation in a transitioning electricity system. A global perspective of issues and challenges are discussed, (iv) Overview of Energy Internet, and its network structure are presented to understand the significance of the futuristic electricity system; and (v) Analysis of literature on energy market mechanisms suitable for Energy Internet is presented to propose future directions in this trajectory.

II. SMART GRID: THE PRECURSOR OF ENERGY INTERNET

In this section we have discussed studies which are related and relevant to Energy Internet. Our discussion on literature comprises recent works done in smart grids and retail energy markets. Smart Grid provides the technology infrastructure which is closest to Energy Internet that facilitate certain features like bidirectional power flow and communication.

A. SMART GRID – THE STATE-OF-THE-ART

A decade ago, smart grid was a concept emerged from a colorful dream, and now it is the most talked topic in the energy systems. Smart grid is a complex energy system concept with various technology options to enhance its functionality. Such a system is bound to propagate variety of definitions [11]. However, there are definitions set by various research agencies. The most prominent ones are discussed here.

The Electricity Networks Strategy Group (ENSG) defines smart grid as part of the electricity system, which can intelligently integrate the actions of users such as generators, consumers, and prosumers to efficiently deliver sustainable, economic, and secure power [12]. Further, Korean Smart Grid Institute defines smart grid as the next generation network that integrates information and communication technologies to the existing power system to improve energy efficiency through two-way exchange of electricity information between energy consumer and suppliers in real-time [13]. The possibilities of smart grid are vast in the modern energy

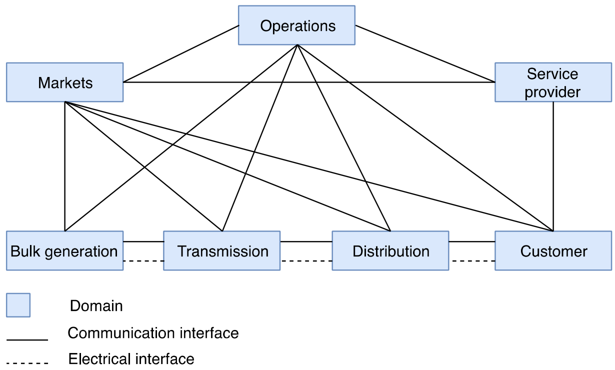

FIGURE 1. Conceptual model for smart grid by NIST.

system domain. It increases the inter-dependence among players in the grid [14].

The National Institute of Standards and Technology (NIST) of the United States provides a conceptual model as shown in FIGURE 1 [15], [16]. This is considered the reference model for the smart grid development work taking place around the globe. It includes seven domains, and each domain encompasses smart grid actors.

B. SMART GRID DEVELOPMENT TRAJECTORY – GLOBAL CONTEXT

The official policy for Smart grid initiative came alive in the United States in the 110th U.S. Congress and it was formalized in 2007 as Energy Independence and Security Act (EISA 07) [2]. Under section 1305 of EISA 07, the NIST developed three phase plan to deploy smart grid [17]. In phase one, a roadmap for the interoperability standards of smart grid was created. Based on this, a smart grid interoperability panel was created in second phase. In third phase, a robust framework for conformity and certification system for smart grid devices was developed. In the U.S., two smart grid initiatives are Smart Grid Demonstration Program (SGDP) and Smart Grid Investment Grant Program (SGIG). SGDP focuses on advanced energy storage systems and its applications. Whereas SGIG explores the possibilities of improving performance of grid through transmission infrastructure upgradation. Similarly, in Europe, smart grid is visualized as the infrastructure which provides integration of all national electricity grids to build a new European electric grid. Introduction of Strategic Energy Technology Plan (SET-Plan) led to creation of European Industrial Initiatives (EII) and European Energy Research Alliance (EERA) to move the SET plan forward [18]. EERA founded in 2008 has a major goal of ensuring investments are made on best available technologies [19].

The technological evolution of smart grid started with the automated meter reading infrastructure (AMR) which is one-way communication. AMR gave way to integration of two-way communication through Automated Metering Infrastructure, smart sensors, and distributed control. However, smart grid infrastructure becomes complete only when

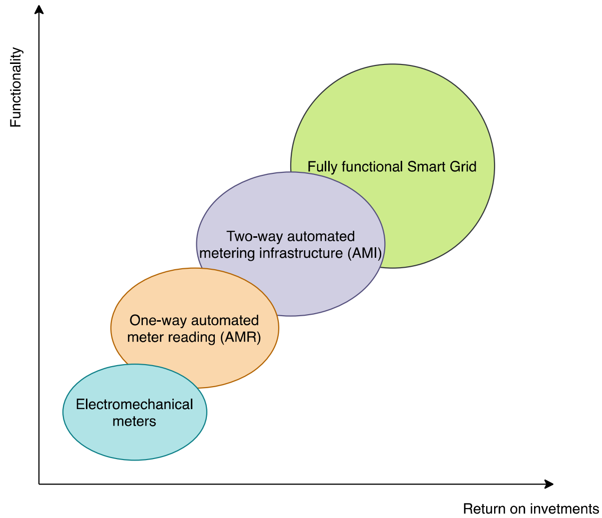

FIGURE 2. Evolution of smart grid Source: [21].

it achieves certain capabilities such as substation automation, self-healing, load management, emission control, consumer portal systems, and intelligent appliances [20]. This evolution has been depicted in FIGURE 2.

Evolution of smart grid has been extended to conceptualization of micro-grids, virtual power plants and virtual energy storages. Virtual power plants work as a cloud-based service to aggregate the distributed energy resources to enhance power generation. Nosratabadi *et al.* [22] have reviewed the scheduling problems in distributed energy resources in the context of micro-grid and virtual power plants.

Another important aspect of micro-grid evolution is virtual storage. Pandžić *et al.* [23] have performed the analysis to clarify the role of battery storage units owned by merchants in a day-ahead market. The model defines virtual storage plant as a group of battery storage units. The optimization model helps is assessing virtual storage plant profit maximization and market clearance. The model is expanded as a game of multiple virtual storage plants which try to maximize own profits. The study shows the importance of storage facilities in the day-ahead scheduling which otherwise may lead to price hikes and eventual loss for the virtual storage plants. In the context of transitioning electricity system, Cheng *et al.* [24] studied the cost effectiveness of virtual energy storage system to provide functionality to the conventional energy storage systems by utilizing existing network assets. The study proposed virtual energy storage system as a facilitator of energy transitions and low carbon technologies. The coordinated system reduces the impact of uncertainties of demand response by optimally managing other storage systems. The study concludes that, virtual energy storage systems contribute to the reduction of carbon emission by providing replacement to the fossil fuel based spinning reserves. A different aspect of virtual storage by considering buildings as batteries has been researched by Kats and Seal [25]. They anticipate that the next grid evolution is the widespread adoption of virtual storages by harnessing the potential of buildings transforming into smart buildings. Opportunities for virtual storage are available at smart buildings in the form of variable power demand, optimal management of heating/cooling devices, local power generation facilities, and storage devices. Authors argue that this way of virtual storage is larger, faster, less risky, and cost effective than the installation of stationary storage battery of same capacity. Further, Lund *et al.* [26] analyzed the history of smart grids based on study by Amin and Wollenberg [27] till evolution of the concept of smart electricity systems. Authors observed that smart grid concepts rarely touched the wide realm of intelligent management of multi-energy systems such as electricity, hydrogen, heat, and biofuels.

Drawing insights from the global transformation of smart grid into virtual power plants, virtual storage systems, and smart energy systems, we expect future decentralized electricity markets to be more cost-effective and efficient. With this information, we have attempted to study the features of smart grid which are enablers of future energy internet.

C. SMART GRID AS AN ENABLER OF ENERGY INTERNET

Smart grid is an important dimension of the modern electricity system. Prominent research in the context of smart grid which are related to Energy Internet can be classified into several categories as discussed in the following sections.

1) HOME ENERGY MANAGEMENT

Home energy management systems enable the end-consumer to monitor, control and manage the power consumption by home appliances [28]. Home energy management systems provide user interface for the household energy cells to control and operate the Energy Internet. Legacy energy systems provide information on energy consumption on a periodical basis in the form of monthly bills. Whereas home energy management systems in Energy Internet provide information on real-time energy consumption, local electricity production from rooftop SPV, real-time energy price, available storage capacity and much more. The architecture of the home energy management system comprises smart appliances, control systems, communication systems, and in-home displays. Home energy management systems (HEMS) provide energy feedback and smart features. Energy consumers take appropriate decisions based on the information shown in the in-home displays [29]. For instance, company called smarter homes [30] deploy home energy management technologies using internet-of-things and consumer electronic devices like iPad and Amazon Alexa to control the solar rooftop PV, storage devices, and home appliances.

Home energy management systems aid coupling of energy storage to the household system. For example, a study by Roumila *et al.* [31] have presented a hybrid wind, photovoltaic, and diesel system with battery storage. The power balancing system is designed using a fuzzy logic control based intelligent supervisor. Similarly, another study has chosen ultracapacitor as the energy storage medium to control the power balance between the peak power demand and fuel cell which stores energy converted by photovoltaic panel in an isolated load [32]. Thus, home energy management systems in the smart grid can facilitate the household consumers to manage their energy consumption by providing various hardware and software solutions [33]. The envisioned energy internet is expected to have an efficient HEMS to facilitate comprehensive energy trade practices. Further in this section, we have presented (TABLE 1) other related studies which enables Energy Internet at the household level.

2) PLUG-IN ELECTRIC VEHICLES AND VEHICLE-TO-GRID (V2G)

Plug-in electric vehicles are powered by the rechargeable storage devices and electric motor. The energy source for the rechargeable storage is the energy port which is placed in home or public places [42]. Electric vehicles can play a significant role in the demand-side-management of the smart grid if they are managed in a distributed manner with other electrical loads [43]. The main advantage of electric vehicle as an energy storage medium lies in its ability to move from place to place, whereas the static energy storage devices could be coupled with a network and would not have the liberty to move. Thus, electric vehicles are imperative for the implementation of Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) programs [44]. An optimal design to utilize the storage potential of an electric vehicle shall consider the cost of degradation of the electric vehicle battery [45]. However, charging of electric vehicles affects the power quality in the smart grid by possible harmonic effect, distribution transformer effect, fault current effect and line loss effect [46]–[50].

The willingness of the public to participate in vehicle-to-grid (V2G) program by an electric vehicle owned is determined by range anxiety and the minimum range of the vehicle [51]. Thus, the rate of adoption of electric vehicle is low even in developed countries. However, from a power system point of view, vehicle-to-grid offers ancillary services such as peak load management and voltage/frequency regulation services. Even private electric vehicles parked in the parking facility can inject significant net power to the grid while the vehicles are not in use with minimum discomfort to the vehicle owner [52]. Despite these benefits, public is skeptical about how V2G works. A study by Kester *et al.* [53] suggest that this skepticism is due to the lack of technological know-how about V2G. In addition, on the policy side, many countries lack comprehensive policy framework intended for V2G which emphasizes the major actors such as automotive industry, charging station companies, distribution utility, governments, regulators, and consumers. On the technology side, planning of the distribution infrastructure to incorporate V2G [54] and planning of V2G infrastructure to optimally operate the distribution network [55] are also areas where research is focused.

In the scheme of Energy Internet, the vehicle-to-grid technology is used to utilize the battery storage facility in the

TABLE 1. Summary of literature on hems.

Study	Category	Description
Sami et al. [34]	Conceptualization of prototypes	Development of a prototype to improve electricity generation using autonomous hybrid system including PV source and fuel cell back-up. Authors demonstrated flexibility of the system through critical constraints and multi-agent strategy. Vehicle-to-grid is not implemented in this model.
Shareef et al. [35]	Conceptual review	Comprehensive review on previous and current research related to HEMS along with various demand response programs. Review on application of artificial intelligence for load scheduling is also included.
Zhou et al. [36]	Conceptual review	Paper presents overview on architecture and functional modules of HEMS, analysis on advanced HEMS infrastructure and home appliances, and investigation on home appliance scheduling strategies
Beaudin and Zareipour [37]	Conceptual review	Paper presents comparative analysis of literature on HEMS. Major focus on modelling approaches. Discussion on HEMS challenges.
Shakeri et al. [38]	Control algorithm	New control algorithm for HEMS for appliance wise power monitoring and scheduling. Features like prioritization of appliances, battery optimization, and smart plug are provided. Model does not incorporate energy market for the household consumers
Correa-Florez et al. [39]	Optimization model	Study proposes stochastic approach for day-ahead operation of HEMS. System optimization model includes batteries, SPVs, and electric water heaters using two-stage MILP problem decomposed using Competitive Swam Optimize to calculate battery cycling aging cost.
Killian et al. [40]	Optimization model	Mixed integer quadratic programming model with predictive control scheme. Model demonstrate the optimal utilization of building's storage capacity to minimize the usage of battery storage.
Jin et al. [41]	Prediction algorithm & Optimization model	Study proposes a user-preference-driven HEMS called as foresee. Machine learning algorithms to predict the household energy consumption, comfort needs, energy costs etc. Optimization algorithm to address how home shall operate to meet the concurrent need of occupants.

electric vehicle. Thus, it is imperative to discuss the literature and recent studies related to the vehicle to grid technology. We have presented important literature related to vehicle to grid technology in Table 2.

3) RENEWABLE ENERGY INTEGRATION TO GRID AND DISTRIBUTED GENERATION

Smart grid facilitates smooth integration of renewable energy sources (RES) into the power transmission and distribution networks. Electrification process in many countries is stagnant due to the economic unviability of grid extension to remote locations. Electrification of such remote locations can be done by deploying micro-grid networks with renewable energy systems.

Self-sustaining island energy systems have been the topic for academic research for a long time [62]–[68]. There are studies on 100% renewable island energy systems from the past [69]. Pfeifer *et al.* [70] have proposed an interconnection model between a group of islands to integrate local renewable energy production. Besides the interconnection provided, a plan to optimally manage the electric vehicle battery for a demand response technology is also proposed. The EnergyPLAN [71] model designed in the study has tested two scenarios, namely, a big central battery concept, and several distributed small sized batteries. Results showed that distributed storage systems can provide more energy security than a concentrated big storage system. Such a system is capable of utilizing the renewable energy potential and managing the peak demand using V2G technology.

Surprisingly, RES integration is a solution for complicated energy water nexus in island nations [69]. For such nations, the motivation is to transform from a state of 'full input of energy & water (FIEW)' to 'zero input of energy & water (ZIEW)' to become independent from the mainland on energy and water imports. Such a system for Maldives has been proposed in study by Liu *et al.* [72] which makes use of RES coupled energy water system.

In recent years, networking of micro-grid has received attention [73]. Wang *et al.* [74] have studied the possibility of networking of micro-grids through a two-stage optimization model. The model consists of a hybrid management system at day-ahead scheduling stage with an objective to minimize the operational cost of the grid. In the second stage, the uncertainty in the demand and supply is balanced with a real-time dispatch algorithm. Output is a techno-economic plan for the micro-grid networking and a risk-hedging strategy.

Renewable energy systems are relevant not only in the context of rural micro-grids but also in the context of urban energy systems. A study by Weir [69] has critically reviewed urban energy systems at the cluster level to incorporate envelope solutions based on RES. It also discusses the operational and control methods which include the optimization algorithms for the energy hub concept.

Energy landscape is undergoing an accelerated change in terms of decarbonization of centralized energy systems and deployment of distributed energy systems with renewable energy as the primary source [75]. The concept of micro-grid has emerged based on the central idea of integrating distributed energy sources, controllable loads, and storage devices [76]. However, control of distributed energy sources in the micro-grid is a complex task due to the variability and

TABLE 2. Summary of literature on vehicle-to-grid technology.

Study	Category	Description
Staudt et al. [56]	Optimization modelling & energy markets	Study asses the ability of the transmission system to cope with the additional demand of uncoordinated EV charging by formulating transportation problem. In addition, a local flexibility market is proposed for the EV owners.
Robledo et al.[57]	Conceptual modelling	First study in V2G measurements with a hydrogen fuel cell EV. Study based on a two-week pilot living experiment in a house using fuel cell EV to grid. Study elaborates various implementation challenges, and model limitations. Fuel-cell EV found to be a good choice as power source for a single home.
Mozafar et al. [58]	Optimization modelling	Research proposed a novel model to study the effects of V2G program in terms of demand profile, operational stability index, and reliability indices. Model proved to be effective in improving the reliability indices
Xiong et al. [59]	Optimization modelling	Study proposed optimal bi-directional changing control strategies to integrate EVs in commercial parking spaces. Authors used two-stage optimization problem and water-filling algorithm. Stochastic behaviors of the electric vehicle users are modelled by modified Latent Semantic Analysis
Lin et al. [60]	Optimization modelling	Multi-agent system to simulate the operation of EVs in energy hub. Model accounts different penetration rates, and various charging patterns.
Jian et al. [61]	Optimization modelling	Scheduling scheme for V2G operation based on stochastic scenario of PEV connection. Proposed model updates the schedule based on the events takes place including unexpected disconnection.

intermittency issues of the renewable energy systems [77]. Such complexities can be managed by multi-agent based approaches which compose multiple interactive intelligent agents [78]. In addition to the enhancement of efficiency and reduction of carbon emission, distributed generation can also contribute towards deferral of transmission line upgradation and expansions [79]. Thus, distributed generation is recognized as the future power paradigm because of its economic, technological, and environmental benefits [80], [81]. Further, small-scale generators connected to the distributed energy systems can adapt better and faster with the variations in the load curves than the large traditional grids [82]. In brief, the smooth functionality of the distributed energy resources with the distribution network is dependent on the intelligent decisions taken by the underlying technology associated with the smart grid environment. Therefore, improving the integration of distributed generation resources to the smart grid is a major research agenda in the current smart grid research and development projects [83].

4) ENERGY STORAGE SYSTEMS

Electric power storage facility is the critical driving force towards the rapid deployment of renewable energy and smart grids [84], [85]. Energy storage systems in the past had a limited relevance, value, and functionality because of their high cost and inefficiency [86], [87]. For a low carbon electricity transitioning system, it is imperative to embrace the benefits of renewable energy generation, and storage to establish a fully functional and optimized dynamic grid [88]. Several researchers propounded that energy storage shall be established as a new asset class. Essential set of financial and regulatory policies need to be framed to support their development [89], [90]. Energy storage devices can meet the peak power demand by negating the need for extra generation which is often expensive. Energy storage can defer transmission and distribution upgrades. In addition, storage devices can act as a key enabler to offset the demand and supply mismatch to operate the distribution network in an economical, efficient, and environmental friendly manner [14], [91]–[94]. As energy storage can benefit smart grid deployment, smart grid can also benefit the optimized operation of energy storage [95]. Information aggregation facilitated by smart grid has improved the accuracy of price and demand forecasting. Exploitation of such information can be utilized to optimize the gain in the short term energy market through arbitrage [94]. Finally, the scope of energy storage in smart grid is not confined to the individual household level. Barbour *et al.* [96] have studied community energy storage as the choice for energy storage in smart grid. Their findings indicate that community energy storage option yields more internal rate of return (IRR) than household level storage. Further, the energy markets shall be designed in such a way that it promotes the community energy storage options, especially in regions where solar potential is high. Lund *et al.* [97] have discussed the cross-sectoral smart energy systems approaches. Such approaches can lead to identification of inexpensive technologies for thermal, gas, and liquid fuel storage. For instance, heating systems can connect electricity sector to thermal storage. Similarly, electric vehicles can connect electricity sector to storage in transport sector.

In addition, in the context of smart energy system, it is to be always noted that, energy conversion and storage pathway such as ‘Power-to-X’ concept which includes ‘Power-to-gas’, ‘Power-to-hydrogen’ are highly significant [98], [99]. Table 3 shows the categorized analysis of relevant literature on energy storage systems in smart grid.

TABLE 3. Summary of literature on storage systems in smart grid.

Study	Category	Description
Zhang et al. [100]	Conceptual review	Review on several battery system for grid energy storage. Summary on features of current and future grid energy storage battery. Application status of the energy storage system in the renewable energy systems.
Koirala et al. [101]	Conceptual review	Overview on state of the art in community energy storage (CES). Conceptualisation and analysis of a socio-technical system. Authors have presented different dynamics of CES such as coordination and interaction of actors and components.
Kakran and Chanana [102]	Conceptual review	Study provides a detailed discussion on, demand side management, distributed generation, demand response, technical issues, and key advantages in connection with energy storage in smart grids.
Qiu et al. [103]	Optimization model	Proposal for a two-stage stochastic optimization planning framework for photovoltaic, battery energy storage, and gas-fired micro turbine. Study investigates the interactions between electric and thermal energy and provides optimal planning perspective from an integrated perspective.
Bucciarelli et al. [104]	Optimization modelling	Study on sizing of storage in a distribution network. Focus on computational aspect of stochastic programming. Decomposition approach is used to solve the two-stage optimization problem.
Granado et al. [105]	Conceptual review and optimization modelling	Author propose valuation model for end-user energy storage in smart grid. First concrete study on incorporating demand side storage to balancing energy markets.
Lund [106]	Modelling	A comparison of various strategies to transform the heating sector into 100% renewable energy-based solutions are studied in this paper. Study focuses on the consequence of infrastructures across electricity, gas, and heating sectors in terms of grid and storage. Findings suggest that, in the context of Denmark, Smart Grid requires 2-4 times expansion compared to implementation of 'smart energy systems'.

5) COMMUNICATION TECHNOLOGIES

Advanced metering infrastructure (AMI) integrates smart meters and communication networks, meter data management systems (MDMS), software platforms and user interfaces [107]. AMI facilitates two-way communication of information between the consumer and utility regarding the energy consumption by the end-consumer and price signals, or load controlling signals from the utility [108]–[110]. AMI measures and acquires energy consumption and power quality data from an end-consumer [111]. The collected information is communicated to the central server for further analysis. Thus, establishment of communication channel which facilitates the transfer of information is a need [112]. The communication channel which facilitates information exchange is bidirectional. Bidirectional communication helps to improve the asset maintenance, energy demand management, and energy planning capability of the utility [111].

The future of AMI is predicted to be 'smarter'. It is observed that, in future Artificial Intelligent Meter (AIM) will be the choice which can manage the energy consumption of the consumer without the external control signals. This would be performed with the support of artificial intelligent power quality diagnosis coupled with the AI meter device [113]. AIMs monitor and control the household appliances with the consent from the inhabitant of a house [114]. A Smart Multi-Power Tap (SMPT) device can work in association with the home area network (HAN) for monitoring activity of a household's appliances to provide improved quality of power supply [115]. AIM also minimizes the human involvement in the certain decision-making processes.

Alam *et al.* [116] have presented a radio based smart grid communication network. The smart grid has three layers namely, Home Area Network (HAN), Neighbourhood Area Network (NAN), and Wide Area Network (WAN). Recent development in the radio communication technologies and standards such as Cognitive Radio (CR) [117], Smart Utility Networks (SUN) [118] and TV White Spaces (TVWS) [118] are profoundly accepted for the deployment of smart grid infrastructure. Further, as the technology begin to mature, and the rate of adoption of smart grid grows rapidly. This requires computational technology to be adequate to analyse the data fetched by the measuring devices in the smart grid. For the data storage, data clouds are established. Providing a lightweight communication architecture for the big data transmission which swiftly responds to the network congestion and management requirements is a challenge with respect to the computational power and channel bandwidth limits. Therefore various high capacity data transmission algorithms are being developed [119].

D. ISSUES AND CHALLENGES

In this section we discuss certain issues and challenges that faced smart grid implementation from a global perspective.

Firstly, there remains a skepticism among the industries regarding the development of smart grid projects. Industries are under the belief that the progress of current smart grid projects is slow, and government could not achieve what it has promised. In addition, though governments provide financial support for the research and demonstration of smart grid pilot projects, the investment enthusiasm by the companies involved in smart gird deployment is low which is reflected in its development [120].

Secondly, smart grid architecture and infrastructure are prone to myriads of security threats and related challenges. Some of the threats and challenges are; cyber-attacks, thefts, natural disasters, and terrorism. The actual event for security breach can lead to power outages, information and technology infrastructure failure, power market chaos, cascade failure of network, or even it can affect the safety of human [121]. In addition, there are other threats and security challenges which have been discussed in other similar studies (refer [122]–[126]). In brief, smart grid security challenges can be recognized in terms of authentication, authorization and privacy of technologies [124], [127]. Energy Internet can face similar challenges, however incorporation of technologies such as blockchain and Internet of Things (IoT) are expected to reduce the chance of occurrences and impacts of such security breaches and expected to take recovery actions with minimal human intervention.

Thirdly, low penetration of electric vehicles in the market embedded with vehicle to grid (V2G) functionality is a challenge which hinders the adoption of electric vehicles in energy market. Effective V2G operation involves frequent charging and discharging of the battery which causes battery wear. Though researchers hold a good hope on lithium ion (LFP) battery, further research on maximization of battery life of vehicles engaged in V2G is imperative for its successful deployment [128].

Fourthly, enhancement of smart grids with micro-grids. There are few technical and regulatory challenges associated with the micro-grid implementation with smart grid [129]. Micro-grids are subjected to frequency and voltage problems caused by imbalance between demand and supply [130], [131]. These problems can become severe in cases where the 'plug-and-play' feature is provided to connect and disconnect the generators [132]. Variation in the power output from the renewable energy systems connected to the micro-grid imposes challenges on maintaining the microgrid at stable state [133], [134]. In addition, increasing share of renewable energy may lead to transmission and distribution congestion in the existing network [135]. Increasing complexity in the system also necessitates integration of appropriate protection devices. In micro-grid infrastructure, the protection system is different from the traditional power system as it involves bi-directional flow of power [131]. More about the micro-grid protection schemes are presented in Basak *et al.* [136], Mirsaeidi *et al.* [137], and Che *et al.* [138].

Finally, the challenges caused by interoperability and conformance to standards [139], standardization of communication devices [140] and cyber-security devices [141] are needed to be addressed. Countries have assigned various organizations for the development of smart grid standards and its inter-operability [142]. Design, development, and manufacture of devices under the global standards are key challenges faced for the deployment of smart grid infrastructure.

Energy Internet is proposed as a solution to address many of the aforementioned challenges. It is being presented as the future revolution in the energy system that can enable a shift in focus from large-scale centralized power generation to large number of small distributed generation systems. This shift in electricity generation ownership to prosumers can lead to a deferral of investment on generation facilities by the government. Energy Internet fosters investments by the household and other small-scale consumers who can build local power plants to sell/buy electricity. This reduces the investment burden of the governmental organizations to focus more on providing infrastructure with advanced facilities to enable smooth electricity trade through Energy Internet. When this infrastructure is backed by emerging technologies like blockchain and IoT, present day security threats and challenges are addressed, however, as the advancements in technology takes place, new security threats are prone to emerge which are expected to be addressed by constant innovations in cybersecurity.

Our study in Energy Internet contributes towards the optimization of storage devices to minimize the battery wear. In addition, persisting issues in smart grid related to variability and uncertainty of renewable energy systems in the smart grid can be optimally managed by Energy Internet through distributed energy systems management algorithms (by future integration of Artificial Intelligence (AI) and Machine Learning (ML) algorithms to Energy Internet which does not fall under the scope of this study). Finally, standardization and interoperability are issues that need to be addressed by the government agencies in coordination with other concerned international agencies. Energy Internet can bridge the gaps where the smart grid had failed to achieve.

III. THE ENERGY INTERNET – AN OVERVIEW

The emergence of the concept of Energy Internet is a result of continuous evolution of the electricity systems. Invention of electricity was a scientific breakthrough during the second industrial revolution (1860-1900). Electricity struck with an immediate deviation in the economic growth trajectory of world countries [143]. Since then, there was a rapid transformation in the electricity generation technologies like steam turbine driven generators to solar photovoltaic panels. There was a shift in the mode of consumption at the consumer end as well. Towards the end of 1880s, there were few city blocks of United States were lighted up through Edison's design of decentralized power generation and distribution. Slow but steady rise in the primary demand of electricity urged the erection of large-scale centralized power stations. As energy intensive economic activities challenged the reliability and quality of existing electricity systems, engineers and policymakers relied on addition of more and more generation capacity and they believed that meeting demand by addition of more generation capacity is the panacea to the prevailing challenges. However, rapid advancements in the Information Technology (IT) in the twenty first century manifested its ability to integrate it for the enhancement of reliability, quality, and efficiency of the power systems. Penetration of technology made it easier to manage the transmission and distribution networks through sophisticated devices and its functional software platforms [144]. The concept of 'Smart Grid' emerged through the incorporation of IT infrastructure in the power system that catalyzed the expansion of the sector. Smart grid infrastructure facilitated smooth deployment of micro-grids to facilitate the distributed power generation and its distribution through off-grid and on-grid topologies. It also ensured coordination between the distributed generators and consumption centers in optimal configuration with the hardware and software support like sensors and artificial intelligence.

Evolution in the network structure also resulted in concomitant effects in the business perspective of the power sector. Emergence of power markets, integration of small-scale renewable energy systems, incorporation of electric vehicle charging stations, etc., became too complex to manage with a basic smart grid network. Energy Internet is an advancement from the smart grid, which is envisaged as capable of managing millions of Distributed Energy Resources (DERs), storage devices, and loads effectively [145].

Energy Internet as an emerging technology provides a platform for the prosumers to generate, consume and sell their own surplus electricity generated at the backyard [146]. The proposition of 'Energy Internet' concept was inspired by the evolution took place in the information internet (world wide web) since its inception [7]. The centralized computing infrastructure of 1980s gave way to a new generation computing infrastructure which is distributed and resource optimized [147]. Modern computing devices like desktop PCs, laptops, and iPads do function like distributed computing by sharing the information through cloud infrastructure. Similar paradigm shift can be achieved in the Energy Internet, where, the role designated by the centralized power stations to serve the power demand, would be performed by large number of small distributed renewable energy systems connected to the reliable distribution infrastructure supported by modern technologies [6].

Rifkin [3] presented the concept of Energy Internet with four main features. First, renewable energy is the primary energy source in the Energy Internet. Second, Energy Internet should support integration of large number of distributed renewable energy systems and storage devices. Third, it should facilitate bi-directional flow of energy and communication. Fourth, it should support the future needs of electric mobility [145]. These characteristics induce conducive environment for the development of new power system business models, integration of new storage technologies to energy systems, and to shift from internal combustion engine centric mobility to electric mobility which is more environment friendly.

The Energy Internet architecture is analogous to the consumer-to-consumer (C2C) e-commerce business like e-Bay where a consumer directly interacts with another consumer without the presence of any third party [148], [149]. In Energy Internet, there are millions of selfish entities including residential, commercial, and industrial consumers which interact with each other through the network to maximize their own benefits [6]. These entities are called as Energy Cells [6], [7]. An Energy Cell consists of local electric generator, storage devices, dispatchable/non-dispatchable electric loads and electric vehicles [2], [150]. Energy Cells are connected to the Energy Internet for energy trade through the network infrastructure provided by Utility Cell. Utility Cell operates and maintains the infrastructure for the energy transactions and a clearance house facilitate the actual energy trade through appropriate price discovery mechanism [6], [7], [148].

The plug-and-play feature of Energy Internet facilitates fast and smooth coupling and decoupling of distributed renewable energy systems and storage devices to the network. Presence of plug-and-play interface is crucial because the coupling and decoupling of renewable energy systems and storage devices can cause disruptions in the grid, and selection of apposite converter topology is important [151], [152]. The plug-and-play interface and an open-source-standard based software for the communication would be integrated to a device called Energy Router [153], [154] which functions similar to the network router in information internet. Research and development of energy router are at the nascent stage [155]. Yet, there are innovative prototype designs based on solid state transformers [5], and multilevel converter topologies [156], [157], which are under the development.

A. STRUCTURE OF ENERGY INTERNET

Rifkin [3] has presented four characteristics for Energy Internet. Those are; (1) Renewable energy is considered as the main primary energy source in the system; (2) Energy Internet should support integration of large-scale distributed generation and energy storage devices; (3) Internet is the base technology for the energy and information sharing; and (4) Energy Internet should support the electrification of the transport systems.

The implication of these characteristics can lead to shift to a new way of management of the power system like incentivizing the prosumers, deployment of charging stations for plug-in electric vehicles, bolstering of Internet network backbone for the reliable data transfer, and promotion of new storage technologies including pumped storage hydro power plant.

The plausibility of plug-and-play mechanism to connect the energy cells to the Energy Internet has been studied since 2010 [5]. FIGURE 3 shows the layout of the Energy Internet at various levels. The new power distribution system discussed here is different from the legacy power distribution system in terms of energy delivery mechanism. The doted box represents the participants of Energy Internet market mechanism. While the green box denotes the energy cell, the blue box indicates the utility cell. Detailed characteristics and functions of energy cells and utility cells are discussed in the next section. All energy cells are connected to the

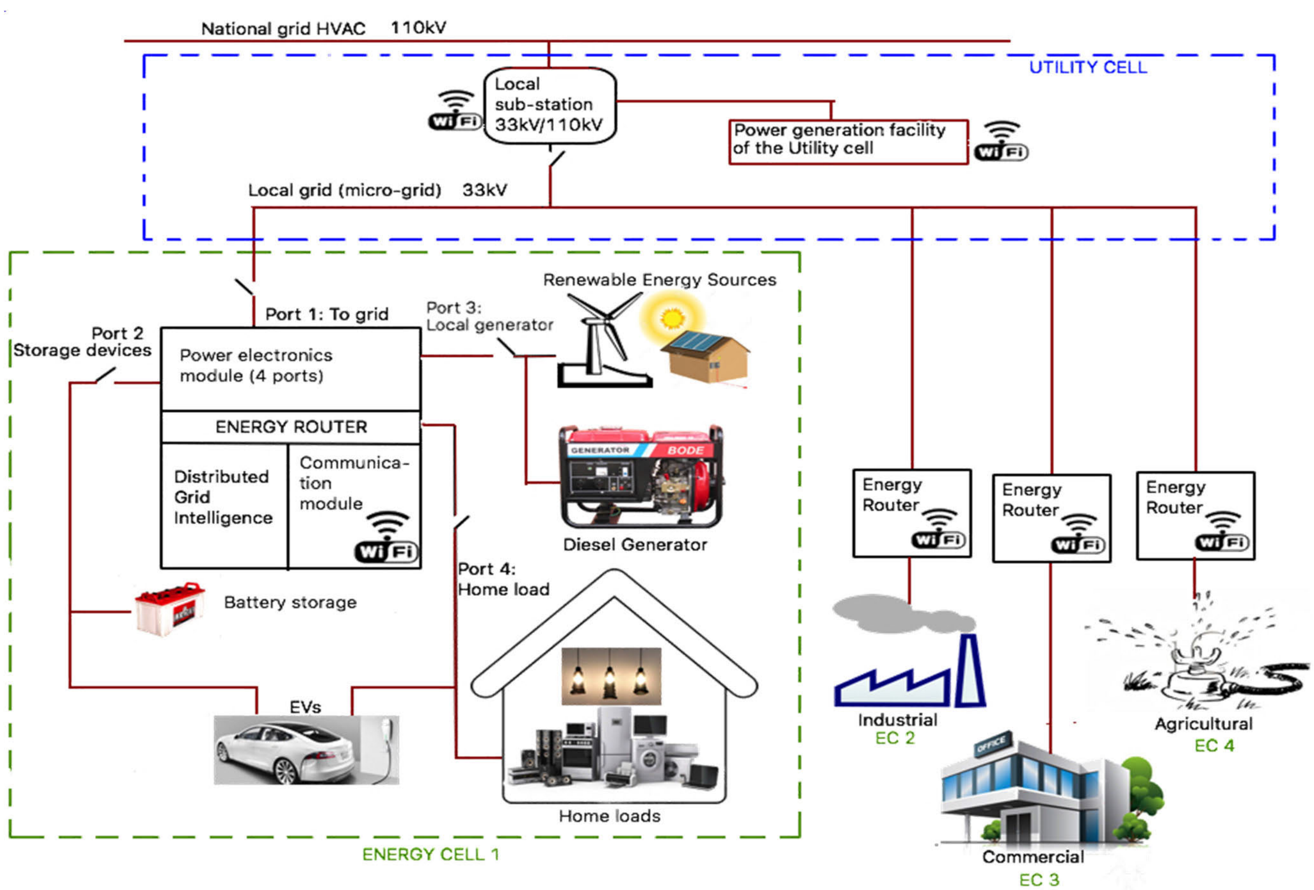

FIGURE 3. Energy internet architecture.

network through a device called Energy Router [153]. The power electronics module of the energy router connects the device to the power grid, storage devices, local generator, and loads. Utility cell injects power to the network to balance the demand and supply in case the supply from the energy cells is not matched with the demand. Communication module in the energy router communicates with other energy routers to transfer the demand and supply parameters data [154], [153]. Energy storage plays an important role in the Energy Internet, but so far, the impact of energy storage has not been studied extensively. We hope that, electric vehicle and other virtual storage mechanisms can have a significant role in the energy storage.

In the envisioned energy internet model, there can be a facility to optimally manage the network depending on the power surplus and deficit status. If the power is deficit in a particular location, power can be drawn from the idle plugged-in electric vehicle in the same locality. If the power is surplus, then the vehicle can be charged. Thus, the losses associated with the transportation of power can be minimized.

TABLE 4 presents a comparison of the Energy Internet architecture to the Information Internet architecture. As the Energy Internet scenario is a paradigm shift from the present personal computing and internet architecture, many technological concepts can be adopted for the betterment of the system.

B. ENERGY MARKET MECHANISMS FOR ENERGY INTERNET – A REVIEW

Future renewable heating, green gas and liquid fuel markets would influence the electricity market [158]. In this aspect, Energy Internet is capable of reforming itself to be a multi-energy system. However, in this study, the focus is limited to Energy Internet that facilitates an electricity trading mechanism which is different from multi-energy system. Energy Internet architecture is capable of incorporating a fully functional energy market for the energy cells [148]. For example, the existing power exchanges in India function based on the auction-based bidding mechanism [159]. This mechanism is suitable for static liberalized markets where the network topology and market structure are easy to predetermine. However, in Energy Internet, energy cells integrated with the Energy Internet are heterogeneous in nature with conflicting interests. With such a characteristic, auction-based bidding may not be an efficient market mechanism [6]. The possible solution is a real-time pricing of electricity which reflect the dynamic demand and supply balance. Our exploration to find a suitable real-time pricing mechanism

TABLE 4. Comparison between information internet and energy internet.

	Information Internet	Energy Internet
Primary Objective	Inter-connection between computing devices for information sharing	Power distribution system that inter-connects between all consumers for efficient delivery of energy through two-way communication and two-way power flow.
Plug-and-play interface	Carries the feature of instantaneous detection and recognition of the device connected. Examples are; Ethernet, and USB	Detection and recognition of devices connected like DRER, DESD, or loads.
Information Router	Internet router	Intelligent Energy Management (IEM) device which recognizes and manages all devices connected to the system
Open Standard Operating system	Operating systems like Linux, or Windows	Distributed Grid Intelligence (DGI) feature must be integrated to the IEM device

for trading among energy cells in the Energy Internet has ended up in selection of game-theoretical algorithms, which we have been explained in the upcoming sub-sections.

1) GAME-THEORETIC POWER MARKET MODELS IN PRE-SMART GRID ERA

Studies which deal with conflicts between the interactive decision makers have been analyzed with game theory models. Scalability of game-theoretic algorithms catalyzed its wide adoption for designing energy markets in recent years [160]–[165]. For example, Ruusunen *et al.* [161] have proposed a design of transaction agreement of an electricity exchange in power pool. Using cooperative game theory, the problem of contract definition is approached. Authors have modelled based on a non-additive function to maximize the individual cost reductions. This has ensured the fair division of cost savings. In an another example, Min *et al.* [166] modelled a coordination procedure for an independent system operator. Study proposes a non-cooperative dynamic game to find the optimal strategy for generation companies. Model has been validated using numerical example of three-Genco system. The approach given by Min *et al.* [166] is a typical example for game theoretic algorithms designed to validate small samples which can be also applied to a large setting. In literature, even before the conceptualization of Energy Internet, there were power market algorithms designed using game theory.

Geerli *et al.* [167] have attempted to derive an operational rule for a power market with an independent power producer (IPP) and a utility service provider. The model has been designed based on a non-cooperative game to analyze the negotiation between a utility and a coalition of IPPs. Further, the analysis has been extended to carryout negotiation between utility and individual IPPs. The key finding from this paper signifies that the price of electricity which is procured from the IPPs is cheaper than the utility owned generators. Further with negotiation models, Xing and Wu [160] have proposed a Stackelberg game based on oligopolistic theory. The model has designed a negotiable long-term contract between build-operate-transfer (BOT) investor and a power utility. The model shows that, for a BOT power plant, electricity price and fixed annual energy can be simultaneously determined using Stackelberg model. Later, Jia and Yokoyama [168] have proposed a scheme to allocate the profit between the cooperating IPPs in a retail market. Profit allocation is decided based on Shapley value and the nucleolus. Result of the model shows that cooperation between the IPPs will result in more profit than individual competition. Meanwhile, auction game models could contribute insights on pool-based electricity markets existed in the same period. Gan *et al.* [169] observed that in pure strategy sense, games in electricity market need not possess a Nash equilibrium. In such cases, quasi-equilibrium provides an alternative approach. In a similar context of single auction power pools, Kang *et al*. [170] have modelled a simultaneous-move game by the suppliers. They found that pure strategy Nash equilibrium solution concept is apt for simultaneous non-cooperative games which contradicts the findings of Gan *et al.* [169]. As an addition in pool market, Generation expansion planning (GEP) in a pool power market is addressed by Shayanfar *et al.* [171]. They have presented a master and a slave algorithm where the master level is modelled with modified game theoretic algorithm and slave level is modelled with improved Genetic Algorithm (IGA). The method determined the requirement of power plant installations for the GEP horizon. It has been observed that expansion planning of generation companies decreases market clearance price.

2) GAME-THEORETIC POWER MARKET MODELS IN THE PRESENT CONTEXT

As we discussed in the earlier sections, the legacy power grid evolved into smart grid and the research in game theory domain also adapted to the same evolution. Saad *et al*. [172] studied game theoretic method for smart grid applications.

They elaborated how cooperative and non-cooperative strategies are possible in a micro-grid. Saad also suggested future extensions of coalitional and non-cooperative game theory applications in micro-grid distribution networks. In the paper by Dabbagh and Sheikh-El-Eslami [8], a stochastic programming approach is used to study the participation of a Virtual Power Plant (VPP). A day-ahead market and a balancing market have been designed by considering uncertainties associated with renewable energy systems, prices, and consumer loads. Day-ahead market algorithm is run to schedule the power dispatch and real-time correction of forecasted demand and actual demand, is performed by day-of power delivery algorithm.

3) GAME-THEORETIC POWER MARKET MODELS FOR ENERGY INTERNET

Application of game theory in Energy Internet is relatively new. Su and Huang [6] applied Nikaido-Isoda function and Relaxation algorithm (NIRA) to formulate a mathematical model to design a day-ahead market for the non-cooperative energy cells. Adoption of special class of numerical algorithm called relaxation algorithm in trade is old as more than three decades. Earlier works in relaxation algorithm [173]–[176] is perfect example for the relatively fast convergence of the algorithm with a fair accuracy. Earlier work by Contreras *et al.* [177] presented how NIRA algorithm is used to calculate Nash-Cournot equilibria in electricity markets with coupled constrained algorithm. Bilateral Shapley value and kernel are used for the fair distribution of profit among the cooperating consumers. Further, the study was extended by Zhang *et al.* [7] by formulating an energy market model for profit allocation among the cooperating energy cells using NIRA algorithm. Profit allocation among the cooperating energy cells is performed with Shapley value method.

Optimization models from the aforementioned literature were adopted to formulate energy market for Energy Internet. In TABLE 5 we have presented the most relevant literature related to Energy Internet and day-ahead energy market based on Energy Internet published in the past.

4) BLOCKCHAIN TECHNOLOGY AND ITS VIVID APPLICATIONS

Blockchain is an incorruptible digitally distributed ledger of economic transactions that can record virtually everything of value [178]. The working principle of blockchain technology is based on shared ledger broadcasted to all the participants (see FIGURE 4). It uses distributed consensus algorithm [179] to make everyone to agree on the proposal to ensure consistency [180], smart contracts [181] for compliance tracking of each participants [182], and cryptography based security measures to facilitate the trade [183]. Thus, it provides a robust and resilient cybersecurity solution with anonymity to the user [184]. Blockchain also mitigates the risk of double-spending associated with digital money [185]. The double-spending risk mitigation is dependent on the compute-intensive algorithm. This computing algorithm is used to confirm transactions and to add new blocks to the blockchain. In order to confirm these transactions, experts compete with each other (called as miners) to verify the transactions by solving the puzzles. This 'proof-of-work' (consensus algorithm to confirm the transaction and to add new blocks to the existing blockchain) [184] is energy demanding and currently used for bitcoin applications, it is in the order of 100 MW and nonetheless it is debated [185]. Further, blockchain provides features such as, (1) transparency thereby providing access to easily auditable data, (2) redundancy thereby distributing a copy of data to all the participants to prevent malpractice by third party, (3) immutability thereby making the alteration in the records extremely arduous, and (4) disintermediation thereby eliminating middlemen such as banks or energy utility [186]

Application of Blockchain technology is not limited to Bitcoin or in the area of finance. Blockchain has been used in supply chain, healthcare, retail, agriculture, etc. For instance, blockchain applied in automotive supplier payments by Australian vehicle manufacturer Tomcar to pay to the suppliers in Israel and Taiwan. Likewise, in healthcare sector, applications such as; patient data management, drug counterfeiting [187] and many more [188].

Blockchain in energy markets provides complete transaction log and continuous tracing of all the energy transactions [9]. However, the technology still poses certain challenges. Some of the challenges are; storage of metadata and digital data, disputes over the copyrights, network effect issues and legal issues [186].

5) BLOCKCHAIN TECHNOLOGY IN ENERGY DOMAIN

We have categorised the literature in blockchain based energy trading into direct energy trading models and indirect energy trading models. In direct energy trading model category, the discussion is focused on literature related to trading in actual energy on the peer-to-peer consumer platform, and in indirect energy trading model, literature which discusses energy traded in its equivalent forms are included.

Sikorski *et al.* [189] has demonstrated blockchain based model for small-scale electricity market. Model successfully established blockchain for machine-to-machine electricity market in a chemical industry based on proof-of-concept implementation. The model consists of three participants, namely, two producers and one consumer, and market transaction takes place according to the bids and offers. Authors argue that, blockchain can successfully support an electricity market. In the context of Citizen utilities, Green and Newman [190] argues that, there would be a paradigm shift in the present role of utilities to local community micro-grids with blockchain support. The grid is also expected to be more resilient with these micro-grids dominated by Solar Photovoltaic distributed generators.

Applications of blockchain can be found in both public and private domains. Bitcoin is an example of public blockchain. In energy trading applications, such as micro-grids [191] and

TABLE 5. Relevant literature related to energy markets based on energy internet.

Study	Category	Description
Rifkin [3]	Conceptual model	Author coined the term 'Energy Internet' for the first time. First study in the area. Conceptual model is presented with essential features and operational strategies.
Huang et al. [153]	Conceptual model	Discussion on engineering aspect of Energy Internet architecture. Detailed discussions on plug-and-play mechanism and energy routers using solid state transformers.
Su and Huang [6]	Conceptual review and optimization model	Conceptualization of energy cells and utility cell. Proposal for operational strategies for energy internet. Application of non-cooperative game theory for day-ahead energy market clearance.
Zhang and Su [7]	Optimization model	Formulation of day-ahead energy market using cooperative game theory.

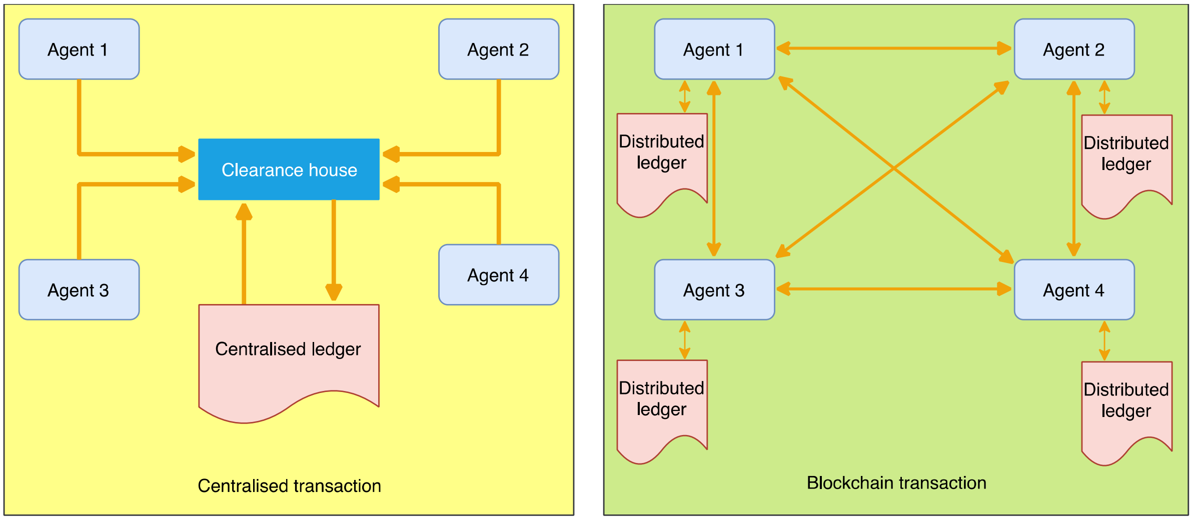

FIGURE 4. Centralized transaction vs. blockchain transaction.

energy internet, private blockchain is more desirable [192]. Energy trade can take place based on virtual currency for transaction settlement. Mihaylov *et al.* [193] have introduced NRGcoin for renewable energy market. Energy can be injected and absorbed from the grid and equivalent NRGcoin can be earned or spent. Value of the coin is determined based on the exchange rates. This model is claimed to be scalable as the new entrants would not increase the complexity of the system. Further, blockchain can facilitate a local market model to trade carbon emissions as demonstrated in Kawasmi *et al.* [194] using Bitcoins. Model features an anonymous trading platform for carbon emission trading. Similarly, a study by Aitzhan and Svetinovic [195] have simulated and presented a token based peer-to-peer energy transaction mechanism using proof-of-concepts, multi-signatures, and anonymous messaging for the price negotiations by eliminating the reliance on third party. Authors argue that, appropriate combination of blockchain, multi-signature, and anonymous message streams can achieve higher degree of privacy and security compared to legacy grid.

A project called TransActive grid, initiated by LO3 energy has started the project with 200 smart meters in the neighborhoods of Brooklyn, New York. The residents are facilitated to sell their surplus energy and consumers can buy power from the same platform through virtual micro-grid based on blockchain [196]. Mengelkamp *et al.* [9] has analyzed the Brooklyn Micro-grid Project by LO3 and their findings suggest that, there are several advantages of blockchain based energy markets, like, local community participation for renewable energy integration to the system, lower transaction costs, and shorter payment cycles. Nevertheless, local authorities should revise the regulations to maximize the benefit of these advantages. However, Brooklyn micro-grid works by appropriately matching the bids and offers from the buyers and sellers, which is a common practice by the present-day energy trading.

Energy Market clearance using game-theory and facilitation of energy trade with the support of blockchain technology has received wide appreciation in the academic research domain. However, in the present electricity business models, its deployment is at nascent stage. Energy markets across globe make use of dispatch based on merit order of offers and bids which is often solved using linear programming [197]. In a practical sense, energy market operators shall be encouraged to adopt game theory-based energy market mechanism to evaluate its economic efficiency. Implementation process shall take up a small-scale to large-scale levels and replication of network-by-network implementation strategy.

IV. DISCUSSIONS

Existing works in smart grids and Energy Internet provides enlightenment in the technical aspects. Studies have discussed the concepts, architectures, structures, and energy trading mechanisms of Energy Internet. However, from a real-world implementation perspective, this study discusses development of Energy Internet from the existing smart grid infrastructure by focusing on the relevant technologies which act as key enablers. Few of these enabling technologies are already established and accessible. However, cost of these products remains high for an individual to access. Apprehensions over the reduction of cost of technologies such as storage systems, renewable energy systems, etc., over the years deter large investors on diffusing funds. In such cases, utilities can promote establishment of essential infrastructures by the end-consumers at their premises for the development of Energy Internet.

Study presents Energy Internet as a futuristic electricity system which can be made ready for implementation by transforming existing smart grid infrastructures. With the advancements in the current communication, energy management and payment technologies, Energy Internet is not a distant dream. It is capable to take various configurations to match the needs of the electricity system. For a network with few generators, prosumers, and consumers, Energy Internet can facilitate a peer-to-peer energy trading platform. Whereas, for a nation-wide network, Energy Internet can interconnect small-scale and large-scale energy sharing networks to facilitate energy trades. In countries where smart grid is well established can deploy Energy Internet in the form of small-scale energy sharing networks with existing smart grid technologies such as home energy management systems, renewable energy integration to the grid, energy storage systems and vehicle-to-grid technology. However, there are few hindrances related to policies which make these technologies arduous to access. On the policy frontier, regulatory bodies shall ease the procurement and deployment of advanced infrastructures at right specifications. Policies shall support utilization of data from such advanced devices to transform to a big data based artificial intelligence supported supervision system. Further, policy requirements for standardization and interoperability coordination between devices and agencies involved in the process shall be addressed.

V. CONCLUSION

This paper presented a synthesis of state-of-the-art of smart grids. Smart grid was recognized as the precursor to the Energy Internet. A detailed discussion on how evolutions in smart grid can play a significant role in enabling transition to Energy Internet was presented. This transition would be possible through features such as; home energy management, vehicle-to-grid program, renewable energy integration to grid, energy storage systems and communication technologies. It was observed that technologies, infrastructures, and operational strategies of energy systems were established for the transition to Energy Internet. However, there existed certain challenges such as; skepticism of investors, cyberthreats, regulatory challenges, interoperability and standardization issues are related to governance, institutions, and policies. Transitioning national electricity systems which can address aforementioned challenges are best suited for the implementation of Energy Internet. Such systems can develop Energy Internet with marginal incremental cost in their budget allocation. Therefore, these aspects play significant roles in deciding the readiness of an electricity system for the transition to Energy Internet. This is an area where further research is required.

The second part of the paper provides an overview of Energy Internet, its structure and energy market mechanisms. Game theoretic algorithms were widely used to formulate energy market algorithms since pre-smart grid era. In the modern era, an energy market based on blockchain is nowhere different from this. In future, researchers can formulate energy blockchain based markets in Energy Internet using game theoretic algorithms. By realizing such energy market model one can observe instantaneous energy trading and payment in Energy Internet through energy blockchains.

REFERENCES

[1] L. H. Tsoukalas, R. Gao, and W. Lafayette, "Inventing energy Internet The role of anticipation in human-centered energy distribution and utilization," in *Proc. SICE Annu. Conf.*, Aug. 2008, pp. 399–403, doi: 10.1109/SICE.2008.4654687.

[2] L. H. Tsoukalas and R. Gao, "From smart grids to an energy Internet: Assumptions, architectures and requirements," in *Proc. 3rd Int. Conf. Electric Utility Deregulation Restructuring Power Technol.*, Apr. 2008, pp. 94–98, doi: 10.1109/DRPT.2008.4523385.

[3] J. Rifkin, *The Third Industrial Revolution: How Lateral Power is Transforming Energy, the Economy, and the World*. New York, NY, USA: Macmillan, 2011.

[4] J. Rifkin, "Leading the way to the third industrial revolution," *Eur. Energ Rev.*, vol. 1, p. 2009, Dec. 2009.

[5] A. Huang, "FREEDM system–a vision for the future grid," in *Proc. IEEE PES Gen. Meeting*, Jul. 2010, pp. 4–7, doi: 10.1109/PES.2010.5590201.

[6] W. Su and A. Q. Huang, "A game theoretic framework for a next-generation retail electricity market with high penetration of distributed residential electricity suppliers," *Appl. Energy*, vol. 119, pp. 341–350, Apr. 2014, doi: 10.1016/j.apenergy.2014.01.003.

[7] N. Zhang, Y. Yan, and W. Su, "A game-theoretic economic operation of residential distribution system with high participation of distributed electricity prosumers," *Appl. Energy*, vol. 154, pp. 471–479, Sep. 2015, doi: 10.1016/j.apenergy.2015.05.011.

[8] S. R. Dabbagh and M. K. Sheikh-El-Eslami, "Risk-based profit allocation to DERs integrated with a virtual power plant using cooperative game theory," *Electr. Power Syst. Res.*, vol. 121, pp. 368–378, Apr. 2015, doi: 10.1016/j.epsr.2014.11.025.

[9] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets: A case study: The Brooklyn Microgrid," *Appl. Energy*, vol. 210, pp. 870–880, Jan. 2018.

[10] A. Joseph and P. Balachandra, "Energy Internet, the future electricity system: Overview, concept, model structure, and mechanism," *Energies*, vol. 13, no. 16, p. 4242, Aug. 2020, doi: 10.3390/en13164242.

[11] M. Shabanzadeh and M. P. Moghaddam, "What is the smart grid? Definitions, perspectives, and ultimate goals," in *Proc. 28th Int. Power Syst. Conf.*, Tehran, Iran, Nov. 2013.

[12] Electricity Networks Strategy Group. (Nov. 2009). *A Smart Grid Vision*. Framework. pp. 1–27. [Online]. Available: http://webarchive.nationalarchives.gov.uk/20100919181607/ and http://www.ensg.gov.uk/assets/ensg_smart_grid_wg_smart_grid_vision_final_issue_1.pdf

[13] Korean Smart Grid Institute. (2010). *Korea's Smart Grid Roadmap 2030*. Accessed: Sep. 29, 2018. [Online]. Available: https://www.smartgrid.or.kr/

[14] M. L. Tuballa and M. L. Abundo, "A review of the development of smart grid technologies," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 710–725, Jun. 2016, doi: 10.1016/j.rser.2016.01.011.

[15] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid—The new and improved power grid: A survey," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 4, pp. 944–980, 1st Quart., 2012, doi: 10.1109/SURV.2011.101911.00087.

[16] *Framework and Roadmap for Smart Grid Interoperability Standards*, NIST, Gaithersburg, MD, USA, 2012.

[17] *NIST Framework and Roadmap for smart grid interoperability standards Release 1.0*, Release, NIST, Gaithersburg, MD, USA, 2010, pp. 1–145. [Online]. Available: https://www.nist.gov/sites/default/files/documents/public_affairs/releases/smartgrid_interoperability_final.pdf

[18] European Commission. (2015). *Accelerating the European Energy System Transformation*. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/publication/Complete-A4-setplan.pdf

[19] L. Martini, "Trends of smart grids development as fostered by European research coordination: The contribution by the EERA JP on smart grids and the ELECTRA IRP," in *Proc. IEEE 5th Int. Conf. Power Eng., Energy Electr. Drives (POWERENG)*, May 2015, pp. 23–30, doi: 10.1109/PowerEng.2015.7266291.

[20] M. R. Hossain, A. M. T. Oo, and A. B. M. S. Ali, "Evolution of smart grid and some pertinent issues," in *Proc. 20th Australas. Universities Power Eng. Conf.*, Dec. 2010, pp. 1–6.

[21] H. Farhangi, "The path of the smart grid," *IEEE Power Energy Mag.*, vol. 8, no. 1, pp. 18–28, Jan. 2010, doi: 10.1109/MPE.2009.934876.

[22] S. M. Nosratabadi, R.-A. Hooshmand, and E. Gholipour, "A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems," *Renew. Sustain. Energy Rev.*, vol. 67, pp. 341–363, Jan. 2017, doi: 10.1016/j.rser.2016.09.025.

[23] K. Pandžić, H. Pandžić, and I. Kuzle, "Virtual storage plant offering strategy in the day-ahead electricity market," *Int. J. Electr. Power Energy Syst.*, vol. 104, pp. 401–413, Jan. 2019, doi: 10.1016/j.ijepes.2018.07.006.

[24] M. Cheng, S. S. Sami, and J. Wu, "Benefits of using virtual energy storage system for power system frequency response," *Appl. Energy*, vol. 194, pp. 376–385, May 2017, doi: 10.1016/j.apenergy.2016.06.113.

[25] G. Kats and A. Seal, "Buildings as batteries: The rise of 'Virtual storage,"' *Electr. J.*, vol. 25, no. 10, pp. 59–70, 2012, doi: 10.1016/j.tej.2012.11.004.

[26] H. Lund, *Analysis: Smart Energy Systems and Infrastructures*, E. Lund, Ed., 2nd ed. Boston, MA, USA: Academic, 2014, ch. 6, pp. 131–184.

[27] S. Massoud Amin and B. F. Wollenberg, "Toward a smart grid: Power delivery for the 21st century," *IEEE Power Energy Mag.*, vol. 3, no. 5, pp. 34–41, Sep. 2005, doi: 10.1109/MPAE.2005.1507024.

[28] F. Baig, A. Mahmood, N. Javaid, S. Razzaq, N. Khan, and Z. Saleem, "Smart home energy management system for monitoring and scheduling of home appliances using zigbee," *J. Basic Appl. Sci. Res.*, vol. 3, no. 5, pp. 880–891, 2013.

[29] A. Nilsson, M. Wester, D. Lazarevic, and N. Brandt, "Smart homes, home energy management systems and real-time feedback: Lessons for influencing household energy consumption from a swedish field study," *Energy Buildings*, vol. 179, pp. 15–25, Nov. 2018, doi: 10.1016/j.enbuild.2018.08.026.

[30] M. Eissa and A. Kassem, "Hierarchical clustering based optimal PMU placement for power system fault observability," *Heliyon*, vol. 4, no. 8, Aug. 2018, Art. no. e00725, doi: 10.1016/j.heliyon.2018.e00725.

[31] Z. Roumila, D. Rekioua, and T. Rekioua, "Energy management based fuzzy logic controller of hybrid system wind/photovoltaic/diesel with storage battery," *Int. J. Hydrogen Energy*, vol. 42, no. 30, pp. 19525–19535, Jul. 2017, doi: 10.1016/j.ijhydene.2017.06.006.

[32] E. Durán, J. M. Andujar, F. Segura, and A. J. Barragán, "A high-flexibility DC load for fuel cell and solar arrays power sources based on DC-DC converters," *Appl. Energy*, vol. 88, no. 5, pp. 1690–1702, 2011, doi: 10.1016/j.apenergy.2010.11.002.

[33] R. Ford, M. Pritoni, A. Sanguinetti, and B. Karlin, "Categories and functionality of smart home technology for energy management," *Building Environ.*, vol. 123, pp. 543–554, Oct. 2017, doi: 10.1016/j.buildenv.2017.07.020.

[34] B. S. Sami, N. Sihem, and Z. Bassam, "Design and implementation of an intelligent home energy management system: A realistic autonomous hybrid system using energy storage," *Int. J. Hydrogen Energy*, vol. 43, no. 42, pp. 19352–19365, Oct. 2018, doi: 10.1016/j.ijhydene.2018.09.001.

[35] H. Shareef, M. S. Ahmed, A. Mohamed, and E. Al Hassan, "Review on home energy management system considering demand responses, smart technologies, and intelligent controllers," *IEEE Access*, vol. 6, pp. 24498–24509, 2018, doi: 10.1109/ACCESS.2018.2831917.

[36] B. Zhou, W. Li, K. W. Chan, Y. Cao, Y. Kuang, X. Liu, and X. Wang, "Smart home energy management systems: Concept, configurations, and scheduling strategies," *Renew. Sustain. Energy Rev.*, vol. 61, pp. 30–40, Aug. 2016, doi: 10.1016/j.rser.2016.03.047.

[37] M. Beaudin and H. Zareipour, "Home energy management systems: A review of modelling and complexity," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 318–335, May 2015, doi: 10.1016/j.rser.2015.01.046.

[38] M. Shakeri, M. Shayestegan, S. M. S. Reza, I. Yahya, B. Bais, M. Akhtaruzzaman, K. Sopian, and N. Amin, "Implementation of a novel home energy management system (HEMS) architecture with solar photovoltaic system as supplementary source," *Renew. Energy*, vol. 125, pp. 108–120, Sep. 2018, doi: 10.1016/j.renene.2018.01.114.

[39] C. A. Correa-Florez, A. Gerossier, A. Michiorri, and G. Kariniotakis, "Stochastic operation of home energy management systems including battery cycling," *Appl. Energy*, vol. 225, pp. 1205–1218, Sep. 2018, doi: 10.1016/j.apenergy.2018.04.130.

[40] M. Killian, M. Zauner, and M. Kozek, "Comprehensive smart home energy management system using mixed-integer quadratic-programming," *Appl. Energy*, vol. 222, pp. 662–672, Jul. 2018, doi: 10.1016/j.apenergy.2018.03.179.

[41] X. Jin, K. Baker, D. Christensen, and S. Isley, "Foresee: A user-centric home energy management system for energy efficiency and demand response," *Appl. Energy*, vol. 205, pp. 1583–1595, Nov. 2017, doi: 10.1016/j.apenergy.2017.08.166.

[42] S. Mal, A. Chattopadhyay, A. Yang, and R. Gadh, "Electric vehicle smart charging and vehicle-to-grid operation," *Int. J. Parallel, Emergent Distrib. Syst.*, vol. 28, no. 3, pp. 249–265, Jun. 2013, doi: 10.1080/17445760.2012.663757.

[43] H. T. Haider, O. H. See, and W. Elmenreich, "A review of residential demand response of smart grid," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 166–178, Jun. 2016, doi: 10.1016/j.rser.2016.01.016.

[44] N. Shaukat, B. Khan, S. M. Ali, C. A. Mehmood, J. Khan, U. Farid, M. Majid, S. M. Anwar, M. Jawad, and Z. Ullah, "A survey on electric vehicle transportation within smart grid system," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 1329–1349, Jan. 2018, doi: 10.1016/j.rser.2017.05.092.

[45] A. Ahmadian, M. Sedghi, A. Elkamel, M. Fowler, and M. Aliakbar Golkar, "Plug-in electric vehicle batteries degradation modeling for smart grid studies: Review, assessment and conceptual framework," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 2609–2624, Jan. 2018, doi: 10.1016/j.rser.2017.06.067.

[46] M. Yilmaz and P. T. Krein, "Review of the impact of Vehicle-to-Grid technologies on distribution systems and utility interfaces," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5673–5689, Dec. 2013, doi: 10.1109/TPEL.2012.2227500.

[47] L. L. Grigsby, D. R. Tobergte, and S. Curtis, "Power systems," *J. Chem. Inf. Model.*, vol. 53, no. 9, p. 327, 2007, doi: 10.1017/CBO9781107415324.004.

[48] D. Manz, R. Walling, N. Miller, B. LaRose, R. D'Aquila, and B. Daryanian, "The grid of the future: Ten trends that will shape the grid over the next decade," *IEEE Power Energy Mag.*, vol. 12, no. 3, pp. 26–36, May 2014, doi: 10.1109/MPE.2014.2301516.

[49] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2151–2169, May 2013, doi: 10.1109/TPEL.2012.2212917.

[50] P. Richardson, D. Flynn, and A. Keane, "Impact assessment of varying penetrations of electric vehicles on low voltage distribution systems," in *Proc. IEEE PES Gen. Meeting*, Jul. 2010, pp. 1–6, doi: 10.1109/PES.2010.5589940.

[51] J. Geske and D. Schumann, "Willing to participate in vehicle-to-grid (V2G)? Why not!," *Energy Policy*, vol. 120, pp. 392–401, Sep. 2018, doi: 10.1016/j.enpol.2018.05.004.

[52] U. C. Chukwu and S. M. Mahajan, "Modeling of V2G net energy injection into the grid," in *Proc. 6th Int. Conf. Clean Electr. Power (ICCEP)*, Jun. 2017, pp. 437–440, doi: 10.1109/ICCEP.2017.8004724.

[53] J. Kester, L. Noel, G. Zarazua de Rubens, and B. K. Sovacool, "Promoting vehicle to grid (V2G) in the nordic region: Expert advice on policy mechanisms for accelerated diffusion," *Energy Policy*, vol. 116, pp. 422–432, May 2018, doi: 10.1016/j.enpol.2018.02.024.

[54] X. Lin, J. Sun, S. Ai, X. Xiong, Y. Wan, and D. Yang, "Distribution network planning integrating charging stations of electric vehicle with V2G," *Int. J. Electr. Power Energy Syst.*, vol. 63, pp. 507–512, Dec. 2014, doi: 10.1016/j.ijepes.2014.06.043.

[55] B. Aluisio, A. Conserva, M. Dicorato, G. Forte, and M. Trovato, "Optimal operation planning of V2G-equipped microgrid in the presence of EV aggregator," *Electr. Power Syst. Res.*, vol. 152, pp. 295–305, Nov. 2017, doi: 10.1016/j.epsr.2017.07.015.

[56] P. Staudt, M. Schmidt, J. Gärttner, and C. Weinhardt, "A decentralized approach towards resolving transmission grid congestion in Germany using vehicle-to-grid technology," *Appl. Energy*, vol. 230, pp. 1435–1446, Nov. 2018, doi: 10.1016/j.apenergy.2018.09.045.

[57] C. B. Robledo, V. Oldenbroek, F. Abbruzzese, and A. J. M. van Wijk, "Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology, photovoltaic power and a residential building," *Appl. Energy*, vol. 215, pp. 615–629, Apr. 2018, doi: 10.1016/j.apenergy.2018.02.038.

[58] M. R. Mozafar, M. H. Amini, and M. H. Moradi, "Innovative appraisement of smart grid operation considering large-scale integration of electric vehicles enabling V2G and G2 V systems," *Electr. Power Syst. Res.*, vol. 154, pp. 245–256, Jan. 2018, doi: 10.1016/j.epsr.2017.08.024.

[59] Y. Xiong, B. Wang, C.-C. Chu, and R. Gadh, "Vehicle grid integration for demand response with mixture user model and decentralized optimization," *Appl. Energy*, vol. 231, pp. 481–493, Dec. 2018, doi: 10.1016/j.apenergy.2018.09.139.

[60] H. Lin, Y. Liu, Q. Sun, R. Xiong, H. Li, and R. Wennersten, "The impact of electric vehicle penetration and charging patterns on the management of energy hub–A multi-agent system simulation," *Appl. Energy*, vol. 230, pp. 189–206, Nov. 2018, doi: 10.1016/j.apenergy.2018.08.083.

[61] L. Jian, Y. Zheng, X. Xiao, and C. C. Chan, "Optimal scheduling for vehicle-to-grid operation with stochastic connection of plug-in electric vehicles to smart grid," *Appl. Energy*, vol. 146, pp. 150–161, May 2015, doi: 10.1016/j.apenergy.2015.02.030.

[62] G. Krajačić, N. Duić, M. da Graça Carvalho, "H2RES, Energy planning tool for island energy systems–The case of the Island of Mljet," *Int. J. Hydrogen Energy*, vol. 34, no. 16, pp. 7015–7026, 2009, doi: 10.1016/j.ijhydene.2008.12.054.

[63] B. Möller, K. Sperling, S. Nielsen, C. Smink, and S. Kerndrup, "Creating consciousness about the opportunities to integrate sustainable energy on islands," *Energy*, vol. 48, no. 1, pp. 339–345, Dec. 2012, doi: 10.1016/j.energy.2012.04.008.

[64] A. K. M. S. Islam, M. M. Rahman, M. A. H. Mondal, and F. Alam, "Hybrid energy system for St. Martin island, bangladesh: An optimized model," *Procedia Eng.*, vol. 49, pp. 179–188, 2012, doi: 10.1016/j.proeng.2012.10.126.

[65] A. Busuttil, G. Krajačić, and N. Duić, "Energy scenarios for Malta," *Int. J. Hydrogen Energy*, vol. 33, no. 16, pp. 4235–4246, 2008, doi: 10.1016/j.ijhydene.2008.06.010.

[66] R. Segurado, G. Krajačić, N. Duić, and L. Alves, "Increasing the penetration of renewable energy resources in S. Vicente, cape verde," *Appl. Energy*, vol. 88, no. 2, pp. 466–472, Feb. 2011, doi: 10.1016/j.apenergy.2010.07.005.

[67] M. Child, A. Nordling, and C. Breyer, "Scenarios for a sustainable energy system in the Åland islands in 2030," *Energy Convers. Manage.*, vol. 137, pp. 49–60, Apr. 2017, doi: 10.1016/j.enconman.2017.01.039.

[68] N. Duic, G. Krajacic, and M. Dagracacarvalho, "RenewIslands methodology for sustainable energy and resource planning for islands," *Renew. Sustain. Energy Rev.*, vol. 12, no. 4, pp. 1032–1062, May 2008, doi: 10.1016/j.rser.2006.10.015.

[69] T. Weir, "Renewable energy in the pacific islands: Its role and status," *Renew. Sustain. Energy Rev.*, vol. 94, pp. 762–771, Oct. 2018, doi: 10.1016/j.rser.2018.05.069.

[70] A. Pfeifer, V. Dobravec, L. Pavlinek, G. Krajačić, and N. Duić, "Integration of renewable energy and demand response technologies in interconnected energy systems," *Energy*, vol. 161, pp. 447–455, Oct. 2018, doi: 10.1016/j.energy.2018.07.134.

[71] H. Lund and J. Z. Thellufsen, "EnergyPLAN—Advanced energy systems analysis computer model (version 15.1)," Zenodo, Sustain. Energy Planning Res. Group, Aalborg Univ., Aalborg, Denmark, Tech. Rep. 15.1, Sep. 2020, doi: 10.5281/zenodo.4017214.

[72] J. Liu, C. Mei, H. Wang, W. Shao, and C. Xiang, "Powering an island system by renewable energy—A feasibility analysis in the Maldives," *Appl. Energy*, vol. 227, pp. 18–27, Oct. 2018.

[73] J. Silvente and L. G. Papageorgiou, "An MILP formulation for the optimal management of microgrids with task interruptions," *Appl. Energy*, vol. 206, pp. 1131–1146, Nov. 2017, doi: 10.1016/j.apenergy.2017.08.147.

[74] D. Wang, J. Qiu, L. Reedman, K. Meng, and L. L. Lai, "Two-stage energy management for networked microgrids with high renewable penetration," *Appl. Energy*, vol. 226, pp. 39–48, Sep. 2018, doi: 10.1016/j.apenergy.2018.05.112.

[75] S. Howell, Y. Rezgui, J.-L. Hippolyte, B. Jayan, and H. Li, "Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources," *Renew. Sustain. Energy Rev.*, vol. 77, pp. 193–214, Sep. 2017, doi: 10.1016/j.rser.2017.03.107.

[76] H. Jiayi, J. Chuanwen, and X. Rong, "A review on distributed energy resources and MicroGrid," *Renew. Sustain. Energy Rev.*, vol. 12, no. 9, pp. 2472–2483, 2008, doi: 10.1016/j.rser.2007.06.004.

[77] W.-D. Zheng and J.-D. Cai, "A multi-agent system for distributed energy resources control in microgrid," in *Proc. 5th Int. Conf. Crit. Infrastruct. (CRIS)*, Sep. 2010, pp. 1–5, doi: 10.1109/CRIS.2010.5617485.

[78] S. D. J. McArthur, "Multi-agent systems for power engineering applications—Part I: Concepts, approaches, and technical challenges," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1743–1752, Nov. 2007, doi: 10.1109/TPWRS.2007.908471.

[79] M. Manfren, P. Caputo, and G. Costa, "Paradigm shift in urban energy systems through distributed generation: Methods and models," *Appl. Energy*, vol. 88, no. 4, pp. 1032–1048, Apr. 2011, doi: 10.1016/j.apenergy.2010.10.018.

[80] T. Ackermann, G. Andersson, and L. Söder, "Distributed generation: A definition," *Electr. Power Syst. Res.*, vol. 57, no. 3, pp. 195–204, Apr. 2001, doi: 10.1016/S0378-7796(01)00101-8.

[81] G. M. Masters, *Renewable and Efficient Electric Power Systems*. Hoboken, NJ, USA: Wiley, 2004.

[82] R. Kamphuis, P. Carlsson, C. J. Warmer, J. Kester, and K. Kok, "Distributed intelligence for supply/demand matching to improve embedding of distributed renewable energy sources," in *Proc. 2nd Int. Conf. Crit. Infrastruct. (CRIS)*, Grenoble, France, 2004, pp. 1–8.

[83] A. Rodriguez-Calvo, R. Cossent, and P. Frías, "Scalability and replicability analysis of large-scale smart grid implementations: Approaches and proposals in europe," *Renew. Sustain. Energy Rev.*, vol. 93, pp. 1–15, Oct. 2018, doi: 10.1016/j.rser.2018.03.041.

[84] R. Hledik, "How green is the smart grid?" *Electr. J.*, vol. 22, no. 3, pp. 29–41, Apr. 2009, doi: 10.1016/j.tej.2009.03.001.

[85] M. Wolsink, "The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources," *Renew. Sustain. Energy Rev.*, vol. 16, no. 1, pp. 822–835, Jan. 2012, doi: 10.1016/j.rser.2011.09.006.

[86] C. Walter, *Le Phénomène Leptokurtique BT–Nouvelles Normes Financières: S'organiser Face à la Crise*, C. Walter, Ed. Paris, France: Springer, 2010, pp. 59–77.

[87] K. Rahbar, M. R. Vedady Moghadam, S. K. Panda, and T. Reindl, "Shared energy storage management for renewable energy integration in smart grid," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Sep. 2016, pp. 1–5, doi: 10.1109/ISGT.2016.7781230.

[88] M. Qadrdan, N. Jenkins, and J. Wu, "Smart Grid and Energy Storage," *McEvoy's Handb. Photovolt.*, vol. 82, pp. 915–928, 2018, doi: 10.1016/B978-0-12-809921-6.00025-2.

[89] A. Mohd, E. Ortjohann, A. Schmelter, N. Hamsic, and D. Morton, "Challenges in integrating distributed energy storage systems into future smart grid," in *Proc. IEEE Int. Symp. Ind. Electron.*, Jun. 2008, pp. 1627–1632, doi: 10.1109/ISIE.2008.4676896.

[90] J. Makansi, *Lights Out: The Electricity Crisis, the Global Economy, and What it Means to You*. Hoboken, NJ, USA: Wiley, 2007.

[91] L. Liu, H. Xu, Z. Song, R. Liu, J. Zhang, and Z. Wang, "Phase difference determination by fringe pattern correlation," in *Proc. Int. Conf. Mechatronics Automat.*, vol. 50, Aug. 2009, pp. 4868–4873, doi: 10.1109/ICMA.2009.5246382.

[92] I. Dincer, "Smart energy solutions," *Int. J. Energy Res.*, vol. 40, no. 13, pp. 1741–1742, Oct. 2016, doi: 10.1002/er.3621.

[93] T. Bocklisch, "Hybrid energy storage systems for renewable energy applications," *Energy Procedia*, vol. 73, pp. 103–111, Jun. 2015, doi: 10.1016/j.egypro.2015.07.582.

[94] B. P. Roberts and C. Sandberg, "The role of energy storage in development of smart grids," *Proc. IEEE*, vol. 99, no. 6, pp. 1139–1144, Jun. 2011, doi: 10.1109/JPROC.2011.2116752.

[95] N. S. Wade, P. C. Taylor, P. D. Lang, and P. R. Jones, "Evaluating the benefits of an electrical energy storage system in a future smart grid," *Energy Policy*, vol. 38, no. 11, pp. 7180–7188, Nov. 2010, doi: 10.1016/j.enpol.2010.07.045.

[96] E. Barbour, D. Parra, Z. Awwad, and M. C. González, "Community energy storage: A smart choice for the smart grid?" *Appl. Energy*, vol. 212, pp. 489–497, Feb. 2018, doi: 10.1016/j.apenergy.2017.12.056.

[97] H. Lund, P. A. Østergaard, D. Connolly, I. Ridjan, B. V. Mathiesen, J. Z. Thellufsen, and P. Sorknæs, "Energy storage and smart energy systems," *Int. J. Sustain. Energy Planning Manage.*, vol. 11, pp. 3–14, Oct. 2016.

[98] H. Lund, P. A. Østergaard, D. Connolly, and B. V. Mathiesen, "Smart energy and smart energy systems," *Energy*, vol. 137, pp. 556–565, Oct. 2017, doi: 10.1016/j.energy.2017.05.123.

[99] K. Hansen, C. Breyer, and H. Lund, "Status and perspectives on 100% renewable energy systems," *Energy*, vol. 175, pp. 471–480, May 2019, doi: 10.1016/j.energy.2019.03.092.

[100] C. Zhang, Y.-L. Wei, P.-F. Cao, and M.-C. Lin, "Energy storage system: Current studies on batteries and power condition system," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3091–3106, Feb. 2018, doi: 10.1016/j.rser.2017.10.030.

[101] B. P. Koirala, E. van Oost, and H. van der Windt, "Community energy storage: A responsible innovation towards a sustainable energy system?" *Appl. Energy*, vol. 231, pp. 570–585, Dec. 2018, doi: 10.1016/j.apenergy.2018.09.163.

[102] S. Kakran and S. Chanana, "Smart operations of smart grids integrated with distributed generation: A review," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 524–535, Jan. 2018, doi: 10.1016/j.rser.2017.07.045.

[103] J. Qiu, J. Zhao, H. Yang, D. Wang, and Z. Y. Dong, "Planning of solar photovoltaics, battery energy storage system and gas micro turbine for coupled micro energy grids," *Appl. Energy*, vol. 219, pp. 361–369, Jun. 2018, doi: 10.1016/j.apenergy.2017.09.066.

[104] M. Bucciarelli, S. Paoletti, and A. Vicino, "Optimal sizing of energy storage systems under uncertain demand and generation," *Appl. Energy*, vol. 225, pp. 611–621, Sep. 2018, doi: 10.1016/j.apenergy.2018.03.153.

[105] P. Crespo Del Granado, Z. Pang, and S. W. Wallace, "Synergy of smart grids and hybrid distributed generation on the value of energy storage," *Appl. Energy*, vol. 170, pp. 476–488, May 2016, doi: 10.1016/j.apenergy.2016.01.095.

[106] H. Lund, "Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach," *Energy*, vol. 151, pp. 94–102, May 2018, doi: 10.1016/j.energy.2018.03.010.

[107] M. A. Piette, D. Watson, N. Motegi, and S. Kiliccote, "Automated critical PeakPricing field tests: 2006 pilot ProgramDescription and results," U.S. Dept. Energy Office Sci. Tech. Inf., Oak Ridge, TN, USA, Tech. Rep., 2007, doi: 10.2172/919387.

[108] D. C. Yeung and F. A. Morgan, "Utilities and two-way customer communication systems," *IEEE Commun. Mag.*, vol. 33, no. 4, pp. 33–38, Apr. 1995, doi: 10.1109/35.372191.

[109] A. Patrick, J. Newbury, and S. Gargan, "Two-way communications systems in the electricity supply industry," *IEEE Trans. Power Del.*, vol. 13, no. 1, pp. 53–58, Jan. 1998, doi: 10.1109/61.660849.

[110] M. Arian, V. Soleimani, B. Abasgholi, H. Modaghegh, and N. S. Gilani, "Advanced metering infrastructure system architecture," in *Proc. Asia–Pacific Power Energy Eng. Conf.*, Mar. 2011, vol. 6, no. 5, pp. 1–6, doi: 10.1109/APPEEC.2011.5749031.

[111] Y. Kabalci, "A survey on smart metering and smart grid communication," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 302–318, May 2016, doi: 10.1016/j.rser.2015.12.114.

[112] J. Zhou, R. Qingyang Hu, and Y. Qian, "Scalable distributed communication architectures to support advanced metering infrastructure in smart grid," *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 9, pp. 1632–1642, Sep. 2012, doi: 10.1109/TPDS.2012.53.

[113] S.-G. Kwack, G.-B. Chung, J. Choi, and G. Choi, "Development of artificial-intelligent power quality diagnosis equipment for single-phase power system," in *Proc. IEEE 2nd Int. Power Energy Conf.*, Dec. 2008, pp. 351–356, doi: 10.1109/PECON.2008.4762488.

[114] H. Cho, T. Yamazaki, and M. Hahn, "Determining location of appliances from multi-hop tree structures of power strip type smart meters," *IEEE Trans. Consum. Electron.*, vol. 55, no. 4, pp. 2314–2322, Nov. 2009, doi: 10.1109/TCE.2009.5373804.

[115] A. G. Ruzzelli, C. Nicolas, A. Schoofs, and G. M. P. O'Hare, "Real-time recognition and profiling of appliances through a single electricity sensor," in *Proc. 7th Annu. IEEE Commun. Soc. Conf. Sensor, Mesh Ad Hoc Commun. Netw. (SECON)*, Jun. 2010, pp. 1–9, doi: 10.1109/SECON.2010.5508244.

[116] S. Alam, M. F. Sohail, S. A. Ghauri, I. M. Qureshi, and N. Aqdas, "Cognitive radio based smart grid communication network," *Renew. Sustain. Energy Rev.*, vol. 72, pp. 535–548, May 2017, doi: 10.1016/j.rser.2017.01.086.

[117] M. Daoud and X. Fernando, "On the communication requirements for the smart grid," *Energy Power Eng.*, vol. 03, no. 01, pp. 53–60, 2011, doi: 10.4236/epe.2011.31008.

[118] C.-S. Sum, H. Harada, F. Kojima, Z. Lan, and R. Funada, "Smart utility networks in tv white space," *IEEE Commun. Mag.*, vol. 49, no. 7, pp. 132–139, Jul. 2011, doi: 10.1109/MCOM.2011.5936166.

[119] Y.-C. Chang and T.-C. Huang, "An interactive smart grid communication approach for big data traffic," *Comput. Electr. Eng.*, vol. 67, pp. 170–181, Apr. 2018, doi: 10.1016/j.compeleceng.2018.03.024.

[120] Y. Zhang, W. Chen, and W. Gao, "A survey on the development status and challenges of smart grids in main driver countries," *Renew. Sustain. Energy Rev.*, vol. 79, pp. 137–147, Nov. 2017, doi: 10.1016/j.rser.2017.05.032.

[121] A. O. Otuoze, M. W. Mustafa, and R. M. Larik, "Smart grids security challenges: Classification by sources of threats," *J. Electr. Syst. Inf. Technol.*, vol. 5, no. 3, pp. 468–483, Dec. 2018, doi: 10.1016/j.jesit.2018.01.001.

[122] S. Goel and Y. Hong, "Security challenges in smart grid implementation," in *Smart Grid Security* (SpringerBriefs in Cybersecurity). London, U.K.: Springer, 2015, doi: 10.1007/978-1-4471-6663-4_1.

[123] F. Li, B. Luo, and P. Liu, "Secure information aggregation for smart grids using homomorphic encryption," in *Proc. 1st IEEE Int. Conf. Smart Grid Commun.*, Oct. 2010, pp. 327–332, doi: 10.1109/SMARTGRID.2010.5622064.

[124] T. S. G. I. Panel and C. S. W. Group, "Smart grid cyber security strategy and requirements," Nat. Inst. Standards Technol., U.S. Dept. Commerce, Gaithersburg, MD, USA, Draft Interag. Rep. 7628, 2010. [Online]. Available: http://www.itl.nist.gov/div893/csrc/publications/drafts/%5Cnnistir-7628/draft-nistir-7628_2nd-public-draft.pdf

[125] A. Sanjab, W. Saad, I. Guvenc, A. Sarwat, and S. Biswas, "Smart grid security: Threats, challenges, and solutions," 2016, *arXiv:1606.06992*. [Online]. Available: http://arxiv.org/abs/1606.06992

[126] P. Yi, T. Zhu, Q. Zhang, Y. Wu, and J. Li, "A denial of service attack in advanced metering infrastructure network," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 1029–1034, doi: 10.1109/ICC.2014.6883456.

[127] A. R. Metke and R. L. Ekl, "Security technology for smart grid networks," *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 99–107, Jun. 2010, doi: 10.1109/TSG.2010.2046347.

[128] F. Mwasilu, J. J. Justo, E.-K. Kim, T. D. Do, and J.-W. Jung, "Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration," *Renew. Sustain. Energy Rev.*, vol. 34, pp. 501–516, Jun. 2014, doi: 10.1016/j.rser.2014.03.031.

[129] Y. Yoldaş, A. Önen, S. M. Muyeen, A. V. Vasilakos, and İ. Alan, "Enhancing smart grid with microgrids: Challenges and opportunities," *Renew. Sustain. Energy Rev.*, vol. 72, pp. 205–214, May 2017, doi: 10.1016/j.rser.2017.01.064.

[130] M. Soshinskaya, W. H. J. Crijns-Graus, J. M. Guerrero, and J. C. Vasquez, "Microgrids: Experiences, barriers and success factors," *Renew. Sustain. Energy Rev.*, vol. 40, pp. 659–672, Dec. 2014, doi: 10.1016/j.rser.2014.07.198.
[131] A. A. Salam, A. Mohamed, and M. A. Hannan, "Technical challenges on microgrids," *ARPN J. Eng. Appl. Sci.*, vol. 3, no. 6, pp. 64–69, 2008, doi: 10.1364/OE.20.021702.
[132] R. Zamora and A. K. Srivastava, "Controls for microgrids with storage: Review, challenges, and research needs," *Renew. Sustain. Energy Rev.*, vol. 14, no. 7, pp. 2009–2018, Sep. 2010, doi: 10.1016/j.rser.2010.03.019.
[133] C. P. Vineetha and C. A. Babu, "Smart grid challenges, issues and solutions," in *Proc. Int. Conf. Intell. Green Building Smart Grid (IGBSG)*, Apr. 2014, pp. 1–4, doi: 10.1109/IGBSG.2014.6835208.
[134] J. Joy, E. A. Jasmin, and V. R. John, "Challenges of Smart Grid," *Int. J. Adv. Res. Electr. Electron. Instrum. Eng.*, vol. 2, no. 3, pp. 976–981, 2013, doi: 10.1007/978-3-319-25391-6.
[135] A. Gaviano, K. Weber, and C. Dirmeier, "Challenges and integration of PV and wind energy facilities from a smart grid point of view," *Energy Procedia*, vol. 25, pp. 118–125, 2012, doi: 10.1016/j.egypro.2012.07.016.
[136] P. Basak, S. Chowdhury, S. Halder nee Dey, and S. P. Chowdhury, "A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid," *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, pp. 5545–5556, Oct. 2012, doi: 10.1016/j.rser.2012.05.043.
[137] S. Mirsaeidi, D. Mat Said, M. Wazir Mustafa, M. Hafiz Habibuddin, and K. Ghaffari, "Progress and problems in micro-grid protection schemes," *Renew. Sustain. Energy Rev.*, vol. 37, pp. 834–839, Sep. 2014, doi: 10.1016/j.rser.2014.05.044.
[138] L. Che, M. E. Khodayar, and M. Shahidehpour, "Adaptive protection system for microgrids: Protection practices of a functional microgrid system," *IEEE Electrific. Mag.*, vol. 2, no. 1, pp. 66–80, Mar. 2014, doi: 10.1109/MELE.2013.2297031.
[139] D. Baimel, S. Tapuchi, and N. Baimel, "Smart grid communication technologies- overview, research challenges and opportunities," in *Proc. Int. Symp. Power Electron., Electr. Drives, Autom. Motion (SPEEDAM)*, Jun. 2016, pp. 116–120, doi: 10.1109/SPEEDAM.2016.7526014.
[140] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "Smart grid technologies: Communication technologies and standards," *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 529–539, Nov. 2011, doi: 10.1109/TII.2011.2166794.
[141] R. Leszczyna, "Standards on cyber security assessment of smart grid," *Int. J. Crit. Infrastruct. Protection*, vol. 22, pp. 70–89, Sep. 2018, doi: 10.1016/j.ijcip.2018.05.006.
[142] N. S. Nafi, K. Ahmed, M. A. Gregory, and M. Datta, "A survey of smart grid architectures, applications, benefits and standardization," *J. Netw. Comput. Appl.*, vol. 76, pp. 23–36, Dec. 2016, doi: 10.1016/j.jnca.2016.10.003.
[143] N. Rosenberg, "EBSCOhost: The role of electricity in industrial development," *Energy J.*, vol. 19, no. 2, pp. 7–24, 1998. [Online]. Available: http://web.ebscohost.com/ehost/detail?sid=e637bbed-ff19-4fac-9580-e59c913785f5%40sessionmgr10&vid=4&hid=18&bdata=Jmxhbmc9ZXMmc2l0ZT1laG9zdC1saXZl#db=a9h&AN=491875
[144] D. P. Kaundinya, P. Balachandra, and N. H. Ravindranath, "Grid-connected versus stand-alone energy systems for decentralized power—A review of literature," *Renew. Sustain. Energy Rev.*, vol. 13, no. 8, pp. 2041–2050, 2009, doi: 10.1016/j.rser.2009.02.002.
[145] X. Zhou, F. Wang, and Y. Ma, "An overview on energy Internet," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, Aug. 2015, pp. 126–131, doi: 10.1109/ICMA.2015.7237469.
[146] K. Zhou, S. Yang, and Z. Shao, "Energy Internet: The business perspective," *Appl. Energy*, vol. 178, pp. 212–222, Sep. 2016, doi: 10.1016/j.apenergy.2016.06.052.
[147] W. Su, "The role of customers in the U.S. electricity market: Past, present and future," *Electr. J.*, vol. 27, no. 7, pp. 112–125, Aug. 2014, doi: 10.1016/j.tej.2014.07.006.
[148] W. Su and A. Q. Huang, "Proposing a electricity market framework for the Energy Internet," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2013, pp. 1–5, doi: 10.1109/PESMG.2013.6672224.
[149] J. Cao and M. Yang, "Energy Internet–towards smart grid 2.0," in *Proc. 4th Int. Conf. Netw. Distrib. Comput.*, Dec. 2013, pp. 105–110, doi: 10.1109/ICNDC.2013.10.
[150] Q. Sun, R. Han, H. Zhang, J. Zhou, and J. M. Guerrero, "A multiagent-based consensus algorithm for distributed coordinated control of distributed generators in the energy Internet," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 3006–3019, Nov. 2015, doi: 10.1109/TSG.2015.2412779.
[151] E. M. Najm, Y. Xu, and A. Q. Huang, "Low cost plug-and-play PV system for DC microgrid," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2015, pp. 4236–4242, doi: 10.1109/ECCE.2015.7310258.
[152] X. Yu, F. Wang, and A. Q. Huang, "Power management strategy for plug and play DC microgrid," in *Proc. 3rd IEEE PES Innov. Smart Grid Technol. Eur. (ISGT Europe)*, Oct. 2012, pp. 1–7, doi: 10.1109/ISGTEurope.2012.6465882.
[153] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, and S. J. Dale, "The future renewable electric energy delivery and management (FREEDM) system: The energy Internet," *Proc. IEEE*, vol. 99, no. 1, pp. 133–148, Jan. 2011.
[154] Y. Xu, J. Zhang, W. Wang, A. Juneja, and S. Bhattacharya, "Energy router: Architectures and functionalities toward energy Internet," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Oct. 2011, pp. 31–36, doi: 10.1109/SmartGridComm.2011.6102340.
[155] J. Miao, N. Zhang, C. Kang, J. Wang, Y. Wang, and Q. Xia, "Steady-state power flow model of energy router embedded AC network and its application in optimizing power system operation," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4828–4837, Sep. 2018, doi: 10.1109/TSG.2017.2672821.
[156] L. Tarisciotti, P. Zanchetta, S. Pipolo, and S. Bifaretti, "Three-port energy router for universal and flexible power management in future smart distribution grids," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2017, pp. 1276–1281, doi: 10.1109/ECCE.2017.8095936.
[157] J. Sun, L. Yuan, Q. Gu, and Z. Zhao, "Startup strategy with constant peak transformer current for hybrid multilevel energy router," in *Proc. 20th Int. Conf. Electr. Mach. Syst. (ICEMS)*, Aug. 2017, pp. 1–6, doi: 10.1109/ICEMS.2017.8056121.
[158] P. Sorknæs, H. Lund, I. R. Skov, S. Djørup, K. Skytte, P. E. Morthorst, and F. Fausto, "Smart energy markets–future electricity, gas and heating markets," *Renew. Sustain. Energy Rev.*, vol. 119, Mar. 2020, Art. no. 109655, doi: 10.1016/j.rser.2019.109655.
[159] S. Mishra and S. N. Singh, "Indian electricity market: Present status and future directions," in *Proc. IEEE UP Sect. Conf. Electr. Comput. Electron. (UPCON)*, Dec. 2015, pp. 1–7, doi: 10.1109/UPCON.2015.7456754.
[160] W. Xing and F. F. Wu, "A game-theoretical model of private power production," *Int. J. Elect. Power Energy Syst.*, vol. 23, no. 3, pp. 213–218, 2001, doi: 10.1016/S0142-0615(00)00059-4.
[161] J. Ruusunen, H. Ehtamo, and R. P. Hamalainen, "Dynamic cooperative electricity exchange in a power pool," *IEEE Trans. Syst., Man, Cybern.*, vol. 21, no. 4, pp. 758–766, Jul./Aug. 1991, doi: 10.1109/21.108294.
[162] A. Kuwahata and H. Asano, "Utility-cogenerator game for pricing power sale and wheeling fees," *IEEE Trans. Power Syst.*, vol. 9, no. 4, pp. 1875–1879, Nov. 1994, doi: 10.1109/59.331444.
[163] H. Singh, "Introduction to game theory and its application in electric power markets," *IEEE Comput. Appl. Power*, vol. 12, no. 4, pp. 18–20, Oct. 1999, doi: 10.1109/67.795133.
[164] A. Haurie, R. Loulou, and G. Savard, "A two-player game model of power cogeneration in new england," *IEEE Trans. Autom. Control*, vol. 37, no. 9, pp. 1451–1456, Sep. 1992, doi: 10.1109/9.159591.
[165] S. N. Siddiqi and M. L. Baughman, "Optimal pricing of non-utility generated electric power," *IEEE Trans. Power Syst.*, vol. 9, no. 1, pp. 397–403, Feb. 1994, doi: 10.1109/59.317585.
[166] C. G. Min, M. K. Kim, J. K. Park, and Y. T. Yoon, "Game-theory-based generation maintenance scheduling in electricity markets," *Energy*, vol. 55, pp. 310–318, Jun. 2013, doi: 10.1016/j.energy.2013.03.060.
[167] L. Geerli, L. Chen, and R. Yokoyama, "Pricing and operation in deregulated electricity market by noncooperative game," *Electr. Power Syst. Res.*, vol. 57, no. 2, pp. 133–139, Mar. 2001, doi: 10.1016/S0378-7796(01)00094-3.
[168] N. X. Jia and R. Yokoyama, "Profit allocation of independent power producers based on cooperative Game theory," in *Int. J. Elect. Power Energy Syst.*, vol. 25, no. 8, pp. 633–641, 2003, doi: 10.1016/S0142-0615(02)00180-1.
[169] D. Gan, J. Wang, and D. Bourcier, "An auction game model for pool-based electricity markets," *Int. J. Electr. Power Energy Syst.*, vol. 27, no. 7, pp. 480–487, Sep. 2005, doi: 10.1016/j.ijepes.2005.06.001.

[170] D.-J. Kang, B. H. Kim, and D. Hur, "Supplier bidding strategy based on non-cooperative game theory concepts in single auction power pools," *Electr. Power Syst. Res.*, vol. 77, nos. 5–6, pp. 630–636, Apr. 2007, doi: 10.1016/j.epsr.2006.05.012.

[171] H. A. Shayanfar, A. S. Lahiji, J. Aghaei, and A. Rabiee, "Generation expansion planning in pool market: A hybrid modified game theory and improved genetic algorithm," *Energy Convers. Manage.*, vol. 50, no. 5, pp. 1149–1156, May 2009, doi: 10.1016/j.enconman.2009.02.001.

[172] W. Saad, Z. Han, H. V. Poor, and T. Başar, "Game-theoretic methods for the smart grid: An overview of microgrid systems, demand-side management, and smart grid communications," *IEEE Signal Process. Mag.*, vol. 29, no. 5, pp. 86–105, Sep. 2012, doi: 10.1109/MSP.2012.2186410.

[173] S. Uryas'ev and R. Y. Rubinstein, "On relaxation algorithms in computation of noncooperative equilibria," *IEEE Trans. Autom. Control*, vol. 39, no. 6, pp. 1263–1267, Jun. 1994, doi: 10.1109/9.293193.

[174] T. Başar, "Relaxation techniques and asynchronous algorithms for on-line computation of non-cooperative equilibria," *J. Econ. Dyn. Control*, vol. 11, no. 4, pp. 531–549, 1987, doi: 10.1016/S0165-1889(87)80006-4.

[175] S. Li and T. Başar, "Distributed algorithms for the computation of noncooperative equilibria," *Automatica*, vol. 23, no. 4, pp. 523–533, 1987, doi: 10.1016/0005-1098(87)90081-1.

[176] J. B. Krawczyk and S. Uryasev, "Relaxation algorithms to find Nash equilibria with economic applications," *Environ. Model. Assessment*, vol. 5, no. 1, pp. 63–73, 2000, doi: 10.1023/A:1019097208499.

[177] J. Contreras, M. Klusch, and J. B. Krawczyk, "Numerical solutions to Nash-Cournot equilibria in coupled constraint electricity markets," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 195–206, Feb. 2004, doi: 10.1109/TPWRS.2003.820692.

[178] D. Tapscott and A. Tapscott, *Blockchain Revolution: How the Technology Behind Bitcoin and Other Cryptocurrencies is Changing The World*. New York, NY, USA: Penguin Random House, 2018.

[179] X. Li, P. Jiang, T. Chen, X. Luo, and Q. Wen, "A survey on the security of blockchain systems," *Future Gener. Comput. Syst.*, vol. 107, pp. 841–853, Jun. 2020, doi: 10.1016/j.future.2017.08.020.

[180] S. Noor, W. Yang, M. Guo, K. H. van Dam, and X. Wang, "Energy demand side management within micro-grid networks enhanced by blockchain," *Appl. Energy*, vol. 228, pp. 1385–1398, Oct. 2018, doi: 10.1016/j.apenergy.2018.07.012.

[181] C. Prybila, S. Schulte, C. Hochreiner, and I. Weber, "Runtime verification for business processes utilizing the bitcoin blockchain," *Future Gener. Comput. Syst.*, vol. 107, pp. 816–831, Jun. 2020.

[182] C. Pop, T. Cioara, M. Antal, I. Anghel, I. Salomie, and M. Bertoncini, "Blockchain based decentralized management of demand response programs in smart energy grids," *Sensors*, vol. 18, no. 2, p. 162, Jan. 2018, doi: 10.3390/s18010162.

[183] S. Mansfield-Devine, "Beyond Bitcoin: Using blockchain technology to provide assurance in the commercial world," *Comput. Fraud Secur.*, vol. 2017, no. 5, pp. 14–18, 2017, doi: 10.1016/S1361-3723(17)30042-8.

[184] Z. Zheng, S. Xie, H. Dai, X. Chen, and H. Wang, "An overview of blockchain technology: Architecture, consensus, and future trends," in *Proc. IEEE Int. Congr. Big Data (BigData Congress)*, Jun. 2017, pp. 557–564, doi: 10.1109/BigDataCongress.2017.85.

[185] F. Tschorsch and B. Scheuermann, "Bitcoin and beyond: A technical survey on decentralized digital currencies," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 2084–2123, 3rd Quart., 2016, doi: 10.1109/COMST.2016.2535718.

[186] A. Savelyev, "Copyright in the blockchain era: Promises and challenges," *Comput. Law Secur. Rev.*, vol. 34, no. 3, pp. 550–561, 2018, doi: 10.1016/j.clsr.2017.11.008.

[187] M. Mettler, "Blockchain technology in healthcare: The revolution starts here," in *Proc. IEEE 18th Int. Conf. e-Health Netw., Appl. Services (Healthcom)*, Sep. 2016, pp. 1–3, doi: 10.1109/HealthCom.2016.7749510.

[188] T. Kumar, V. Ramani, I. Ahmad, A. Braeken, E. Harjula, and M. Ylianttila, "Blockchain utilization in healthcare: Key requirements and challenges," in *Proc. IEEE 20th Int. Conf. e-Health Netw., Appl. Services (Healthcom)*, Sep. 2018, pp. 1–7, doi: 10.1109/HealthCom.2018.8531136.

[189] J. J. Sikorski, J. Haughton, and M. Kraft, "Blockchain technology in the chemical industry: Machine-to-machine electricity market," *Appl. Energy*, vol. 195, pp. 234–246, Jun. 2017, doi: 10.1016/j.apenergy.2017.03.039.

[190] J. Green and P. Newman, "Corrigendum to 'Citizen utilities: The emerging power paradigm' [Energy Policy 105 (2017) 283–293]," *Energy Policy*, vol. 107, p. 370, Aug. 2017, doi: 10.1016/j.enpol.2017.04.036.

[191] F. Imbault, M. Swiatek, R. de Beaufort, and R. Plana, "The green blockchain: Managing decentralized energy production and consumption," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Europe)*, Jun. 2017, pp. 1–5, doi: 10.1109/EEEIC.2017.7977613.

[192] L. Wu, K. Meng, S. Xu, S. Li, M. Ding, and Y. Suo, "Democratic centralism: A hybrid blockchain architecture and its applications in energy Internet," in *Proc. IEEE Int. Conf. Energy Internet (ICEI)*, Apr. 2017, pp. 176–181, doi: 10.1109/ICEI.2017.38.

[193] M. Mihaylov, S. Jurado, N. Avellana, K. Van Moffaert, I. M. de Abril, and A. Nowe, "NRGcoin: Virtual currency for trading of renewable energy in smart grids," in *Proc. 11th Int. Conf. Eur. Energy Market (EEM14)*, May 2014, pp. 1–6, doi: 10.1109/EEM.2014.6861213.

[194] E. Al Kawasmi, E. Arnautovic, and D. Svetinovic, "Bitcoin-based decentralized carbon emissions trading infrastructure model," *Syst. Eng.*, vol. 18, no. 2, pp. 115–130, Mar. 2015, doi: 10.1002/sys.21291.

[195] N. Z. Aitzhan and D. Svetinovic, "Security and privacy in decentralized energy trading through multi-signatures, blockchain and anonymous messaging streams," *IEEE Trans. Dependable Secure Comput.*, vol. 15, no. 5, pp. 840–852, Sep. 2018, doi: 10.1109/TDSC.2016.2616861.

[196] M. E. Peck and D. Wagman, "Energy trading for fun and profit buy your neighbor's rooftop solar power or sell your own-it'll all be on a blockchain," *IEEE Spectr.*, vol. 54, no. 10, pp. 56–61, Oct. 2017, doi: 10.1109/MSPEC.2017.8048842.

[197] F. Lu and H. Gan, "National electricity market of Singapore," in *Proc. Int. Power Eng. Conf.*, Nov./Dec. 2005, pp. 1007–1012, doi: 10.1109/IPEC.2005.207055.

AKHIL JOSEPH received the B.Tech. degree from Amrita Vishwa Vidyapeetham University, Coimbatore, India, in 2012, the M.B.A. degree in power management from the National Power Training Institute, Faridabad, India, in 2014, and the Ph.D. degree in energy economics and sustainability from the Indian Institute of Science, Bengaluru, India, in 2019.

From January 2019 to January 2020, he worked as a Research Associate with the Indian Institute of Science. In February 2020, he took over the position as a Research Fellow with the Energy Research Institute, Nanyang Technological University, Singapore. His research interests include energy Internet, energy markets, vehicle-to-grid integration, and energy systems.

PATIL BALACHANDRA received the Ph.D. degree from the Indian Institute of Science, Bengaluru, India.

He has 33 years of experience as a Faculty Member with the Indian Institute of Science and a Visiting Expert with Harvard University, Cambridge, MA, USA; UNDP, Bangkok, Thailand; and the Asian Institute of Technology, Bangkok; and the Indira Gandhi Institute of Development Research, Mumbai, India. He is an energy, environment, and sustainability expert and ranked among the top ten management researchers in India. He has performed about 40 research and consultancy assignments for UNDP, European Commission, World Bank, SIDA, SANEI, RCUK, AIT, TERI, IGIDR, DST, and various ministries of the Government of India and private sector organizations. He has coauthored six books and published about 150 papers in international and national journals, conferences, and edited books with an H-index of 25. He has supervised 29 Ph.D. scholars (13 completed and 16 on going). His current research interests include energy and environmental economics and policy, sustainability transition, sustainable energy access, energy-technology-empowerment-sustainability nexus, climate change, and techno economic and financial feasibility analysis. He is ranked number one researcher in the strategic management domain in India. He is also ranked among top 2% of Energy Scientists in the World.

Dr. Balachandra was a recipient of the Distinguished Alumni Award of Manipal University in 2011.