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Published in:
Applied Energy

DOI (link to publication from Publisher):
10.1016/j.apenergy.2022.119003

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Wu, Y., Wu, Y., Çimen, H., Vasquez, J. C., & Guerrero, J. M. (2022). Towards collective energy Community: Potential roles of microgrid and blockchain to go beyond P2P energy trading. *Applied Energy*, *314*(2022), [119003]. https://doi.org/10.1016/j.apenergy.2022.119003

Applied Energy 314 (2022) 119003

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Towards collective energy Community: Potential roles of microgrid and blockchain to go beyond P2P energy trading

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HIGHLIGHTS

- Microgrid and blockchain alone and together enable collective energy communities.
- Microgrid as local aggregator of control and communication with regulated grid.
- Blockchain as interactive aggregator of large-scale framework and service in trust.
- Survey on co-creation of microgrid-blockchain in research, applications and pilots.
- Future trends are analyzed on microgrid-blockchain innovation in energy transition.

ARTICLE INFO

Keywords:
Microgrid
Blockchain
Energy community
Grid edge
P2P energy trading
Collective self-consumption

ABSTRACT

Decarbonisation of energy sector is crucial to deliver the future net zero energy system with promoting and facilitating the large-scale electrification of end-user sectors. It is necessary to provide sustainable, cost-effective, resilient and scalable energy solutions to exploit the power of citizens to contribute to the clean energy transition, increasing the flexibility of the overall energy system. Energy community, as the new actor, create an integrated pan energy market by bringing together the local consumers and energy market players. However, diversity of energy community brings huge challenges in integration of decentralized renewables with regulated framework, interaction of decentralized marketplaces, as well as interoperability of the cross-border energy sectors with privacy, security and incentives. This paper intends to provide an in-depth investigation on the role of microgrid and blockchain, alone and together, in facilitating the energy community as the "enabling framework" to boost the potential solutions of electrification in the transportation, building, and industrial sectors, as well as rural/remote areas and islands towards a networking green ecosystem. This paper serves as a comprehensive reference to understand the modern microgrid on its control and communication technology with integration of blockchain services in promoting the techno-socio-economic innovations for the restructuring of the sustainable energy supply chain.

1. Introduction

1.1. Background

Energy sector accounts for almost 75% of greenhouse gas emissions that has an existential threat on global climate change [1]. Sustainability and deep decarbonization is the long-term but urgent goal for energy transition. According to IRENA 2020 report, 70% of the global energy-related CO_2 will be cut by 2050 and over 90% of this reduction will be achieved by renewables, energy efficiency and electrification [2]. Co-design and co-creation under a cyber-physical-social perspective to accelerate the multi-directional electrification is promoted to boost a well-coordinated clean energy transition. It triggers the 'Horizontal' sector-coupling among integrated energy consuming communities as well as the 'Vertical' actor-cooperation between small-scale distributed market players and traditional regulated players. Therefore, it is essential to provide sustainable solutions to create strong links of these increasing flexible units from the cyber, physical and social systems. Especially the following aspects should be highlighted: 1) Engagement and interaction of end users with privacy and security, 2) Integration of

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https://doi.org/10.1016/j.apenergy.2022.119003
Received 14 December 2021; Received in revised form 24 February 2022; Accepted 21 March 2022
Available online 30 March 2022

data-driven innovations for large-scale flexibility and optimization, 3) Cooperation of behind-the-meter activities and in-fond-of-the-meter activities, 4) Interaction and coordination of integrated demand response of multiple energy system.

1.2. State of the art

Digitalization of energy has great impact overall energy value chain and changed the way of selling and buying energy. The use of Information and Communication Technologies (ICT) dramatically increases the interaction capacity of energy resources, market players and new tools for energy management. The development of digital communication and engagement tools are supported by national policy makers all over the world [3], e.g., UK government launched Simple Energy Advice [4], US Department of Energy offered Database of State Incentives for Renewables and Efficiency (DSIRE) [5], The South African opened Smart Buildings [6]. To meet the European Green Deal ambitions [7], European Community (EU) has especially announced the digitalization action plan for energy sector to define a roadmap with concrete steps, which will be completed in early 2022 [8]. It aims to unleash the flexibility potentials of energy supply and demand in different sectors to improve the share of renewables by providing concrete steps for integrating innovative services from ICT, including development of the data-sharing infrastructure, cybersecurity, citizen power and digital technology. Digitalization envisions not only the ubiquitous communication of energy resources, but also the interaction of distributed end users with ability to supply energy with their roof PVs, household storages and electric vehicles (EVs) [9]. A flexible distributed energy sharing and transaction network is initialized to unlock the flexibility potentials of the grid edge, opening a new market dimension for consumers, prosumers and neighbors [10].

Energy community is one of the most successful energy initiatives to active small actors in the energy market. There is a growing interest in citizens' participation in energy transition for long-term sustainability in the world. In May 2019, EU in its "Clean Energy for All Europeans Legislative Package (CEP)" gave the legislative definition of energy community and stressed the significant role of citizen in providing flexibility to help EU meet its climate and energy objectives in 2030 [11]. According to the report "The energy transition to energy democracy" from REScoop, there are more than 2,400 energy communities in Europe at the beginning of 2015 and currently 1500 have been represented in REScoop [12]. The further regulations of renewable energy communities (RECs) and citizen energy communities (CECs) are defined in the European Union with national laws and policies [13]. RECs are centered around the renewable energy resources, while CECs on the other hand, are constrained to electricity only, but can cover wider activities and energy efficiency services [14]. From the BRIDGE[15] report 'Economies of Energy communities', EU Member States have until June 2021 to transpose the concept of CECs and RECs into their national laws [16]. Energy consumers are legally empowered as prosumers of all shapes and sizes to sell and buy energy anytime and anywhere. Especially with the development of affordable small-scale clean energy units and advanced power-to-x (P2X) and vehicle-to-grid (V2G) technologies, the grid edge, which is the interface between the grid and distributed end uses [17], has been empowered to take control of distributed energy supply and demand in integrated energy market [18].

To achieve the grid edge resilience and guarantee the reliable grid interaction, a well-controlled microgrid system is necessary to optimize the grid edge flexibility as well as promote the security of low-cost clean energy injection. Microgrid, representing as a controlled paradigm, has already extended its roles from the cost effective central station for remote or rural electricity access towards more localized energy regulated framework for the sustainable grid-interaction. With two operation modes, microgrid can not only serve its internal loads and its neighborhood communities by 'islanding' itself from the grid in emergencies to enhance the grid edge resiliency [19], but also offer grid dynamic flexibility in connection mode to promote the injection of low-cost clean energy with stability and sustainability. Especially with the integration of advance ICT, microgrid gets its wings to serve as the backbone of the modern grid with its three strong abilities: 1) renewable energy resource integration, 2) grid stability and sustainability, and 3) DR-based energy optimization and individualization [20]. Modern microgrids provide effective solutions to establish a robust supply and demand energy network, which enable the cross-border interconnections for a wider and deeper exchange of flexibility over decentralized resources. With the integration of advanced H_2/MeOH storages and e-mobility charging systems, microgrids offer competitive solutions to optimize and streamline the deployment of local renewables for variable usage [21]. Community microgrid, regarded as the most reliable and economical concept to tackle the techno-social challenges, is integrating the AC, DC and hybrid AC/DC microgrid technologies into communities to maximize the flexibility from the social perspective on consumers/prosumers and from the technical perspective on distributed energy resources [22].

It is no doubt that microgrid efficiently empowers the energy community as an "enabling framework", promoting and facilitating the deployment of clean energy resources. Energy communities have provided great potentials for energy transition, such as flexibility, interconnectivity, bi-directionality and complementarity. A dataset of 67 best-practice cases from 18 countries is investigated to show the importance, opportunities and advantages of energy community in global energy roadmap [23].

1.3. Issues and motivations

It is true that decentralization has brought great potentials for cross-border interactions to improve the transaction capacity. However, diversities of embedded technologies, actors and services will definitely lead to heterogeneous complexities. Especially with the increasing engagement of new distributed players from various energy communities and the development of innovative behind-the-meter flexibility activities, new energy utilization patterns and innovative business models are emerging to promote the utilization of renewable energy, such as aggregators, P2P electricity trading, energy-as-a-service, community-ownership models and pay-as-you-go models [24]. These new actors empower the last mile of the grid, exploiting the power of small or medium-sized distributed energy resources, including distributed generators (roof PV panel, wind turbine), energy storage (private, public), and controllable loads (EVs, heat pumps, households/buildings). It enriches the flexibility capacity, but it also presents huge pressures and challenges to the regulated energy system. The influx of various resources, actors, services and models will definitely bring various uncertainties to the grid due to the intermittent nature of the renewable energy generators, multi-directional power flows, and multi-timescale energy flexibility provisions. Technical, social and economic related issues need to be targeted separately to facilitate energy community as the "enabling framework" to achieve carbon neutrality by 2050[25]. For the technical dimension, the large requirement in cyber connection among energy units promotes the grid stability issues with integration of complicated undispatchable power flows and multi-scale energy management services. For the social dimension, public support from the end users with their awareness and engagement is essential to lead the energy transition from the bottom up [26], but they need incentives to join in with security and privacy. For the economic dimension, decentralized market players definitely change the regulatory market structure, but resilience and dynamic balancing issues are arising on both different time and space scales. Therefore, innovative measures are needed to exploit the power of the small-size and non-professional distributed players as well as maintain the roles and responsibility of the professional big players, such as distribution system operator (DSO), transmission system operator (TSO), and utilities.

To target the above three-dimension issues, this paper investigates the microgrid-blockchain enabled innovative measures and potentials to boost the electrification of grid edge. It systematically discusses the current challenges, research gaps and future methodologies over the following three key fields: transmission before storage, resilience and security of grid, and cross-border integration. It explores their co-creation values to achieve the collective energy community. With the support of ICT, energy-aware data can be collected over the whole energy chain and shared among all energy sectors. More effective demand-side management and secure energy data services in the grid edge will enhance the balancing capacity of supply and demand. IoT, currently acting as the fundamental architecture of modern energy system, enables the generation and management of vast amounts of data by connecting energy suppliers, consumers and grid infrastructure [27]. The availability of real-time data not only help policy makers to set clear targets but also benefit stakeholders to access add-valued services with innovative business models. While blockchain, as a kind of distributed ledger technology with great success in cryptocurrencies, has gained significant attention in energy decentralization for managing the integration of the large-scale and heterogeneous IoT systems with data privacy, cybersecurity and reliability [28]. It is a breakthrough in establishing trust for peer-to-peer (P2P) interaction of different organizations without third parties. Two of the Big Four accounting firms, PricewaterhouseCoopers (PWC) and Deloitte, state out the significant role of blockchain in acting as the backbone of the transactive energy infrastructure to enable a fully automated balance platform for supply and demand [29,30]. There are no shortage of topics and research works on the intersection of microgrids and blockchain, however, to the best of the authors' knowledge, the popular stop of their intersection is on the P2P energy transaction. Blockchain and microgrids, alone and together, go beyond trading. They solve problems, target different challenges and open up new opportunities for cross-border innovations. This paper will explore where, how and why it can go beyond trading with the interaction of blockchain and microgrids. The aim is to address the current knowledge gap via investigating the role of microgrid, blockchain and their intersection in targeting the technical/social/economic challenges and innovations for clean energy transition. A systemic overview on how blockchain boosts the decentralized market places and unlocks the value of microgrids to enable collective energy communities is provided with the state-of-the-art research analysis. Fig. 1 shows the structure of this paper and Fig. 2 presents the role of microgrid, blockchain and their relationship in coordinating of the grid edge, the main grid, and the trusted cross-border data/energy transaction within them. The organization of the following two sections is also marked in Fig. 2 to clearly show the structure of the core building blocks involved in microgrids and blockchain.

1.4. Contributions

The main contributions of this article are as follows:

- Investigate and evaluate the things of the grid edge: microgrid, energy community, blockchain, the relationship between them and the co-creation of all integrated together to target the three key issues for coordination and interaction of the decentralized energy units, the main grid and the end users in a reliable, resilient and sustainable way. The first is control, the second is communication, and the third is service.
- Microgrid's role evaluation (presented in section 2): focus on control and communication. Two research questions are focused on: the first is how microgrid as buffer layer digests uncertainties of the grid edge, coordinating energy communities for self-consumption, and as a controllable unit provides reliable grid integration. The second is how microgrid as a communication bridge establishes a full-scale digital interaction network, which connects the large amounts of the grid edge devices of various IoT protocols with the regulatory framework of the main grid.

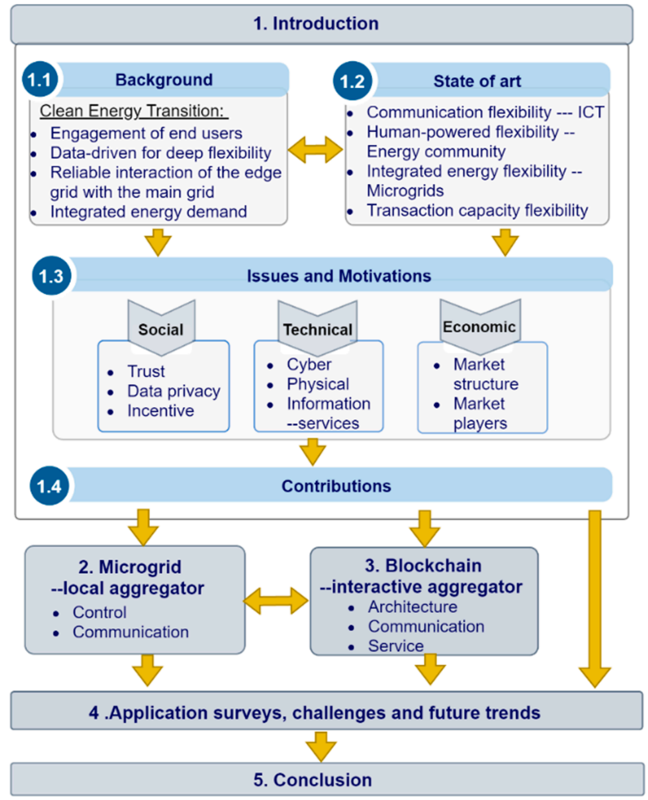

Fig. 1. Structure of the paper.

- Blockchain's role evaluation (presented in section 3): focus on decentralized framework for multi-scale communication and services. Three research questions are focused on: the first is what the difference blockchain makes in communication compared with IoT and microgrids. The second is how blockchain can provide an "enabling framework" for the cross-border networking of multi-level market players, multi-scale energy services and decentralized marketplaces with privacy and security. The third one is why blockchain can enable the large-scale integration of networked microgrids and energy communities.
- The co-creation of microgrid with blockchain (presented in section 4): focus on the analysis of current research/applications/pilots, categorizing the focusing aspects from the perspectives of technical, social and economic dimensions. The challenges, gaps and future trends are discussed and derived.

2. Microgrids from controllable energy system to interactive communication bridge

Microgrids regarded as one of the most effective way provide advanced dispatchability and flexibility for the main grid with well-regulated operation, control and protection services. A microgrid, with integration of distributed generators, storages, loads, can connect or disconnect from the main grid acting as a controllable unit [31]. The concept of Microgrid is not new, but it developed very fast to extend its initial contents to address modern energy challenges. It starts from micro-station of renewable energies targeting a single or small number of customer locations to an extended distributed ecosystem of the broader energy-coupling network targeting thousands of customers with integration of households, buildings, transportation, storage and AC/DC power supply [32]. Modern microgrid envisions a new operating diagram for the future energy system, relying heavily on the distributed clean energy resources. It not only provides the localized communities the cost-effective energy, but also improves the resiliency of the main

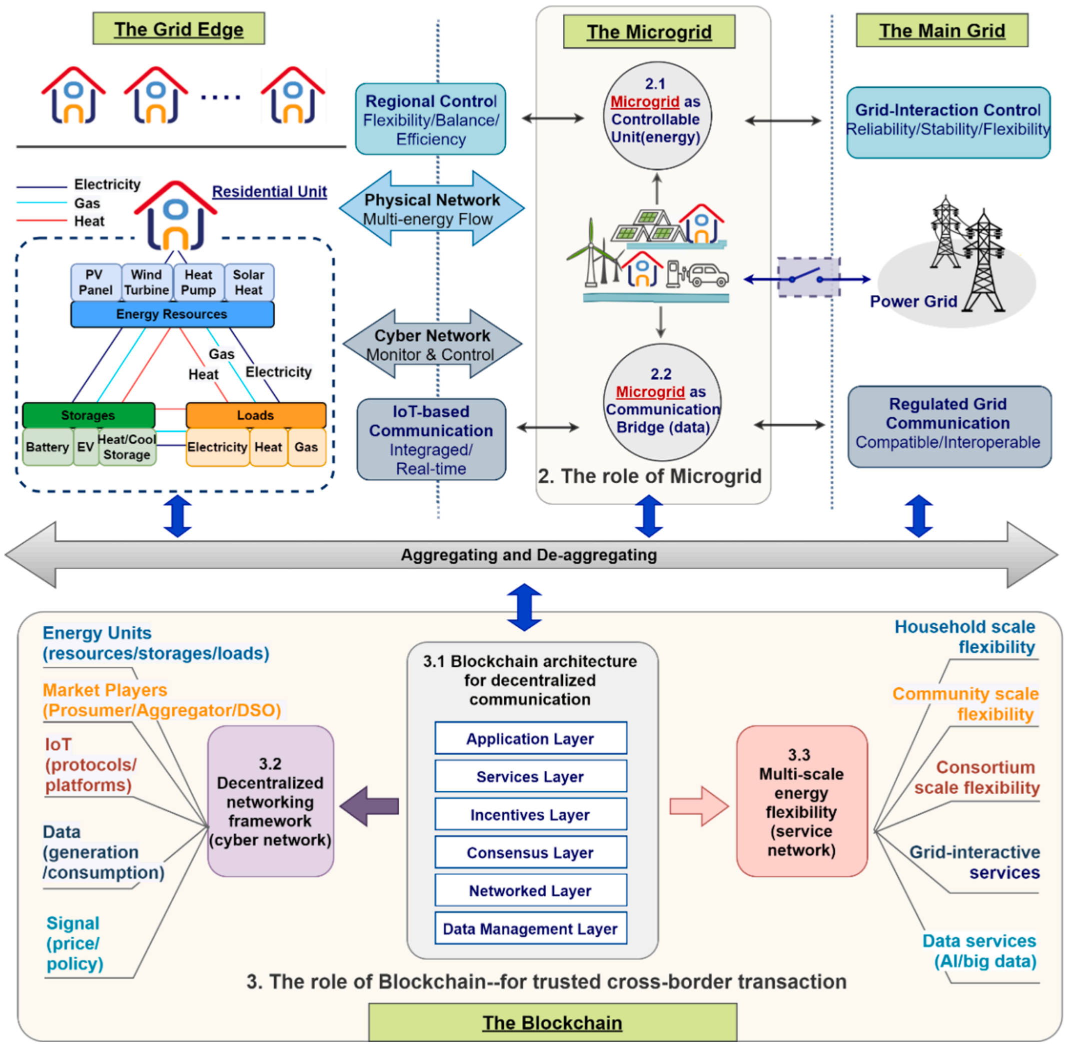

Fig. 2. The role of microgrid and blockchain in and between the grid edge and the main grid.

grid. It offers a middle path to coordinate the cooperation of non-professional distributed market players with the deeply regulated big market players for interactive P2P energy market. This section addresses the two key roles of microgrid. One is microgrid control for community self-consumption and reliable grid-interaction. The other is microgrid communication for establishing interactive bridge between the regulatory framework and the decentralized market player.

2.1. Microgrid control for community self-consumption and reliable grid-interaction

The increasing integration of distributed renewables brings severe issues on the system-level stability, local-level power quality, voltage/frequency regulation, and transaction capability. Microgrid with its well-organized control architecture can flexibly integrate various control strategies to target multi-level requirements covering stability, reliability, dispatchability and resilience. The management of current/voltage magnitudes, frequency/angle information, and active/reactive power flow can be controlled hierarchically in both island mode and grid connected mode. The hierarchical control structure of microgrid is derived from IEC/ISO 62264, responsible for microgrid synchronization, optimizing the management costs, control of power share with neighbor grids and utility grid in normal mode. It can also ensure the load sharing, distributed generation, and voltage/frequency regulation in both normal and islanding operation modes [33]. The IEC/ISO 62,264 is an international standard for enterprise-control system integration based upon ANSI/ISA-95, which is now a common hierarchical control structure for Microgrids. Specifically, it was firstly proposed in [34], and then the four-level hierarchical control structure was comprehensively investigated and defined for Microgrids with two operation modes [35].

Modern microgrids have a variety of types, topologies, networking structures and control schemes. With advanced ICT, the traditional centralized control scheme of microgrid has gradually given way to the development of distributed and decentralized control scheme for easily providing plug-n-play feature to engage more distributed energy resources. A comprehensive survey is provided for microgrid's four control schemes and relative technologies in [36]: centralized, decentralized, distributed and hierarchical. To address the control challenges and solutions of microgrid with a considerable number of distributed energy units in the grid edge, a review of state-of-the-art control strategies is presented respectively in [37]. For stable and resilient operation, microgrid control are enhancing the grid resilience [38], suppressing the power oscillations [39] and guaranteeing the seamless mode transition [40]. For the optimal schedule on the things of the grid edge, specific research works are focusing on the EV charging stations [41], net zero energy buildings (NZEB) [42] and distributed storages [43]. There is no lack of articles investigating microgrids control in control architecture, device-level control, on/off grid operation and switching, power quality and optimal dispatching, as well as coordinative control among energy units and microgrids. However, a systematic overview of what and how the microgrid hierarchical control layered architecture is linked to the grid edge, the main grid and the end users is missing. In this section, each control layer is investigated to show the internal mechanism. Fig. 3 presents the schematic diagram of microgrid control to achieve external grid-interaction and internal community-cooperation. Three parts are included: utility grid, microgrid community, and microgrid control with four layers. Building blocks and methods of each layer are discussed below in detail.

Internal control of generation: This layer is to achieve the 'Plug-n-Play' operation of the distributed energy devices and try to maximize their capabilities. The generation of microgrid consists of large-scale distributed non-dispatchable energy supply, so it is necessary to consider maximizing the power extraction under the specific weather conditions. The first layer control from the bottom is the internal control of power generation implemented in each distributed generator. Maximum power point tracking (MPPT) is the most used method for the wind turbine and PV panel to generate available power as much as possible at the specific time point. Smart inverter is also taken as the most promising embedded low-level controller for distributed energy resources, which has been standardized in IEEE 1547 on smart inverter's regulating, load following, and transient response capability[37,38].

Primary control of stability: This layer is usually responsible for autonomous stability control of microgrid for power sharing as well as the local voltage and frequency support. Due to the lack of synchronous machines, microgrids usually have the low stiffness and inertia with fast dynamics, primary controllers should be fast enough to respond the change and maintain system with time-sales on the order of 10 to 100 ms [44]. They are local controllers for distributed generators, storages, and loads. Methods and functions include: droop control for power sharing, islanding detection for individual distributed energy resources, over current/voltage protection limits for security, and so on. Primary control strategies for AC and DC microgrids are respectively investigated and compared in [45]. With the concept of the distributed bus signaling (DBS), primary control can be easily implemented in the centralized-, decentralized- and distributed control scheme to achieve autonomous stability operation of microgrid in this level [46]. In addition, island-mode primary control has more critical requirements, because it needs to maintain the variation of the voltage and frequency within the required limitations by control of its own inverters without the support of the main grid. Moreover, the primary control of islanded microgrid is responsible for power security, optimal operation, gas-emission reduction and proper transfer to the grid connected mode [47]. To align with the core requirements proposed by the US Department of Energy (DOE) [48], the Consortium for Electric Reliability Technology Solutions (CERTS) involves the standard of IEEE 1547 series to define the critical control functions especially in this layer for microgrids stability and resilience [49].

Secondary control of power quality: This layer is focusing on power quality management to accurately regulate the points of common coupling (PCC) voltage and frequency on the nominal value with time-sales on the order of seconds to hours [50]. It is mainly in charge of generators and loads, providing control services on load shedding/ management, voltage balancing, unit commitment/dispatch, security monitoring, black start, coordinated transition from grid to islanded mode, optimal dispatch of distributed generators and economic operation [43,51]. Secondary control can also be implemented in the centralized-, decentralized- and distributed control scheme with local or remote controller. Technologies of secondary control and challenges for each control scheme are reviewed in [52]. To accurate achieve active power sharing and simultaneously eliminate frequency deviation in a short time in islanded mode, optimal distributed secondary control strategy is discussed in [53] and consensus-based robust secondary control scheme for islanded microgrids is analyzed in [54]. Secondary control is also playing an important role in reliable and secure operation. This layer can help restore system voltage and frequency during and after natural disasters and reject large system disturbances with advanced coordinated voltage/frequency control methods and resilient communication strategy [55].

Ternary control of power flow: This layer is focusing on the power flow control to exchange power with the main grid and other microgrids with time-sales on the order of minutes to days [50]. Ternary control usually gets signals from the above layer in the business perspective to cooperate energy units in different sectors, including household-based community, commercial/residential buildings, transportation, storage system, and middle-sized renewable generation plants. It takes the role to coordinate the demands of specific applications and the behaviors of energy resources to achieve different objectives, such as doing a real-time prediction on generation and distribution at a given time, balancing energy supply and demand at the global level, and optimizing energy flow from business, economic, or environmental perspectives

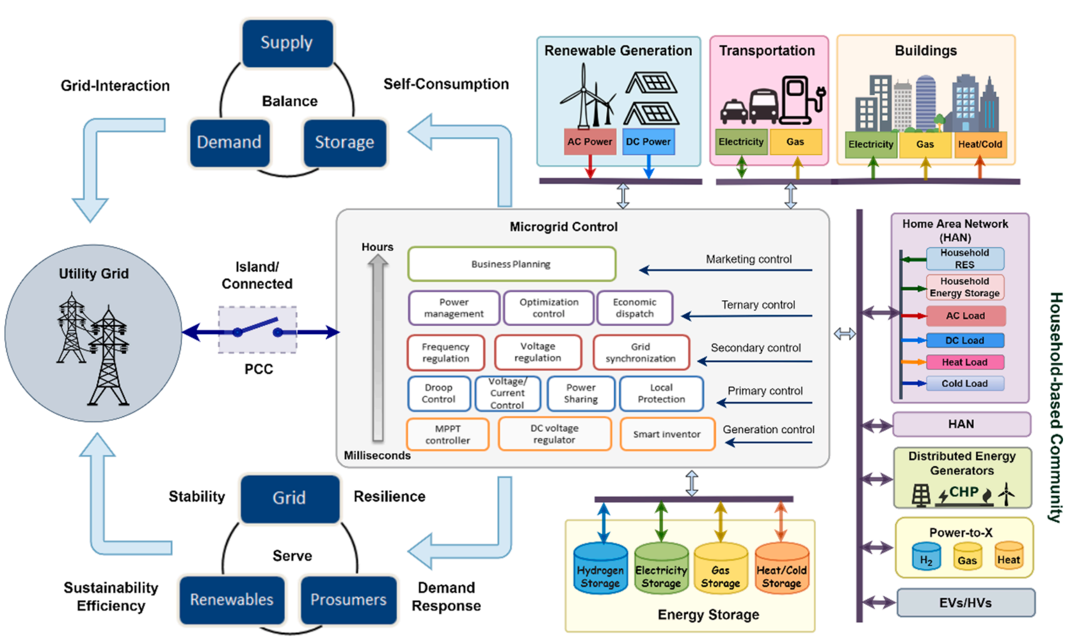

Fig. 3. Schematic diagram of microgrid control for grid-interaction and community-cooperation.

[20]. Ternary control layer in modern microgrid is also responsible for enhancing the intelligence of microgrid by integration of ancillary services to optimize the multi-energy flow within microgrid and among networked microgrids [46]. The control of energy import/export is enhanced by the integration of the end-user demand response, congestion management, and cooperative microgrids energy sharing [49].

High level control of marketing: This layer is on the top of the control structure, related with market business model and market diagrams. The engagement of multiple players triggers multiple transaction modes, including household-to-household, household-to-microgrid, microgrid-to-microgrid, and microgrid-to-grid. The transactional capacity can be measured in different sizes of arrangements from energy, flexibility and storage. Small size players can not only trade energy between each other, but also transact energy with big players. Therefore, different business models will emerge to enhance the distributed P2P trading with interoperation of the decentralized marketplaces for maximizing the collaborative societal and customer value as well as minimizing the whole energy system costs. Specific contracts are predefined to automatically trigger the market control signals which can effectively manage the priority of each layer's control objectives. It is usually preferred to ensure the reliability of system operation rather than to match the energy supply and demand in energy pool with bidding/offering prices. Anyway, market operation controllers can be designed dynamically according to decision makers [34].

2.2. *Microgrid communication for interactive marketplaces with regulatory framework*

With the hierarchical control structure, microgrid as a perfect controllable unit provides the resilient environment for link of the grid edge with the main grid. To facilitate their interaction, communication network is like a central nervous system to establish a full-scale digital network to enhance the control ability of microgrid with fast response.

Traditionally client–server communication mode is adopted by microgrid with centralized architecture. Most of consumers are acting as the passive roles lack of power system management. Supervisory Control and Data Acquisition (SCADA) is the most popular remote monitoring system to enable the end users aware of real-time situation of power system. SCADA uses three-layer Enhanced Performance Architecture (EPA) model to set up direct communication links for data sending and receiving (no Internet link) [56]. The most famous communication protocols used by ERA model include ModBus, ProfiBus, and DNP3. Currently with development of IoT, the TCP/IP-based protocols are widely used in the grid edge to achieve things-to-things communication. To promote advanced monitoring and control, heterogeneous hardware are needed to connect into the sensor network (smart meters, humidity sensors, smoke sensors, motion sensors, solar radiation sensors, UV-Index sensors, temperature sensors, wind speed sensors, wind direction sensors, pressure sensors). Four communication models in microgrids are activated: device-to-device model, device-to-gateway model, device-to-cloud model and back-end data-sharing model. Characteristics, typical protocols, and security concerns for each communication model are comprehensively compared in [57]. Fig. 4 presents the standard protocol stack of microgrid communication network to facilitate the interaction of the grid edge and the regulatory main grid. The protocols shown in the left part of Fig. 4 are for IoT-based consumption side, while the protocols shown in the right part are mainly for generation side and the legacy power system. Microgrid is a smart cyber-physical network, bridging the communication gap of the modern IoT system and the regulated power system. A comprehensive survey considering communication constrains on microgrid communication network is presented in [58], which includes 1) time-varying network topology; 2) time delays; 3) noise disturbances; 4) limited communication bandwidth; 5) uncertainties; and 6) cyber security.

Based on this microgrid-enabled reliable and high compatible communication network, advanced services are developed to promote the cooperation of decentralized marketplaces. One is the big data related services, which include:

- demand side management (demand response, load forecasting, load classification and customer segmentation, dynamic pricing, real-time interaction and energy saving);
- distribution network management (real-time sensing, voltage optimization, transformer health monitoring, fault detection, outage detection and restoration, asset management);
- power transmission management (grid planning, grid loss identification, fault detection, outage detection and restoration);
- distributed generation management (generator planning and optimization, economic load dispatch, renewable energy planning and automation);
- energy efficiency services;
- remote monitoring and control services over all energy domains [59].
- The other is artificial intelligence (AI) based services, which include:
- renewable energy generation forecast (machine learning-based EWeLiNE project with a follow-up project Gridcast [60], data-mining based energy forecasting application Nnergix [61]);

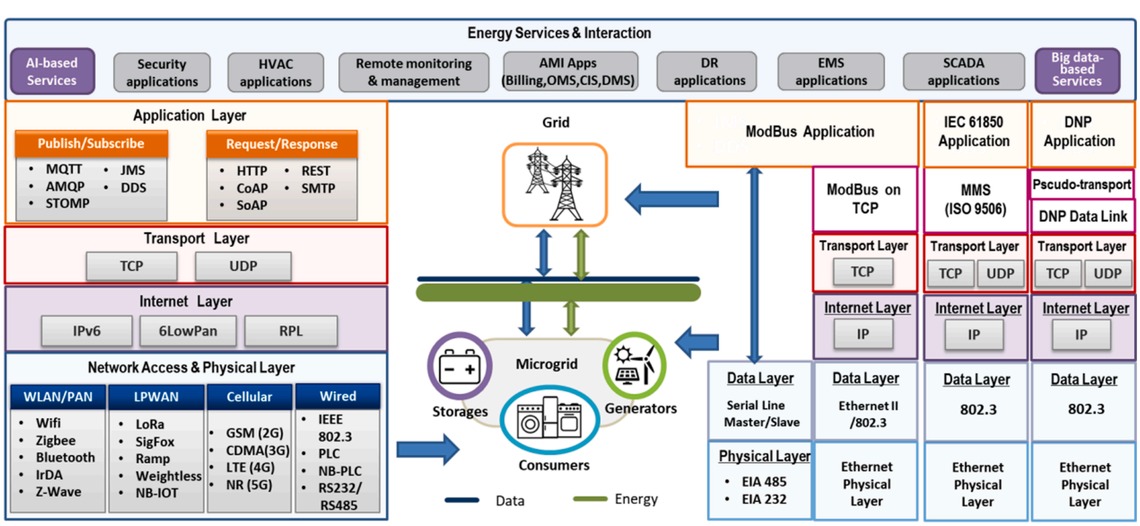

Fig. 4. Microgrid communication network to bridge the modern grid edge and the regulated main grid.

- grid stability and reliability maintenance (user behavior learning based SoloGrid project [62], AI-based dynamic line rating project PrognoNetz project for grid operation optimization [63]);
- demand forecast (artificial neural network (ANN)-based models and support vector regression machine (SVRM)-based models, which have strong capability in dealing with nonlinear consumption forecasting problems, especially in short term load forecasting (STLF) [64]);
- energy efficiency enhancement (AI-powered google's DeepMind AI to reduce cooling energy [60], venture-backed Verdigris Technologies to optimize energy consumption of large commercial buildings and managers of enterprise facilities [65]).

The progressive deployment of the digitalized energy services fosters the promotion of decentralized energy market to open new possibilities for small actors towards a low-carbon and energy-efficient economy. P2P trading enables an innovative energy management mechanism to active decentralized prosumers [66]. From the legal and policy perspective, "P2P energy sharing" is defined by the Council of European Energy Regulators (CEER) as a broad overarching terminology that encapsulates all possible interactions between participants in self-consumption schemes (individual, collective and community self-consumption)[59,60]. P2P electricity trading business model has been widely started in many developed and developing countries, including Australia, Bangladesh, Colombia, European countries, Japan, Malaysia, the United States and others [67]. European Commission further puts the P2P electricity trading on the legal map in the Clean Energy Package (CEP) as "the sale of renewable energy between market participants by means of a contract with pre-determined conditions governing the automated execution and settlement of the transaction" [68]. However, P2P energy trading is still not yet fully commercialized. Big players with definite rights and obligations are still the main decision makers in energy trading market. B2B and B2C market is deeply regulated with the traditional players (DSO, TSO, utilities). It is not easy to break out the regulatory model with interaction of the decentralized marketplaces to maximize the collaborative players' value as well as to minimize the whole energy system costs. A comprehensive analysis of the different P2P electricity market structures is reviewed in Micorgrid playing a key role as the certified third-party market "aggregator" bridges this gap. Furthermore, from the energy savings perspective, it is known that direct current (DC) distribution network and dc residential power paradigms can improve energy efficiency by 5%-15% according to system framework [62,63]. DC micrigrids simplify the integration of PVs, batteries and EVs, because their DC nature can significantly simplify the control structure, reducing the system operating costs and power losses as well as enhancing the power quality [69]. Great interests have been attracted on DC microgrids control in residential buildings [70], automation architecture [71] and potential energy savings [72]. With the DC roadmap from DC buildings to DC distribution network [73], P2P energy markets can be easily formed in different level with integration of multiple energy supplies and carriers. It enables the safe usage of generation, storage, consumption and transaction from the distributed grid edge to high-level energy aggregators. Microgrid as the intermediary facilitates the engagement of various individual household-level peers, promoting P2P energy market coupled with the existing wholesale and retail markets. Fig. 5 presents the role of Microgrid to form P2P energy market from different market levels.

The operation of microgrids is 'vertically' facilitating multi-energy couplings, self-sufficient energy communities and resilient grid interaction under various uncertainties and natural disasters. But how about the 'horizontal' integration to boost the large-scale electrification and cross-border interaction of buildings, transports, industries, rural/remote areas and islands for the delivery of future net zero energy communities? A decentralized but trusted platform is needed to provide the promising solutions from the cyber, physical, information and social dimensions, specifically targeting the following aspects: 1) Identity management of multi-level market players; 2) Full-scale digital communication network with real-time monitoring and control; 3) Cross-border cooperation of end-user energy sectors; 4) Multi-scale energy flexibility services to enhance system schedulability both vertically and horizontally. In this regard, blockchain is coming to the stage. The role of blockchain will be investigated in the next section.

3. Blockchain-enabled decentralized framework for multi-scale communication and services

To promote the newly proposed model of collective self-consumption and renewable energy communities for EU Clean Energy Package, it is necessary to have a cross-border framework to break communication boundaries of market players, energy communities, end-user sectors and ancillary services [74]. Blockchain, as a decentralized networking enabler, is explored intensely by researchers to bridge the collaborative

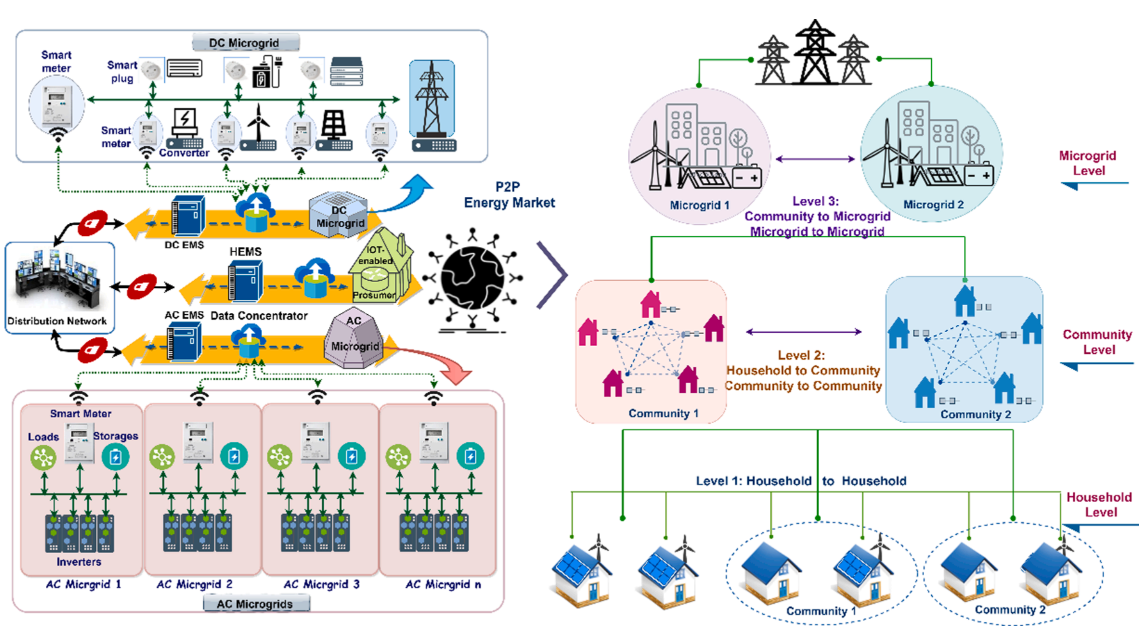

Fig. 5. AC and DC Microgrids driving multi-level P2P energy market.

gaps from the cyber, physical, information and social dimensions. This section discusses the main features of blockchain by answering the three research questions listed in contributions part of section 1.

3.1. Blockchain layered-architecture for decentralized communication

The trend of energy transition is towards 3Ds: decarbonization, digitalization and decentralization. IoT-based architecture has successfully supported the process of digitalization, bridging the gap between physical world and digital world. It provides layer-by-layer services and effectively active the contribution of distributed individuals and devices to clean energy transition from the vertical perspective. How about decentralization to form the customer-centric transactive market? Blockchain, as a promising decentralized and trusted ledger technology, explores the great potentials to connect the distributed grid-edge nodes together and provides a cooperative network for P2P energy/data transactions between mistrusting parties. It breaks up the boundaries of centralized supply chain and enables a wider range of flexible energy exchange across multiple sectors and local communities. The value of blockchain, with its services of distributed data storage, smart contract, distributed consensus and cryptography algorithms, is not only just limited in P2P trading, but also evaluated for grid reliability, resiliency and cybersecurity by National Renewable Energy Laboratory (NREL) [75].

Blockchain is noted to drive a decentralized distributed system. "Distributed" refers to resources distributions in different locations, such as distributed computing or storage across multiple nodes. "Decentralized" is comparative to "centralized", which mainly refers to the levels of control. "Decentralized" refers not to a single central node but multiple entities that control over all processes [76]. What kinds of data structures and communication protocols are used in blockchain to achieve decentralization with strong fault tolerance, attack and collusion resistance? Now let us have a deep investigation of its layered-architecture from bottom to up marked in Fig. 2.

Data management layer: this layer is responsible for data structure, data encryption and data storage. It mainly includes merkle trees, data blocks, block chain and cryptographic algorithm. Merkle tree is a way to structure data with cryptography, which can not only effectively integrate thousands of transactions but also provide a simple mathematical way to verify data. Data block is the basic unit of blockchain that contains transaction information of current block and the information of previous block. Data blocks are linked by hash pointers, which are generated by a fixed length value of data, which provides a more efficient and reliable way for cryptography, authentication and verification.

Networked layer: this layer is responsible for P2P broadcasting, nodes management, privacy and security control. It mainly includes policy configuration, P2P networking protocols, transactions/blocks propagation, data privacy and network security. Compared with centralized architecture, blockchain network consists of a huge number of interconnected nodes with different roles. Taking hyperledger fabric [77] as an example, leader peer nodes are responsible for receiving new block from the order nodes and broadcasting it to other peers, while anchor peer nodes are responsible for communicated with other organizations' peers. Order peer nodes are executing consensus services in addition to package transactions into blocks and distribute them to the anchor peers. Policy is defined in this layer for channel configuration and data evaluation. Data privacy guarantees that data is in hands of users and zero-knowledge proof is a powerful tool to balance the trust and the privacy.

Consensus layer: it is the core of blockchain network. Blockchain is a decentralized distributed system, but the finalization of distributed ledger needs to be the same. Consensus algorithm is needed to ensure the nodes to come to an agreement. This layer is responsible for validating blocks, ordering blocks, keeping all nodes synchronized, and ensuring only a single chain is maintained. Different blockchain platforms deliver different consensus algorithm. Ethereum [78] and Bitcoin [79] use Proof of Work (PoW). Hyperledger fabric [80] uses Kafka and Raft. Quorum [81] uses (Byzantine Fault Tolerance) BFT, and QTUM [82] uses Proof of Stake (POS)..

Incentives layer: blockchain provides a fundamental shift from the internet of things to internet of people, which enables humans and individual devices to actively engage in the edge computing and sustainable innovations. It is necessary to have incentive models and rewards mechanisms to promote the development and maintenance of the blockchain system. Therefore, this layer is essential for blockchain network to keep sustainable and attractive..

Services layer: this layer is responsible for automation of business process, management of identity and certificate of distributed storage. It mainly includes smart contract, certificate authority, wallets, digital identification and channel management for permissioned blockchain network [9]. Smart contract automates the logic implementation process of specific business model in the form of software based on the common sets of rules, data and concepts definition agreed by transacting parties. Identities from different organizations are created by certificate authorities and managed by wallets, which define the rights and functions of each blockchain user.

Application layer: this layer provides the interface for users to interact with blockchain network, invoke smart contract, access distributed ledgers, and engage roles-dependent activities. It mainly includes dApps, scripts, and APIs. Blockchain network is a functional back-end system, which can be integrated with other services-oriented applications, such as IoT systems, big data systems, AI systems and cloud/edge computing systems.

This layered-architecture provides a complete techno-social decentralized model with consideration of data structure, decentralized security, P2P broadcasting, consensus communication and incentive mechanism for involving distributed human participation as miners. Each node is empowered with high computing ability to execute transactions with mutual trust among different market players [83]. It establishes a scalable cross-border networking framework to attract multiple roles of organizations participating energy transaction for collective energy balance over different energy sectors and communities, which is discussed in the next section.

3.2. Blockchain based cross-border networking for cyber-physical-social collaboration

To active citizen and exploit their power to contribute to clean energy transition, it is necessary to establish user-centered digitalized networks for deployment of multi-level flexibility services. To collect real-time energy data from both demand and supply sides, large amounts of sensors are needed on generation, storage and consumption devices. These heterogeneous sensors have different communication protocols, thus IoT gateways with specific acceptable protocols take roles as the network processor to convergence and bridge different sensor networks. The mainly used IoT communication protocols are presented in Fig. 4, including: 1) Wireless local area network (WLAN)/ Personal area network (PAN): Wifi, Zigbee, Bluetooth, IrDA, Z-Wave; 2) Low-power wide area network (LPWAN): NarrowBand (NB)-IoT, LoRa, Sigfox, Ramp; 3) Cellular network (GSM-based 2G, CDMA-based 3G, LTE-based 4G, NR-based 5G), and 4) Traditional wire field network: IEEE 802.3 family, power line communication (PLC), NarrowBand (NB)-PLC, serial communication RS-232/RS-485 [9]. With IoT-based digitalization, it is easy to establish a real-time monitoring and management system for the home area network (HAN), which bridges the gap of individual engagement between the physical energy world and the digital information world. However, the boundaries of large-scale integration and interoperability for achieving deeper and wider energy flexibility as well as guaranteeing the customer-centric security and privacy need to be broken up. Fig. 6 presents the integration diagram from IoT network to blockchain network to achieve the decentralized cooperation of heterogeneous cyber-physical sources with privacy and security. Fig. 6 (a)

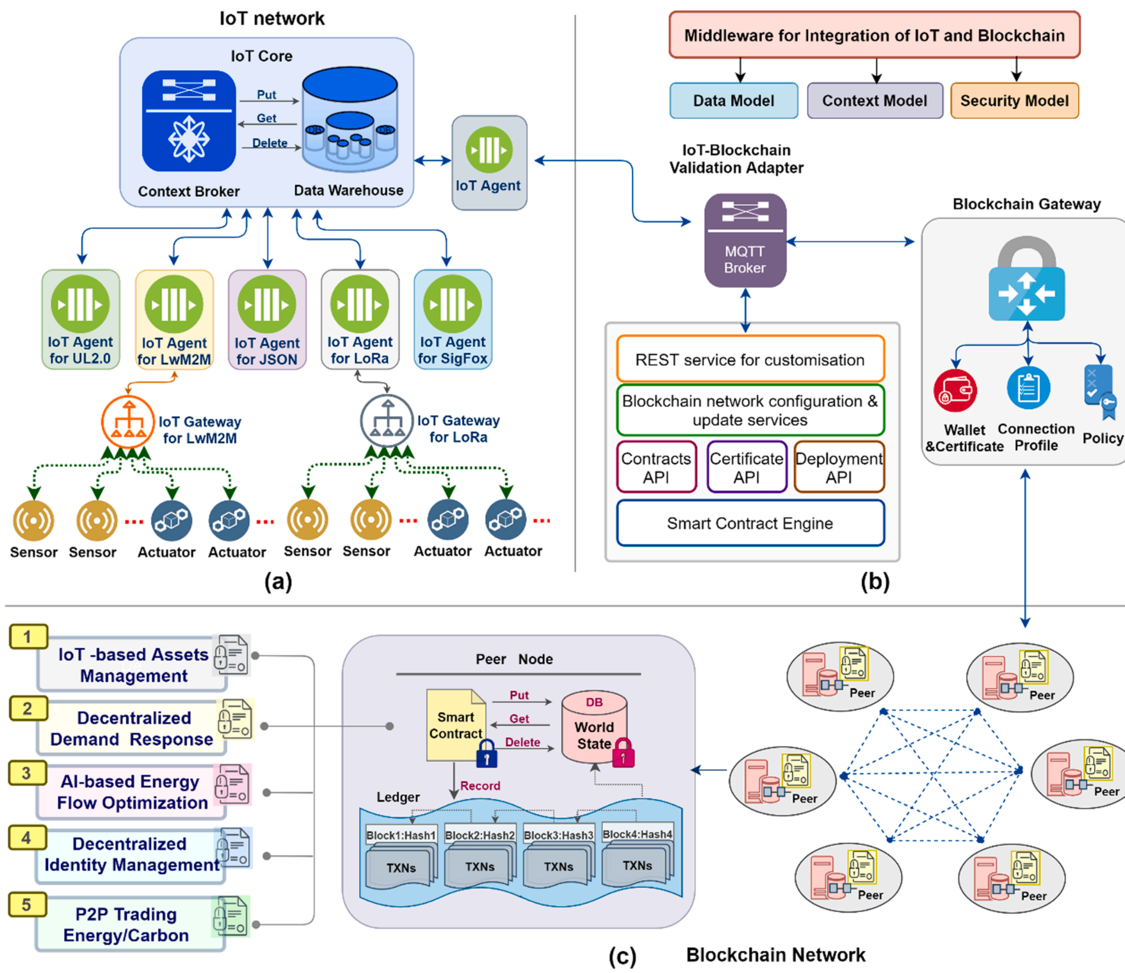

Fig. 6. Integration diagram from IoT network to blockchain network.

shows the role of IoT system acting as the localized node for distributed convergence, Fig. 6 (b) shows the middleware providing the plug-n-play interface and Fig. 6 (c) shows the blockchain network with smart contract triggered energy services.

Compared with the traditional network communication pattern 'Request/Response', the IoT system mainly uses the 'Publish/Subscribe' pattern. It is more efficient for the mass distribution of real-time information to only interested partners [84]. The publish/subscribe mechanism contains three core principles: space decoupling, time decoupling and synchronization decoupling between publishers and subscribers [85]. The 'broker' is the most important role in IoT architecture to enable the interaction among publishers and subscribers. A review of different IoT platforms is given in [20]. FIWARE is one of the most popular open-source IoT platform used in Europe for the smart digital future with cross-domain data-driven innovations [86]. Context broker is the core enabler powered by FIWARE to collect data from different sources and support smart decisions at the right time, which is selected as one of endorsed building blocks of the Connecting Europe Facility (CEF) for European future open and reusable digital solution [87]. Fig. 6 presents the context broker as IoT core for real-time data processing and synchronizing in IoT network. The middleware for integration of IoT and blockchain mainly consists of three models: data model, context model and security model. They are respectively responsible for standard data schema, translation information from different IoT networks and identity management of blockchain network access. With the technology of decentralized identity management (DIM), an emerging concept for building the trusted framework, the end-users from IoT system are provided customized responsibilities to control back over their own identities. Different roles of people, organizations, and devices with their own certificated identity can access blockchain network from the blockchain gateways for further cross-border coordination. The mechanism of this cross-border networking framework is discussed in the following part.

New concepts and frameworks are emerging to facilitate the collective sharing of renewable energy for the different-level self-consumption and load balance. The term of collective self-consumption (CSC) is explicitly mentioned in both the EU Internal Market for Electricity Directive (IMED) and the Renewable Energy Directive (RED II) to refer to any collective form of jointly energy production and self-consumption [66]. From the report of ENEA consultancy in 2020, although the global CSC development is at its very early stage with less than 100 MW of around 500 CSC projects, there will be a large market share among the 150 GW residential and commercial PV to be installed from 2019 to 2024 by CSC projects [88]. Now with the support of the blockchain, the broad energy transaction is boosted among communities and foster the scale up of the CSC market. Fig. 7 presents this hierarchical architecture for the cross-border energy networking framework.

With the six-layered architecture discussed in the section above, blockchain effectively manages the complexity of distributed things from cyber-physical-social dimensions to promote the capacity and dispatchability of renewable energy. New opportunities are offered to achieve multi-level collective energy balance in a legitimized, automatic and trusted way with privacy and security. Three-level energy balance is shown in Fig. 7. The first is in household-level for the individual self-consumption. Prosumer with his own renewable generators can first satisfy his own demand and then store or sell surplus energy to others or

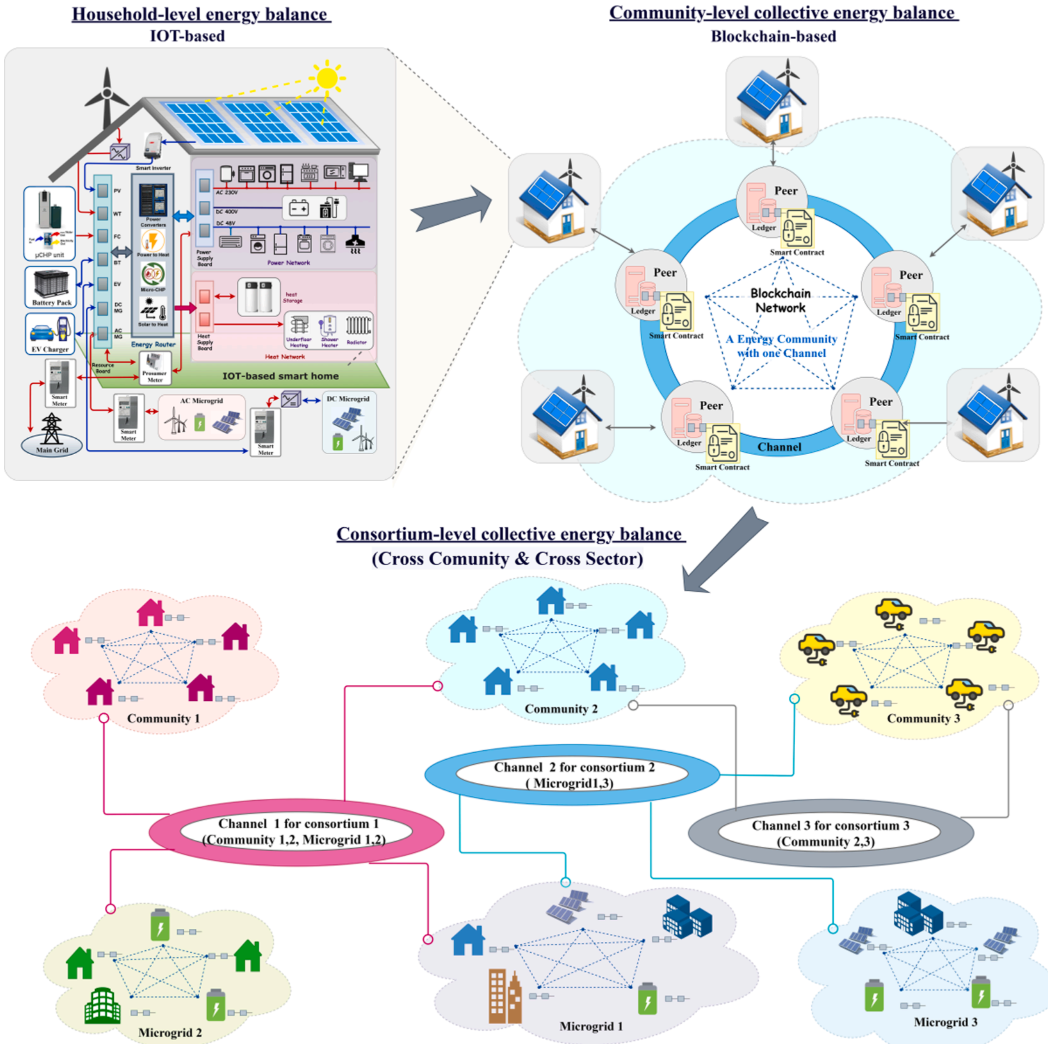

Fig. 7. Blockchain-based hierarchical architecture for cross-border energy networking framework.

the grid utility. The second is the community-level for collective energy balance or the collective self-consumption. A group of prosumers connected in an energy community can exchange electricity for a locally joint energy production and consumption. The IoT-based HAN can be easily connected into the blockchain network with the plug-n-play middleware interface introduced above. A single channel is set up for the communication and energy transaction of a looped energy community without a centralized intermediary. The third is the consortium-level for cross-community and cross-sector energy balance. Fig. 7 presents three energy communities and three community microgrids set up three joint energy cooperative channels for cross-border collective energy balance. Microgrid-based solutions as discussed in section 2 enable an controllable way for the reliable and resilient energy transaction in the interconnected local/regional energy systems, while blockchain promotes the large-scale electrification of energy use in the different end-user sectors of transportation, buildings and industries.

3.3. Blockchain enabled multi-scale energy flexibility for collective self-consumption

Compared with other commodities, energy transaction relies on the regulated system even though P2P energy trading promotes the growth of small size and non-professional distributed actors. To achieve the large-scale collective energy balance, it is necessary to develop and integrate innovative digital services with aggregation of millions of separate supply/demand decisions from multi-level players to improve the local-level transfer capacities as well as maintain the system-level stability and security. Various energy-aware services are promoted for accelerating multi-scale energy flexibility. Fig. 8 presents the schematic diagram from IoT-enabled household self-consumption to blockchain-enabled collective self-consumption in three scales.

Household Scale Flexibility: The legislative framework for energy communities is recognized and enabled by the European Union (EU) in the CEP to foster the bottom-up, citizen-driven collective community business models [89]. The legal concept of RECs and CECs are defined in CEP with a set of rights, privileges and responsibilities [90]. It is estimated that EU energy communities could own some 17% of installed wind capacity and 21% of solar by 2030 and half of EU households are expected to be producing renewable energy [89]. A flexible network with active prosumers/consumers fosters the distributed control over decision-making in energy supply and demand. Especially with the implementation of the integrated energy technologies in household scale network, such as heat pumps, μCHP, solar thermal, small biomass power generation, EV chargers and district heating networks. The household self-consumption is enhanced by the demand-side management activities and sector coupling flexibility provisions. The active households are the fundamental flexibility units to facilitate a larger share of renewable energy, lower the energy cost and the grid stress, as well as promote the co-creation of socio-technical approach for the clean energy transition.

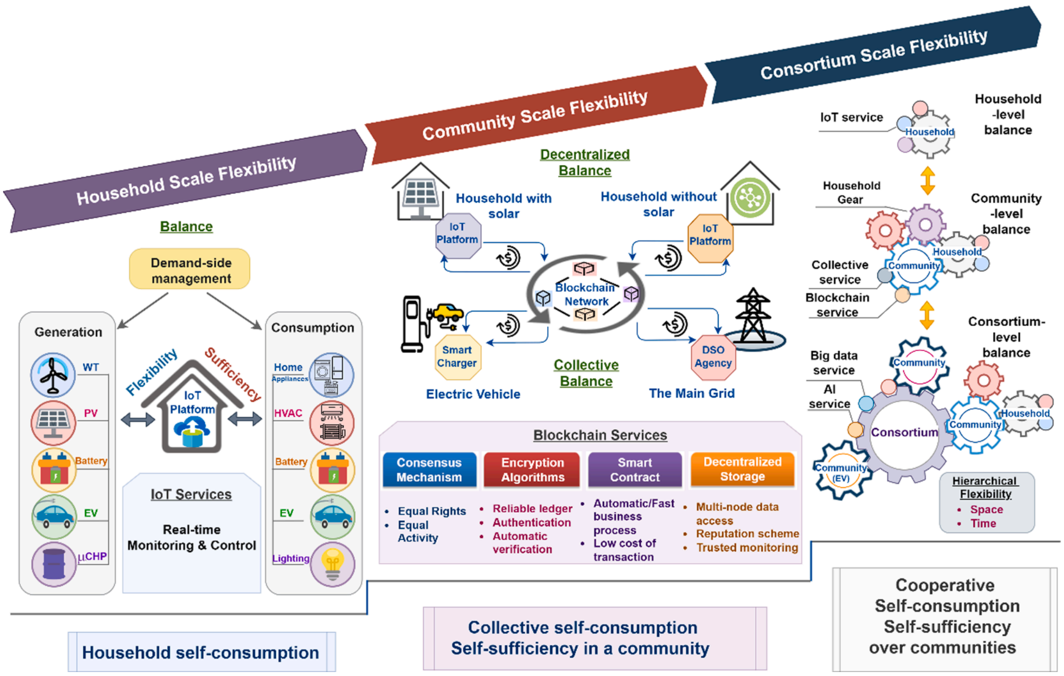

Fig. 8. Schematic diagram of multi-scale energy flexibility with the operative enablers.

Community Scale Flexibility: Energy community organizes the collective actions of the fundamental flexibility from households. It promotes the local scalability and dispatchability without upgrading the traditional power network. With the legal involvement of distributed actors and small/medium-sized energy generation/storage units, energy community offers a mean to re-organize the energy system to make it easier for the collective energy balance and flexibility [91]. In this level, blockchain network is responsible for interconnecting the IoT platforms of the grid edge and coordinating various energy market players, while microgrid is responsible for the controllable energy distribution to achieve the community self-consumption as well as the reliable grid-interaction. Multi-aspect flexibility services are needed here to support the local-level transfer capacities, demand response performances, as well as system-level stability, multi-time scale energy scheduling and exchange [92]. The International Energy Agency (IEA) - International Smart Grid Action Network (ISGAN) classifies the overall timescale flexibility solutions into four categories in its recent report ‘flexibility needs in the future power system’: flexibility for power, flexibility for power, flexibility for transfer capacity, and flexibility for voltage [92].

Consortium Scale Flexibility: A deeper and wider cooperation of different energy communities is promoted for both physical and virtual ones. Hierarchical flexibility on different time scales (from second to days) and space scales (from one sector to multiple cross sectors) can be achieved by the interaction of various energy communities for the cross-border balance of supply and demand in the consortium scale. The operation scheme of consortium scale flexibility is shown in the right-most of Fig. 8. The balance is running from top to bottom in three different levels. In the first household-level balance, the IoT-based digitalization services, data processing services and energy aware services act as the plug-n-play functional accelerators to help end users form more sustainable energy usage behavior patterns. In the second community-level balance, the household-level gear acting as the controllable fundamental energy unit is mounted into the big energy-community gear. In this community-level gear, innovative ICT and data services are integrated as the functional accelerators to enhance the interoperability of the whole system. The third consortium-level balance envisions a large-scale energy sharing network with the valued-added innovative solutions provided by cross-domain stakeholders, integrated with big data processing and analyzing systems for data innovations, as well as artificial intelligence (AI) tools for intelligent decision makings..

4. Application surveys, challenges and future trends

According to Navigant Research, the global market for integration of blockchain technology with microgrids (remote/grid-connected) is set to expand by 67.8% from 2019 to 2028 [93]. Although Europe and North America will remain market leaders, microgrid and blockchain investors are exploring project opportunities in developing countries where people still lack access to electricity [94]. Microgrids are self-contained energy system, lightening the last-mile communities, while blockchain allows the interoperability of the smaller scale of microgrid-based projects with privacy and security. The co-creation of microgrid and blockchain technology, which connects energy transition and cross-border innovations in a new framework, is accelerating the electrification progress with the maximum multi-dimensional cooperation. There is a rapid growing interest towards developing microgrid-blockchain research and applications. Related directions are covering technical, social and economic dimensions to address various issues and challenges, which enables a range of startups and pilots all over the world. Table 1 presents the summary and comparison of micorgrid- blockchain research innovations. The main methods, services, challenges and trends are listed respectively in each aspect in Table 1 to help readers broaden collective insights and derive future directions.

The co-creation of microgrid and blockchain facilitates a sustainable, cost-effective, low-transmission-loss, resilient and scalable energy network. The survey results of Table 1 show that microgrids are responsible for control of physical energy network and blockchain is responsible for management of cyber communication network. Microgrids with blockchain can encourage the innovative services ‘horizontally’ across consuming sectors and ‘vertically’ from the distributed grid edge to regulatory power grid for overall balance and flexibility.

Furthermore, energy poverty is still a big issue in remote/island counties. Roughly 13% of the global population (940 million) doesn’t have access to electricity. Among others 70% of households in the Pacific Island region are isolated from the main grid [95]. Microgrid-based solutions are widely studied and implemented to deal with the technical and economic issues in rural areas. The feasibility of blockchain-enabled

Table 1
Summary and comparison of microgrid-blockchain research innovations.

Focus aspects	Country	Blockchain Method	Energy Service	Challenge/ Trend	Capacity	Ref.
Energy flow optimization	Netherlands	• Blockchain platform –Ethereum Smart contract –Virtual aggregator	• Day-ahead forecastingAlternating direction method of multipliers (ADMM) for optimal power flow (OPF)	• Grid coordination EV behavior Acceptance of trade-only/grid-only/ combined scenario	• Number of households: 22 Assets: Solar EV Storage	[108]
	US	• Blockchain platform –Ethereum Data services –Distributed computation Smart contract –ADMM coordinator	• ADMM for distributed optimization and control for OPF	• Real-time control layer for faster operation Stochastic generation and demand	• SCE-55bus test network Assets: Solar Micro-turbine EV Storage	[109]
Local load balancing-Quartierstrom	Switzerland	• Blockchain platform –TendermintData services –Compliance with EU General Data Protection Regulation (GDPR) Identity services– Self-sovereign identity management	• User behavior investigation for business model Price-based market mechanism	• Automation for P2P energy markets Regulatory framework barrier for P2P markets. Policy/legislative progress	• Number of households: 37 Assets: Solar Storage electric boilers	[110]
P2P trading—market management	US	• Blockchain platform – EW Chain Market services – Virtual community market platform	• Demand-side programs with EV charging P2P trading. DSO regulatory cooperation	• Socio-economic impact evaluation Pricing mechanism Networked microgrid markets Scalability and robustness	• Number of households: 150 Assets: Solar EV charger Storage	[90–92]
	Australia	• Blockchain platform – Monash Market services –DERs incentives	• Passive/Active/Transactive energy management Distributed pricing optimization pricing	• DERs Incentives for different markets Regulatory issue Power quality	• Monash Microgrid Assets: Solar EV charger Storage	[93–94]
P2P trading—energy/ environmental commodities	Australia	• Blockchain platform – Solana Trading network –Virtual trading network of solar and storage	• xGrid/μGrid tradingPower Purchase Agreements (PPAs), carbon and renewable energy credits exchange	• Community awareness and support Cross-country marketplaces Automation of flexibility services	• Number of households: over 100 Assets: Solar Storage	[108–110]
P2P trading—Game theory	Singapore	• M—leader and N-follower Stackelberg game approach Distributed iterative algorithm	• Modeling of decision-making process of prosumers Pricing competition model	• Stochastic nature of prosumers P2P network for community microgrid clusters	• Number of households: 5 Assets: Solar Storage	[111]
	China	• Balance responsible party (BRP) based reserve services mechanism Risk-implemented simultaneous game approach	• Hour-ahead/real-time market Solve DERs uncertainties	• Fluctuating price risks Stochastics behaviors Network constrains Deviation risk of DER outputs	• Number of households: 21 Assets: Solar EV Storage	[112]
	US	• Coalitional-game-theory-based local power exchange algorithm Shapley value method for coalition utility of allocation	• Incentive for neighboring microgrids cooperation Auction-theory-based method for optimizing trading order	• Operation of autonomous microgrids Coalitional microgrids in islanded mode High reliability	• Number of microgrids: 30	[113]
P2P trading—Islanded microgrids network	US	• Two-phase consensus algorithm (practical BFT and modified PoS)	• Price adjustment mechanism Multi-agent negotiation mechanism	• Trading price determination Transaction model with tie-line congestion and voltage stability	• Number of microgrids: 20	[114]
	China	• Periodic trading framework Game-theoretic approach/ backward induction for non-convex optimization	• User satisfaction model Robust optimization for REGs uncertainties	• End user types (strategic/ normal) Limited energy resources	• Number of households: 30 Assets: Solar	[115]

(continued on next page)

Table 1 (*continued*)

Focus aspects	Country	Blockchain Method	Energy Service	Challenge/ Trend	Capacity	Ref.
				Uncertainties of islanded microgrids	Wind Wave Storage	
Open-source platform -Yale Opensolar Lab&MIT Media Lab	US	• Blockchain to unlock trusted impact investments Smart solar contract for direct connection between investors and end-users	• Transactive microgrids for energy democracy Contractual automation for driving solar community projects	• Adaptive and data-driven pay-to-own model Adaptive P2P open platforms for contractual automation	• Puerto Rico island Hundreds of communities Over 700 schools	[116–117]
Smart contract	UK	• Blockchain platform –Ethereum Web3 interface Smart contract for decentralized exchange market	• Continuous double auction Uniform-price double-sided auction Agent bidding strategy logic	• Automated transaction matching Agents' strategic behavior Software trading agents	• Number of households: 3 Assets: Solar Wind EV charger stations Storage	[118]
Real-time demand response	China	• Fuzzy possibilistic programming Smart contract for real-time DR conducted	• Robust multi-objective optimization Overcome uncertainty in data, lack of knowledge and epistemic	• Smart contract for fair deal for various stakeholders Metaheuristic approaches for uncertain environments	• Vietnam's Ho Chi City pilot Number of households: 300	[119]
	Italy	• Blockchain platform –Hyperledger fabric Smart contract for distributed DR Privacy-preserving	• Customer remuneration	• Availability of customer profile Data privacy Decentralized identity management	• Number of households: 2	[112–113]

energy trading among networked minigrids/microgrids is also actively investigated to speed up the global electricity supply [96]. Opportunity and challenge are the two sides of one coin. For the large-scale decentralized networked energy system, cybersecurity and stability are the most crucial and urgent issues need to be targeted. Main findings in cybersecurity refer to cyber-attack detection [97] and identification [98], security enhancement with resilient control strategy [99], with game theory [100] and distributed source authentication [101]. Main findings in stability refer to distributed formal analysis (DFA) of networked microgrids dynamics [102], stability control under communication constraints [58], transient stability analysis [103], reachability analysis with large disturbance [104], and deep reinforce learning

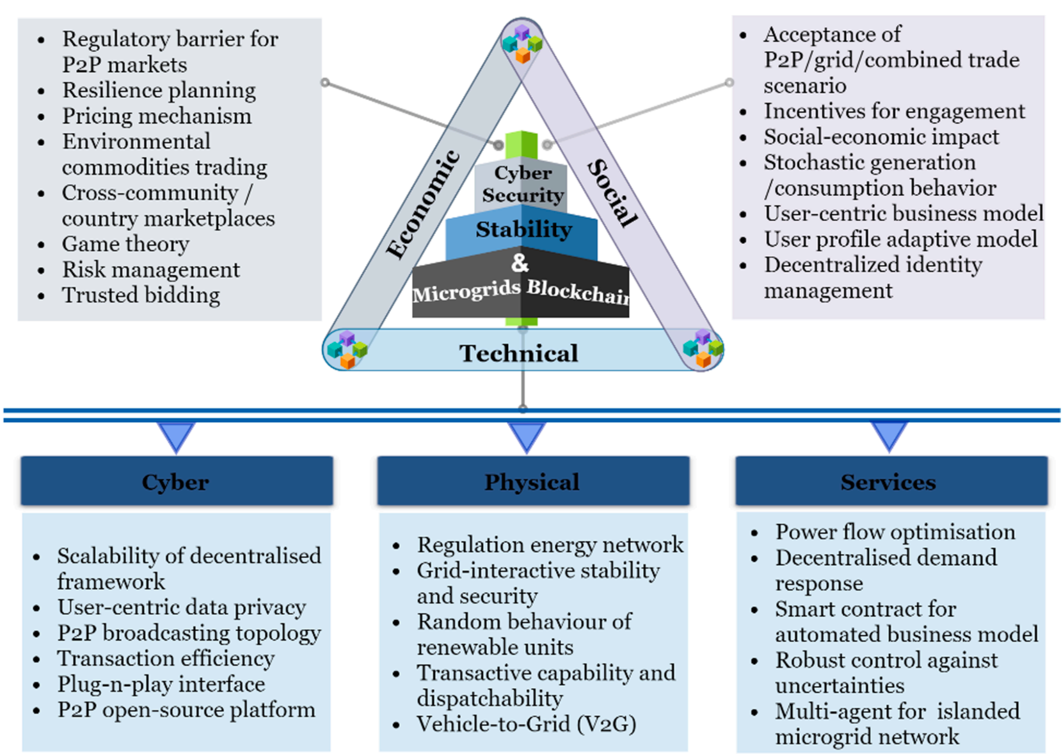

Fig. 9. Microgrid with blockchain research/application directions in three dimensions.

(DRL)-based power flow control for stability[105].

To better identify the challenges and future trends concerning the integration of blockchain with micorgrids for innovations in clean energy transition, the existing and potential research/application directions are summarized in Fig. 9 into three dimensions.

5. Conclusion

The concept of energy community is not only legislatively defined in EU clean energy package, but also initiated widely in the form of pilots or practical projects. Although the participation of decentralized small- or medium-sized prosumers promotes the system flexibility, multi-directional power flows will definitely complicate the energy management and also bring various uncertainties. This paper investigates the challenges, solutions and future trends in building an "enabling framework" to facilitate the deployment and exploit the potentials of the energy community for promoting the sustainable energy transition. A significant overview with modularized analysis is carried out to investigate the cyber-physical-social framework of the grid edge to motivate the collective energy sharing among communities. Firstly, it addresses the core issues that researchers and stakeholders are much concerned: (1) regulatory cyber-physical environment to integrate energy communities, (2) grid-interactive stability and reliability, (3) cybersecurity with decentralized identity management, (4) integrated energy flexibility and optimization with active end users, (5) cooperative market structure to maximum the interests of all market players. Then, it identifies and evaluates the role of microgrid and blockchain, alone and together, to enable the collective energy communities from three dimensions (technical, social, economic). Specifically for microgrid, it focuses on the control architecture and communication protocols to bridge the gap of the grid edge and the main grid in the regulatory environment. It analyzed how microgrid can integrate advanced P2X and V2G technology for integrated energy flexibility as well as guarantee the grid-interactive stability and reliability. For blockchain, it focuses on the decentralized networking framework, cross-border communication and collective service sharing. It analyzed how blockchain can enable the cross-border energy transaction with the trusted identity management of various stakeholders and the plug-n-play integrated services sharing for multi-scale energy flexibility. Finally, the co-creation of microgrid with blockchain is investigated based on the comprehensive survey of current research works, applications and pilots. Challenges, methods, future directions are presented with categorized aspects respectively from the technical, social, and economic dimension to further broaden the insights and exploit the potentials of microgrid with blockchain innovations in promoting the clean energy transition.

To conclude, it is no doubt that decentralized local sourced energy products in the grid edge is right on trend. PV panels, home batteries and EV chargers will proliferate into the energy ecosystem. To achieve 100% renewable energy penetration as well as grid stability are the two-side goals. It is not easy to shot at the same time. It is really a great challenge to monitor and control millions of decentralized energy resources in the grid edge to minimize their destabilizing effects, as well as optimize the flexibility in supply, storage and demand. The best way to manage them is from the bottom up [106]. It is essential to have microgrid to manage the unpredictable nature of customer-owned energy resources and to have blockchain to extend the aggregation of energy units, data and prosumers across various energy communities with trust and privacy. The co-creation of microgrid and blockchain will definitely enhance the self-organization of the grid edge and promote the cutting-edge innovations by effectively interacting different stakeholders from academic researchers, industrial partners and decision makers. It has already achieved valuable results from focus-oriented research activities reviewed in Table 1, program-oriented completed and on-going EU funded H2020 projects reviewed in [107]. It also triggered progressing future research trends in different dimensions presented in Fig. 9.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by VILLUM FONDEN under the VILLUM Investigator Grant (no. 25920): Center for Research on Microgrids (CROM), AAU Talent Programme: The Energy Internet - Integrating IoT into the Smart Grid.

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