P2P energy trading

Blockchain-enabled P2P energy society with multi-scale flexibility services

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Review article

P2P energy trading: Blockchain-enabled P2P energy society with multi-scale flexibility services

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A B S T R A C T

A deeper decarbonization perspective is undergoing with the increasing engagement of new distributed players and the deployment of innovative behind-the-meter flexibility services. Peer-to-Peer (P2P) trading has emerged as an innovative mechanism to foster the direct energy sharing among multi-level market players with pre-determined responsibility and privacy. However, compared with other P2P assets trading, P2P energy trading is facing huge challenges in achieving a large-scale commercialization due to the cooperation obstacles between non-professional distributed players and regulated players as Distributed System Operator (DSO), Transmission System Operator (TSO) and utilities. It is related to not only business and marketing, but also energy system operation to keep secure and reliable with injection of new roles, new utilization patterns, and new markets. This paper investigates the socio-technical interaction and mechanism for the sustainable P2P energy trading from the social dimension on the cooperation of multi-level market players, the technical dimension on the cutting-edge exchange of flexibility, and the economical dimension on the inter-operative decentralized/regulated marketplaces. Three questions are targeted on: (1) How Information and Communication Technology (ICT) enables co-creation of decentralized heterogeneous user-centered digital frameworks for the large-scale P2P trading interaction, (2) What specific energy services drive the cross-border interactions for exchange of multi-scale P2P flexibility, (3) How operational framework in P2P energy trading achieves the inter-operative marketplaces with the formation of trusted P2P energy society and the injection of multi-scale flexibility services. Finally, regulation challenges on P2P energy trading implementation are discussed for the guide of future work.

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1. Introduction

The global energy system is undergoing a massive revolution, from the long-established fossil-based status towards a decarbonized, renewables-centered one. It is necessary and urgent to take actions on climate change and environmental issues. The world emits around 50 billion tons of greenhouse gases each year and the energy sector accounts for almost three-quarters of emissions (Ritchie, 2021). Fig. 1 shows the share of global greenhouse gas emissions by each sector. According to IRENA Energy Transformation 2050, the scenario of deeper decarbonization perspective (DDP) is addressed to reduce energy and process-related CO2 emissions to zero in 2050–2060 (Renewable Energy Agency, 2020). The transition to a modern, low-carbon and energy-efficient economy is well underway. Five pillars are proposed for the future of energy (Renewable Energy Agency, 2020), which are electrification, increased flexibility, conventional renewables, green hydrogen, and foster innovation. The progressive deployment of digitalization in energy system is playing a leading role to foster innovation for the promotion of clean energy transition, boosting the transformation and opening new possibilities. It enables multi-level integration of efficient utilization of new advanced technologies, operation and planning principles, regulation and business models. Great potentials for cross-border interconnections and interactions are activating small actors on energy transition in decentralized energy market of grid edge. Energy consumers are empowered as prosumers to sell energy to the utility grid and to transact energy with each other in different shapes and sizes. Innovative business models and marketplaces are needed to minimize the whole energy system costs, as well as simultaneously maximize the collaborative societal and customer value.

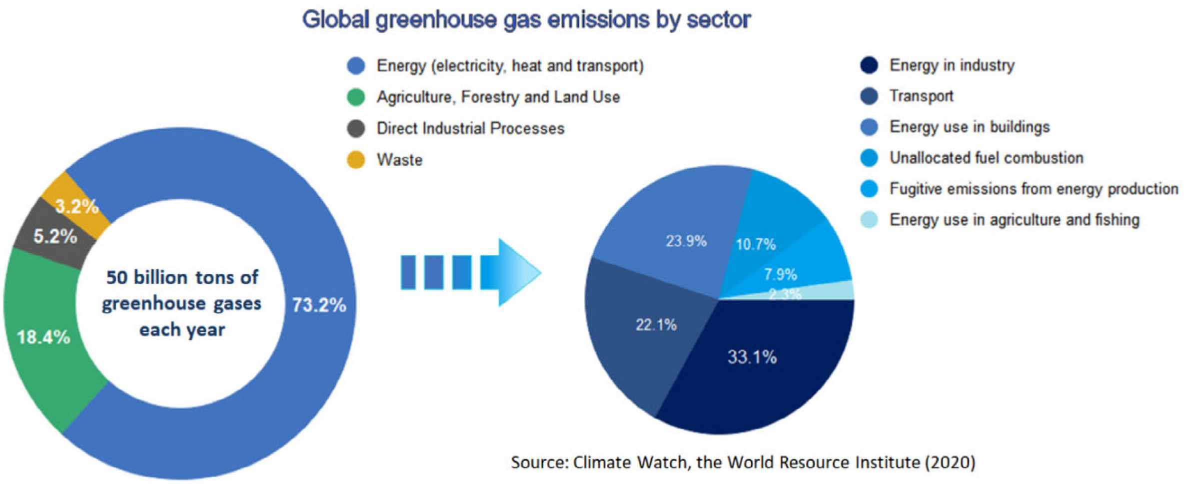
P2P energy trading is an innovative model of transactive energy. It clashes with the traditional vertical structure of energy value chain and enables a horizontal energy platform for sharing, transferring, exchanging, and trading among consumers or prosumers as peers (de Almeida et al., 0000). From the legal and policy perspective, "P2P energy sharing" is defined by the Council of European Energy Regulators as a broad overarching terminology. It encapsulates all possible interactions between participants in self-consumption schemes (individual, collective and community self-consumption) (de Almeida et al., 0000; Council of European Energy Regulators, 2019). European Commission also puts P2P electricity trading on the legal map in the Clean Energy Package. It is defined as "the sale of renewable energy among market participants by means of a contract with pre-determined conditions. The contract is governing the automated execution and settlement of the transaction, either directly among market participants or indirectly through a certified third-party market participant, such as an aggregator" (EUR-Lex, 2021).

There is no doubt that P2P energy trading has emerged as the next generation energy management mechanism with its existing and potential contributions to power sector transformation. The research and implementation of P2P energy trading foster the co-creation of technical, economic and social methodologies for cutting-edge provision in the following aspects: cross-space integration of energy physical communities, multi-scale energy flexibility services, and coordination of multi-level marketplaces. There is no shortage attention of P2P energy trading research from both academic and industrial fields all around the world. Current approaches, challenges and future work have been reviewed and discussed in a wealth of articles, including the following key aspects: (1) Legal aspects and challenges, (2) Market design and business models, (3) Key technologies, (4) Trading platform, projects and startups, (5) User behavior, (6) Trust trading, security and privacy. Table 1 shows the detailed contributions and future research trends of each aspect. It can be seen that P2P energy trading has not been much exploited. Although there are several comprehensive reviews to identify and discuss the key technologies, most of them are presenting the general knowledge in the introduction level or provide solution for specific challenge. The internal mechanism that drives and supports P2P energy trading has not been revealed. It should consider not only cyber (ICT technology) - physical (energy network) dimension, but also the social dimension. It is because P2P energy trading can foster the formation of P2P energy societies with multi-level user engagement (generators, consumers, DSOs, utilities), building on the mutual trust for P2P interactions of different organizations without third parties. Therefore, a P2P energy society is necessary to be formed with integration of multi-scale flexibility services for achieving inter-operative marketplaces.

To establish a P2P energy society successfully, cross-discipline integration of advanced research fields needs to be exploited to enable participants and interaction of stakeholders in various areas with security and privacy. On one hand, ICT developers are making their endeavor to bridge the data gap for data availability and accessibility. Appropriate ICT infrastructure can make sure the real-time monitoring and control over multiple energy resources, regarding the data collection and safe usage of generation, storage, consumption and transaction from distributed grid edge to high-level energy aggregators (DSO, TSO). On the other hand, compared with the pure digital system, the integration of ICT with energy systems should consider the challenges of legacy energy systems with their limited existing infrastructures and applications. To effectively make interoperability of various datasets for maximizing the profits of multi-level stakeholders in P2P energy society with minimum costs, it is necessary to dig data value over multi-area energy applications in a security and privacy way. It includes AMI (Advanced metering infrastructure), MDMS(Meter Data Management System)-based OMS(Outage Management System), CIS(Consumer Information System), DMS(Distribution Management System), Billing system, SCADA(Supervisory control and data acquisition system), EMS(Energy management system), HVAC(heating, ventilation, and air-conditioning), DR(demand response), Remote monitoring & management and so forth (Wu et al., 2021). Therefore, key technologies and their interactions to support and drive P2P energy trading are worth to investigate, which will expose HOW: (1) ICT enables co-creation of decentralized user-centered digital frameworks for broad-scale interaction from science–society dimensions, (2) Energy services drives the cross-border interactions for a wider and deeper exchange of P2P flexibility, (3) Maximizing the co-operation and interoperability of decentralized marketplaces based on ICT and energy services.

This paper exposes and analyzes the socio-technical interaction and mechanism for sustainable P2P energy trading by investigating the technical building blocks behind the three questions listed above. Two main lines are set up to present the co-creation strategy of P2P trading from the most essential backbones: **blockchain-enabled P2P energy society** and **multi-scale flexibility services for inter-operative marketplaces**. One is energy digitalization with ICT to build the platform for the engagement of distributed/regulated decision makers. The other is energy flexibility services to achieve control for the enhancement of transaction capability and power quality at regional/system level. The main contributions of this paper are summarized as follows:

- Discusses the challenges of energy as assets for P2P trading from social dimension (cooperation of multi-level market players), technical dimension (cutting-edge exchange of flexibility) and economical dimension (inter-operative decentralized/regulated marketplaces).



Source: Climate Watch, the World Resource Institute (2020)

Fig. 1. Greenhouse gas emissions by sector (Ritchie, 2021).

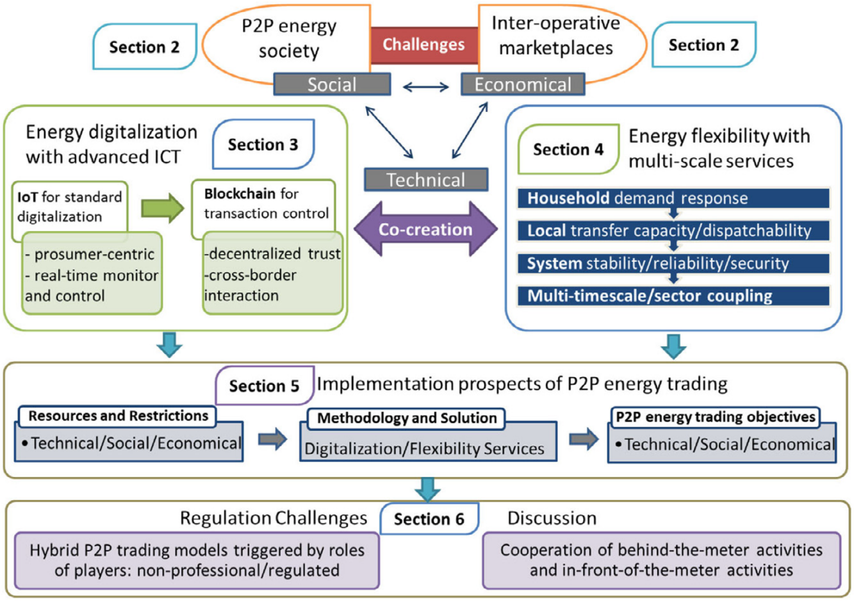


Fig. 2. Structure of the paper.

- Presents the operational key technologies determined by energy digitalization and flexibility services to form the P2P energy society for inter-operative marketplaces from both social- and scientific-dimensions.
- Characterizes the logic technical procedures on IoT-based digitalization for P2P interoperability and Blockchain-enabled automated flexibility services for customer-centric P2P energy trading with role-oriented privacy and security.
- Exposes the implementation prospects of P2P energy trading on how to achieve inter-operative energy marketplaces from IoT-based digitalization to blockchain-enabled automated operating energy system with over-all flexibility services by integration of new roles, new utilization patterns and new markets.
- Discusses the regulation challenges for P2P energy trading to coordinate the non-professional distributed players and professional regulators in the perspectives of hybrid trading models and interactive activities from behind-the-meter and in-front-the-meter.

The rest of the paper is organized as follows. Section 2 presents the relationship of P2P energy society and inter-operative marketplaces in P2P energy trading. Section 3 discusses the energy digitalization methods in P2P energy trading while Section 4 analyzes the over-all flexibility services solutions in perspectives of multi-timescale and multi-level energy trading. Section 5 exposes the implementation prospects of P2P energy trading and Section 6 discusses the regulation challenges. The conclusions are drawn in Section 7. The structure of this paper and relationship of each section is shown in Fig. 2.

2. P2P energy society for inter-operative marketplaces in P2P trading

More and more small or medium-sized distributed energy resources are connected to the distribution network, including distributed generators (roof PV panel, wind turbine), energy storage (private, public), controllable loads (EVs, heat pumps, households/buildings) (van Soest, 2019). The traditional trading model in which residential consumers or prosumers transact energy

Table 1
Overview of papers surveyed on key research aspects of P2P energy trading.

Key research aspects	Highlight/Contribution	Conclusion/Trends	References
Legal aspects and challenges	• Emerging modes of energy exchange: individual self-consumption, collective self-consumption, P2P trading, energy community • P2P trading legal challenges: energy regulation, consumer law, contact law, tort law, property law, competition law and data law.	• EU Clean Energy Package (CEP) legally defines P2P and energy community in regulatory framework • Standards will be conducted	de Almeida et al. (0000)
	• European energy law: energy markets, business models, EU-level regulation, cross-border trading, consumer rights and responsibilities.	• EU energy law allows P2P energy trading, but lack of specific provisions in practice	van Soest (2019)
Market design and business models	• Design categorization: centralized, decentralized, distributed • Differentiation of electricity products • Stability and competition in forming coalitions • Relationship with retail/wholesale markets • Game-theoretic perspectives	• Stability issue when design market rules or pricing mechanisms • Game-theoretic approaches used for the modeling of peer trading behaviors	Zhou et al. (2020a)
	• Bidding algorithm with privacy-preserving protocols • Transactive controllers as price negotiators for active users • Transactive management architecture. • Virtual power plant aggregator with blockchain	• The preservation of privacy • Scalability and standardization related with blockchain architecture • Regulation with DSOs and TSOs	Yang and Wang (2021), Siano et al. (2019)
	• P2P energy trading market layered architecture • Micrograds as market incentive roles • Smart contract trading architecture • Pilot installation of P2P energy markets	• Community interested models for a more fair and ecological-friendly solution for future energy market	Mazzola et al. (2020)
	• Alternative incentive mechanism as energy policy instruments for local markets • Market pricing and market parameters analysis • Fair incentive distribution mechanisms	• Incentive mechanisms will accelerate diffusion of decentralized local market structures	Cali and Cakir (2019)
	• Business models: behind-the-meter trading, local flexibility, multi-class energy trading, federated power plant formation • Prosumer-centric market frameworks: price-based distributed optimization, mean-field game theory, Stackelberg leader–follower games, double-sided auctions, cooperative energy sharing, networked matching markets.	• Prosumers and system operators have conflicting flexibility requirement • New mechanisms need to enable negotiation • P2P energy trading introduces uncertainty, losses and transmission constraints	Morstyn and McCulloch (2020b)
	• P2P market structure: full P2P market, community-based market, hybrid P2P market • Optimization technologies for negotiation and market clearing.	• Future P2P market coupled with wholesale/retail markets for consumers switch • Target the human dimension modeling of consumers	Sousa et al. (2019)
Key technologies	• Game theory: non-cooperative/cooperative game • Auction theory • Constrained optimization • Blockchain	• Network charge identification • Large-scale network trading and simulation • Ancillary service to the grid	Tushar et al. (2020), Thukral (2021), Joshi et al. (2020), Aloqaily et al. (2020)
	• Demand response optimization models: game theoretic, incentive-driven, cooperative-based, centrally controlled • Power routing: power routers, routing algorithms • Enablers: software defined network (SDN), blockchain	• Security • Privacy • Mobility • Energy Internet	Abdella and Shuaib (2018)
Trading platform, projects and startups	• Piclo, PeerEnergyCloud, Smart Watts, SonnenCommunity, TransActive Grid, PowerPeers, EnerChain, LO3 Energy, Power Ledger, Brooklyn Micro grid, PROSUME	• Multi-level P2P energy trading • Tradeoff between flexibility and resilience • Conductive regulatory framework	Küfeoğlu et al. (2019), Zhang et al. (2017), Georg Vogt (2020), Renewable Energy Agency (2020b)
User behavior	• Heterogeneous user behavior in real P2P energy market with different price-setting mechanisms • The role of households in P2P market: needs, acceptance and interaction • Participant in market user interface with products and services.	• P2P energy markets may foster sustainable practices: self-consumption or load-shifting • User engagement will foster the future diffusion of DERs	Ableitner et al. (2020)
Trust trading, security and privacy	• Dishonest trading behavior solution • Blockchain as an enabler to prevent untrusted energy market failures • Distributed framework for data privacy • Distributed security-constrained economic dispatch algorithm	• Solutions to malicious trading actions • Quantitative method to evaluate blockchain value in security • Trustful bidding with selective participant of honest/dishonest	Chen et al. (2021b,a,?)

only with utilities is changing with the engagement of various market players, who can sell or buy energy in a more flexible and efficient way. A new economic model, broadly termed as the "sharing economy", is driven by advanced ICT to facilitate the collaborative transaction of "underutilized assets" among individual "peers" (Schneiders et al., 2020). However, compared with other P2P assets trading, such as Airbnb for P2P accommodation sharing, and TaskRabbit for P2P freelance labor matching in the local market (TaskRabbit, 2021), P2P energy trading is quite different from other fields and is facing huge challenges. It is BECAUSE: (1) Energy as assets for P2P trading needs to consider not only individual demand matching, but also the balance of the whole energy system with different sizes of infrastructure. The power network needs to be operated stably, safely and be kept balanced at different time scales with distributed power flow injections from different directions. (2) Provision of P2P energy trading in a wider and deeper level means the cutting-edge exchange of flexibility across energy sectors and multi-scale energy physical communities with coordination of decentralized marketplaces. The development of advanced energy flexibility services inside the extensive energy supply chain to reveal and support the new roles of distributed actors is important to establish a P2P energy trading mechanism. (3) P2P energy trading involves not only individual household-level peers, but also multi-level aggregators, such as community manager in community-based market (Tushar et al., 2020), system operator and market operator in hybrid market (Sousa et al., 2019). Therefore, it is necessary to consider the interoperability of different marketplaces and the challenges on how to promote the P2P energy trading with existing market structures. It should not only allow trading peers to have the new P2P trading market but also enable them to cooperate with the traditional actors to deploy P2P market coupled with the existing wholesale and retail markets. Facing such huge challenges, more building blocks are needed to establish a P2P energy society with the increasing engagement of multi-level market players from both digitalization and services perspectives for cooperation of social- and scientific-dimensions. Fig. 3 presents the overview of building blocks to form a P2P energy society for inter-operative marketplaces aligned with energy digitalization and flexibility services.

In a P2P energy society, participants are from different market level, shown in Fig. 3. For example, distributed prosumers can switch their roles to sell or buy electricity by flexibly selecting the trading target according to their power status and transaction price. Various P2P energy trading mechanism and business models are proposed and discussed, which has already been listed in Section 1. These models can drive different trading marketplaces as shown in Fig. 3, such as household to household trading in a community, collective trading among communities, microgrids trading in microgrid clusters, and any peer to the grid trading. Therefore, P2P trading of multi-level participants over different marketplaces can form the P2P energy society. Right status and roles of participants in P2P energy society should ensure the interoperability of different marketplaces. They can interact with each other and get mutual achievement with technical support. It covers the two main lines: energy digitalization with ICT and energy flexibility with services. Categorizations of key building blocks for each specific technology over these two lines are shown in Fig. 3. The methodology is discussed in detail in the following sections.

3. Energy digitalization with advanced ICT

To empower the prosumer-centric P2P energy trading business models and enable the coordinative mechanism for decentralized marketplaces, advanced ICT knits the P2P network from both technical and social dimensions. This section focuses on the core building blocks of three aspects: IoT for digitalization, blockchain for decentralization and P2P platform for transaction. The IoT acting as the fundamental architecture of digital energy system paves the way for the heterogeneous integrations of various resources, including hardware and software, networks and communication protocols, services and applications (Wu et al., 2021). Blockchain acting as the decentralized incubator allows a cooperative and ever-growing network of mistrusting parties to securely transact with each other directly by establishing a science–society interface to balance trust and privacy. The IoT and blockchain technology-based P2P platform can provide a virtual trading layer with different kinds of services, such as carbon credit trading, energy as products traceability (Virtual Global Trading, 2021; Solar Impulse Foundation, 2021), data transaction business (de Almeida and van soest, 2021), IoT assets management (Dreamziot, 2021; Transparsoft, 2021; Dutsch and Steinecke, 2017), supply chain efficiency (Gaur, 2021; Jabbar et al., 2020) and XaaS-Any services transaction (Bornstein, 0000).

3.1. IoT-based household scale network and communication

To meet the 2050 climate-neutral objectives (Guterres, 2021), it is essential to directly activate individual household to contribute to green energy transition through smart daily solutions. IoT has been evaluated as a global standard infrastructure to enable heterogeneous sources to talk with each other. The emergence of IoT standards and IoT reference architecture models enables the convergence and interoperability of heterogeneous resources. The existing IoT related standards include ISO/International Electrotechnical Commission (IEC) Standard 21823 for the interoperability of the IoT in framework and transport, IEEE Standard 1451 for the smart transducer communication interface, IEEE P2431 draft standard for an architectural framework of the IoT, and other IoT-related IEEE standards for information technology (802.11, 802.15, and 802.22) (Wu et al., 2020). The popular IoT reference architectures include: the basic three-layer architecture (Qin et al., 2016; Mashal et al., 2015; Said and Masud, 2013), five-layer architecture (Qin et al., 2016; Mashal et al., 2015; Said and Masud, 2013; Omoniwa et al., 2019), Fog/edge-based architecture (Omoniwa et al., 2019; Bonomi et al., 2012), ITU-T architecture (ITU Standard, 2020), IEEE P2413 IoT architecture (IEEE Standards Association, 2020) and IoT-A architecture (Qin et al., 2016; Mashal et al., 2015; Said and Masud, 2013; CORDIS(EU research results), 2020).

With IoT architecture, a feedback closed-loop structure can be built to dynamically control the end-user resources in P2P energy trading system by real-time monitoring and control. Efficient power transfer can be ensured among the peers by the effective use of data flow. Energy-aware information is running through several building blocks, firstly from perception of energy resources, then through data collection, communication, analysis and identification, finally to automation of energy resources with feedback control signals. For IoT-based implementation, commercial companies have also proposed several IoT business architectures, including AIOTI WG03 IoT Reference Architecture (Wu et al., 2020), Cisco IoT Architecture (Qin et al., 2016), IBM Watson IoT Architecture (Mashal et al., 2015), Intel IoT Architecture (Said and Masud, 2013), Microsoft Azure IoT Reference Architecture (Omoniwa et al., 2019), and Huawei EC-IoT Architecture (Bonomi et al., 2012).

The realization of P2P energy trading can indispensably benefit from 'flatting' effect of internet by implementing IoT-based digitalization (Anon, 2021). The contribution of IoT to P2P trading includes: (1) Convergence of various energy sources across decentralized marketplaces, including generation, storage and consumption devices, (2) Collection of real-time energy data from

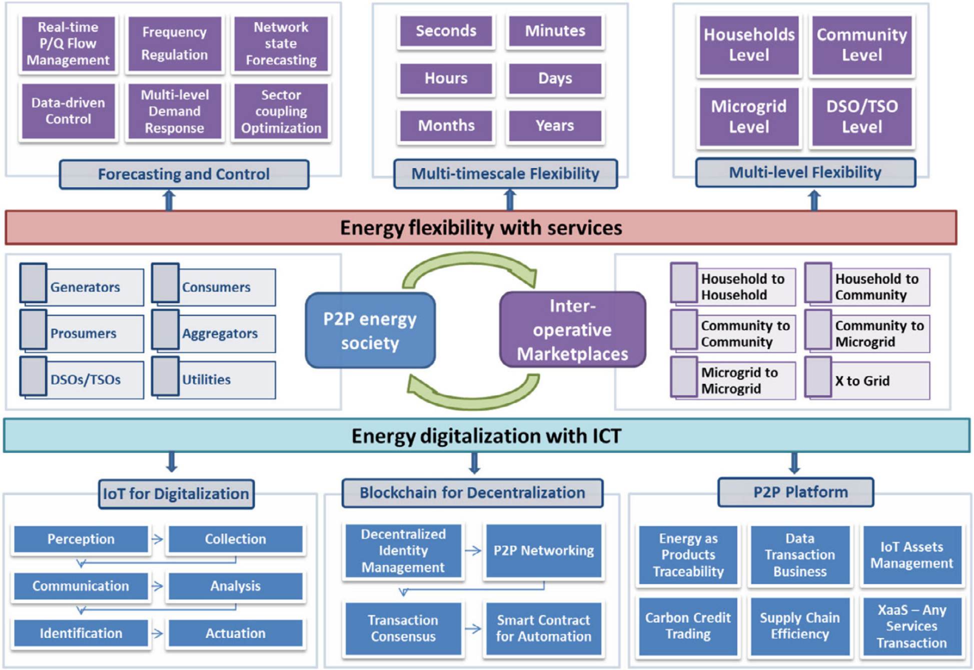


Fig. 3. Overview of building blocks to form P2P energy society for inter-operative marketplaces.

distributed demanding sides and supply sides, (3) Coordination of heterogamous communication networks, (4) End-to-end interoperability of monitoring and control.

An overview is given below from the perspective of layer-oriented IoT services. It presents how IoT enables the interoperability in household scale network to organize data flow, control flow and power flow in P2P trading.

- **Physical things layer**: it can be also called energy-oriented layer, which includes energy generation, storage, transformation and consumption in the household. The trend of electrification with various energy conversion technologies produces multiple energy supplies for different kinds of demand, such as electricity, heating and cooling. These supplies include storage, micro-CHP, solar-to-heat and so on. For the demand side, all the loads should be monitored, such as HVAC (Heating, Ventilation, Air Conditioning) systems, home appliances (washing machines, refrigerators, ovens, etc.), lighting systems, and so on. EV is a special energy unit. With advanced vehicle to grid (V2G), the charging–discharging behavior of EV can be dynamically optimized and cooperated from both time and space dimensions (Ping et al., 2020).
- **Perception & actuating layer**: this layer is responsible for identifying heterogeneous devices, seeing them, knowing them and controlling them. The main devices in this layer are including sensors to collect generation and consumption data (smart meters, prosumer meters, weather station, indoor environmental sensors, etc.), actuators to control supply and demand (smart plug, smart relay, inverters, converters, smart cables, smart thermostats, etc.)
- **Connectivity & network lay**er: it can be also called internet-oriented layer, which is responsible for the integration of various kinds of wireless and wired communication networks with different protocols. IoT gateways are the main devices to do sensor data convergence, translation and transmission to somewhere via Internet where they can be utilized, such as for visualization, monitoring, analyzing, automation and so on. They can easily bridge complex loads of IoT communication protocols and standards, such as wire field network (IEEE 802.3 family, power line communication, serial communication RS-232/485), wireless field network (IEEE 802.11 family, IEEE 802.15 family), mobile field network (GSM-based 2G, CDMA-based 3G, LTE-based 4G, NR-based 5G), and low power network (NarrowBand IoT, LoRa, Sigfox) (Wu et al., 2021).
- **Middleware layer**: this layer serves as an adaptable interface to pad the communication gap between the IoT world and high-level cross-domain services and applications. It needs to consider not only abstraction of the complexities of the lower layers but also communication and data services to upper layer. It is always presented as a huge integration software system, sitting in the middle to support and simplify various distributed applications, such as functional services (resource discovery, resource management, data management, event management, code management) and non-functional services (scalability, security, availability, reliability, real-time, privacy, and so on) (Ying Wu et al., 2020). The middleware solutions include VM-based, database oriented, fog node based, and service oriented (Middleware-as-a-service) (Razzaque et al., 2016). Developments can be implemented based on these solutions to extend our IoT system to integrate with other systems for different purposes, such as integration with blockchain platform for decentralized network, integration with big data processing and analyzing systems for data innovations, and integration with artificial intelligence (AI) tools to perform human-like tasks.
- **Application layer**: this layer enables a wide range of energy-aware applications, which makes data valuable to provide valued-added energy solutions for consumers, prosumers, utilities, and other stakeholders, such as demand side management, P2P energy transaction and so on. Applications are normally presented in form of web or mobile APPs. Therefore, human–computer interaction design should also be included in this layer to encourage prosumers to actively participate in energy-aware programs and contribute to reduce their energy-related carbon footprint.

3.2. Blockchain-driven P2P network and cooperation

As discussed above, IoT provides layer-by-layer services to enable individual engagement in energy trading markets by its digital ability on convergence and interoperability. However, it is still facing several serious challenges to adaptively extend the digital networking for the large-scale application with customer-centric privacy and security. Multi-level market players can be involved in different roles and responsibilities. Therefore, the following issues need to be considered in forming the robust P2P trading network: (1) Cross-border interconnections for a wider and deeper exchange of flexibility among energy sectors and communities, (2) Integration and interoperability of large-scale heterogeneous IoT systems with the participation of different stakeholders, (3) Decentralized trust for P2P interaction of different organizations without third parties, (4) Consumer/prosumer-centric marketplaces with customized applications and automatic business processing.

Blockchain, as one of distributed ledger technology (DLT), gets on the stage with provision of the transactional energy infrastructure which could offer operational cost reductions, improved operating efficiency, automated fast processes, and transparent transaction records for energy firms (Wu et al., 2021). Two of The Big Four, Deloitte and PWC, also known as the huge consulting firms in the world, marked blockchain as the biggest digital disruption for the energy industry years (Vakil, 0000; PWC, 2017). Deloitte states out that blockchain is a breakthrough trust mechanism which serves as the backbone of the transactional energy infrastructure, enabling an unprecedented level of transparency, coordination, and information sharing across energy industry as well as giving each market player a competitive advantage in the marketplace (Vakil, 0000). PWC states out that blockchain is in its stage to radically change energy as we know it by starting with individual sectors first but ultimately transforming the entire energy market (Hasse and von Perfall, 0000). In this section, the following questions will be discussed to uncover the contribution of blockchain to P2P energy trading and how blockchain can address the four issues mentioned above to form the healthy P2P energy trading network. It is discussed from the perspective of processing-oriented blockchain services.

- **Decentralized identity management (DIM) -** form the trusted P2P society: It is a user-centric digital identity mechanism to minimize the identity control points but automatically fulfills the four processes: identification, authentication, authorization and auditing (Zwitter et al., 2019). System entities, such as people, organizations, and things, gain ability and responsibility to control back over their own identities and trusted interactions with each other (Elliman et al., 2021). In P2P energy trading, DIM can support the integration and extension of various roles, responsibilities and interactions of decentralized market players. DIM can provide customized gateway for different organizations (TSOs, DSOs, aggregators), individuals (consumers, prosumers), and distributed energy resources (generators, storages) or IoT devices (sensors, smart meters, smart controllers). They should have their own digital identities and role responsibilities with privilege to access the role-fit information, share different parts of their identities without third-party but with more security and privacy. DIM favors the establishment of a more interoperable, unified, transparent and trusted energy society. The top uses cases of blockchain in DIM are (CONSENSYS, 2021a; TYKN, 2021): self-sovereign identity (SSI) (Grech et al., 2021), data monetization (Ali et al., 2021), data portability (Finck, 0000) and zero-knowledge proofs (Pandit and Dayamam, 2021).
- **P2P networking** - establish a flat communication mechanism: compared with traditional network communication architecture, blockchain network consists of a huge number of interconnected nodes. Each of them takes part in recording information and transacting messages with its neighboring nodes without a centralized authority. Different blockchain platform has different P2P networking mechanism. Taking hyperledger fabric (developed by IBM and led by Linux foundation) as an example (Hyperledger Foundation, 2021), there are four types of peers: committing peer for validation of generated blocks of transaction records, endorsing peer for generation of digital signature on transaction response, leader peer taking the responsibility for distributing transactions to other peers of the same organization, and anchor peer responsible for communication with peers of other organizations. After the transaction event is triggered, for example, the distributed consumer or generator is publishing their required buying/selling energy on blockchain network with bidding/offering prices, and then a transaction response is generated by endorsing peer and later distributed by leader peer for internal organization networking and anchor for cross-organization networking. Finally, this event is validated and recorded by committing peers. A similar P2P networking process can happen to the buying, selling and clearing events (Zhang et al., 2020, 2018; Zhou et al., 2020b; Angaphiwatchawal et al., 2020).
- **Transaction consensus** - ensure the distributed entities to arrive at perfect agreement. It is the root of blockchain to process the random nature of distributed transactions to be finalization without rollback. It ensures consistency, fairness and equality across the distributed network. To achieve distributed consensus, many challenges need to be targeted for research. The first one is the consensus algorithm, which is a process in computer science to achieve agreement among distributed processes involving multiple unreliable nodes (TechTarget Contributor, 2021). There are different types of consensus algorithms, which can be mainly categorized into two groups (Chami, 2021): Crash Fault Tolerant algorithms (CFT) and Byzantine Fault Tolerant algorithms (BFT). For the CFT, two famous algorithms are Paxos (Wikipedia, 2021)and RAFT Ongaro and Ousterhout (2021). The famous hyperledger fabric blockchain platform is using RAFT consensus. For BFT, there are lots of well-known consensus algorithms, such as Proof-of-Work (PoW) used by Ethereum 1.0 (Agarwal, 2021), Proof-of-Stake (PoS) used by Ethereum 2.0 (Wackerow, 2021), Delegated Proof-of-Stake (DPoS) (Cryptopedia Staff, 2021), Leased Proof-of-Stake (LPoS) (Andy Amora, 2021), Practical Byzantine Fault Tolerance (PBFT) (Alqahtani, 2021), and so on. A detailed introduction and comparison are given in (Anwar, 2021).
- **Smart contract** - automate the user-centric business process: It is a business-level programming abstraction, which not only defines the responsibility of each kind of transaction event and the processing activities of the whole transaction lifecycle but also governs the moving states and shared data across different organizations referred in the transaction. Smart contract can automatically seek trading peers, matching pairs from the supply and demand side, and encouraging direct energy transaction between generators and consumers based on the predefined rules without human interaction (Han et al., 2020). Smart contract is autonomously operating on the blockchain platform and is triggered automatically when a transaction happens (Seven et al., 2020). In P2P energy trading as analyzed above, multi-level and -timescale energy flexibility services should be integrated into system to make market players more energy sensitive for the provision of deeper and wider flexibility. Smart contract can enable the automation of flexibility processing. It includes a clarification of roles and responsibilities of future flexibility service providers and their positions as market facilitators, allowing roles-oriented automatic control of data and energy flow within power networks in a replicable, secure, verifiable and trustworthy way.

4. Energy flexibility with multi-scale services

Flexibility is a valuable currency for power system to manage changes. Solutions to provision of over-all system flexibility are of the utmost importance for the future energy system (Hillberg

Antony Zegers et al., 0000a). Modern energy flexibility needs to be considered from multi-aspect perspectives, because it needs to drive a giant, multi-faceted modern power system with aggregation of millions of separate energy supply and demand decisions across different timescales. It is from fractions of a second to minutes and hours to months and years (AEMO, 2020a). The operation of flexibility in fact covers both the technical and commercial dimensions. The technical capacities refer to the development of multi-aspect energy services, which can support system-level stability, frequency and energy supply, local-level transfer capacities, voltage and power quality, as well as timescale-level flexibility scheduling and exchange (Hillberg Antony Zegers et al., 0000a). The commercial capacities refer to the coordination of different marketplaces and their regulations (Hillberg Antony Zegers et al., 0000a). Technical capacities promote the commercial capacities, while simultaneously commercial capacities enable better utilization of technical capacities. Therefore, when the developed energy flexibility services cover over-all levels with integration of the relative market players, innovative marketplaces and their interoperation can benefit the stability and sustainability of P2P energy society for the deeper and wider energy flexibility in P2P energy trading.

In this section, energy flexibility services are discussed from the multi-timescale and multi-level perspectives. Specific energy services are categorized and matched into different P2P trading levels according to the predictability of system forecasting and dispatchability of system control. The building blocks are shown in Fig. 3 and the specific solutions for different conditions are shown in Fig. 4. It can be seen that flexibility is needed in the perspective of multi-dimension, which means that specific flexibility service can be implemented at the point determined by specific timescale and specific space level. For example, On-Load Tap-Changer (OLTC) is adopted for short-term flexibility for voltage from seconds to tens of minutes, and it is used in local/regional level to keep the bus voltages stable. It can solve the issue of the voltage variation caused by the injection of the multi-directional power flow (Laaksonen et al., 2021). It can be also seen that flexibility is not only referred to the balance of energy supply and demand but also needs to consider the quality and security in energy transaction (Hillberg Antony Zegers et al., 0000a).

A detailed diagram on energy flexibility for P2P energy trading is presented in Fig. 4, including: what specific flexibility services are needed in different transaction level? which timescale and in which method they can provide flexibility? Why they are used? – The purpose and their contribution. The answers are obtained based on the investigation of the research papers from International Smart Grid Action Network (ISGAN), International Energy Agency (IEA), EU Flexcoop, and EU BRIDGE (Hillberg Antony Zegers et al., 0000b; Flexcoop, 2021; HomeBridge, 2021; AEMO, 2020b).

According to 'Flexibility needs in the future power system' published for ISGAN (Hillberg Antony Zegers et al., 0000b), the flexibility services presented in Fig. 4 can be categorized into four groups: (1) **Flexibility for power**: short term equilibrium (from seconds to an hour) between power supply and demand to maintain the system frequency. Bi-directional power flow caused by distributed energy generators can increase the amount of intermittent power supply and DC connection to neighboring system. Therefore, the frequency control service should be used in system level, and BESS, as well as demand response services should be used in local level. (2) **Flexibility for voltage**: short-term ability (from seconds to tens of minutes) to guarantee the bus voltage stability with a local/regional redefined limitation requirement. It is important to ensure the power quality and system security during P2P trading process when large amount of bi-directional power flows are intertwined in energy trading network. Therefore, OLTC used in local level and FACTS used in TSO level can effectively provide voltage support during P2P energy trading. (3) **Flexibility for transfer capacity**: short to medium term ability (from minutes to several hours) to transaction power in local/regional networks with different topology, capacity and constraints. It refers to provide trading flexibility with various capacities for different market players. Identification of accurate operational state over different levels is required for network state forecasting and dynamic response to complicated trading processes. Therefore, Phasing-shifting transformer (PST) used for system level and multi-timescale network state forecasting services can effectively enhance the transaction capability and fast balance the supply and demand in different level. (4) **Flexibility for energy:** medium to long-term equilibrium (from hours to several years) to balance system supply and demand with storage-based support and energy-coupling services. It can be deployed from household level to system level. With installation of battery and EV charger, households could provide more flexibility to system over a longer time span with energy coupling cooperation services. Also using the long-term BESS-based services, such as hydrogen storage services, can effectively decrease the utilization amount of fuel energy and increase the trading capacity in a medium- and long-term time span. Therefore, flexibility services can not only exploit the power of different market players to contribute more to the clean energy transition but also act as the key pillars to guarantee the energy system operating in a secure and reliable condition with injection of new roles, new utilization patterns and new markets. In the next section, we will investigate the implementation prospects of these flexibility services on the digitalized P2P energy trading platform for the cooperation of different marketplaces.

5. Implementation prospects of P2P energy trading

Building blocks from the perspectives of energy digitalization and flexibility services have been discussed in Section 2 to form P2P energy society for inter-operative marketplaces. The operational key technologies and methodologies are analyzed respectively from these two perspectives in Section 3 to devise the efficient and effective P2P energy trading mechanism. This section exposes the implementation prospects of P2P energy trading on how to achieve inter-operative energy marketplaces from IoT-based digitalization to blockchain-enabled automated flexibility services. Firstly, implementation of the decentralized P2P trading architecture is presented. Then implementation of flexibility services with available resources to promote the cooperation of different marketplaces is discusses.

5.1. Energy digitalization implementation with ICT

The growing interest in enabling and activating citizens to contribute to green energy transition through smart daily solutions is strongly supported by the world-wide governments, scientific and commercial organizations. As discussed above, the power of citizen can be easily exploited by IoT-based household scale network with layered architecture to promote the utilization of renewable energy as well as simultaneously managing the flexible load units, local distributed generation and improving the grid performance. The blockchain approach ensures the data privacy and security for IoT-enabled users, as well as the provision of a robust, open and scalable system with the flexibility to integrate plug-n-play solutions for the over-all P2P energy trading in a decentralized but trusted way. This section presents the implementation architecture of the integration of distributed IoT platform with blockchain network for the P2P cross-border

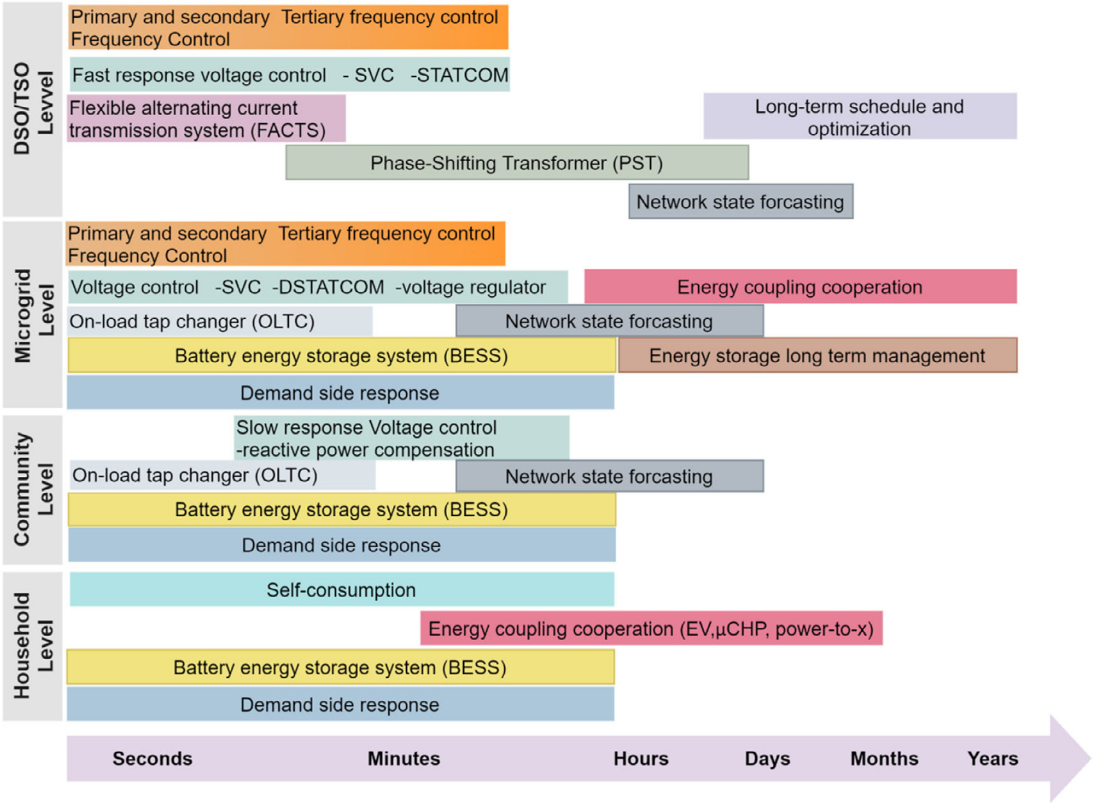


Fig. 4. Flexibility services solutions in perspectives of multi-timescale and multi-level energy trading.

interoperability of different marketplaces. Fig. 5 shows the modularized implementation architecture from IoT for digitalization to blockchain for decentralization in P2P energy trading.

There are mainly four modules in this architecture, which is fundamental and powerful in supporting interoperability. "Interoperability as a Service" is the need of the market, offering the decentralized and user-centric approach to promote the complete transparency and privacy-respectful share of services. It opens the doors towards seamless interoperability between IoT islands and resembles a decentralized cross-domain communication network, fulfilling the combination of modular and pluggable services to get connected and interoperated within the decentralized ecosystem in an easy, open, trusted way (Belesioti et al., 2018).

In the modular implementation architecture for achieving P2P energy trading, special attention should be placed to efficiently deal with the distributed generators and renewables-based devices to enhance the P2P trading capacity from bottom up. It is important that the basic unit "household" is acting as a plug-n-play component in energy system. The connection and disconnection of households should not affect the stability of power system, and the generation and consumption status of households can be detected in real-time for reliable control of energy transaction. Therefore, the advanced monitoring and forecasting services should be deployed on the household level to help market players or decision makers achieve the complete knowledge of the network states in real-time. In this way, the IoT-based household, as a key basic integrated player with continuous expansion feature of the total number, recaptured its control ability to schedule energy-consuming appliances according to energy forecasts and personal goals to achieve more sustainable behavior patterns. To connect the IoT-based households and enable the interoperability, blockchain technology provides the interface between these end-users, distributed energy networks, utility grid and multi-level energy market players, giving each of them an active role in the provision of innovative energy market paradigms. It integrates not only the IoT platforms, data sources and services in a secure, scalable and decentralized way but also the energy system market players from different level in a P2P, privacy-respectful and cooperative way. The details of these four modules are discussed as follows.

- **Module 1 - IoT for digitalization:** It is responsible for the energy assets digitalization, management and control with the localized open-source centralized IoT platforms. It enables users to describe their IoT devices with semantic description and enables their discoverability within the platform. A set of standard protocols and data management capabilities are available to map raw data coming from a variety of sensors to a standardized data representation in the cloud. A complete and advanced IoT-based household is shown in Fig. 5. A smart household contains various energy equipment: distributed generators, home appliances, smart devices (smart meters, smart plugs, smart cables, smart switches, smart relays, smart inverters, smart sensors), hybrid DC and AC power devices for future households, and energy coupling facilities (heating–cooling system, a controllable micro-combined heat and power generator, EV charging infrastructure, and a battery bank). Smart sensors and actuators are deployed to connect the physical equipment to the digital network. They can have different languages. With the help of IoT gateway, IoT agent can converge the different protocols to communicate in the appropriate channel over the sensor networks. The popular communication protocols used by IoT agent for bridging the IoT devices and IoT digital platforms include UL2.0 (Telefónica I+D, 2021), LwM2M (OMA SpecWorks, 2021), MQTT (OASIS Standard, 2021), LoRa (LoRa Alliance, 2021), SigFox (SIGFOX COMMUNITY, 2021), JSON (lightweight data format) (ECMA Standard, 2021), and so on. For example, SmartPort IoT gateway uses LwM2M protocol to collect data from generation side with the weather

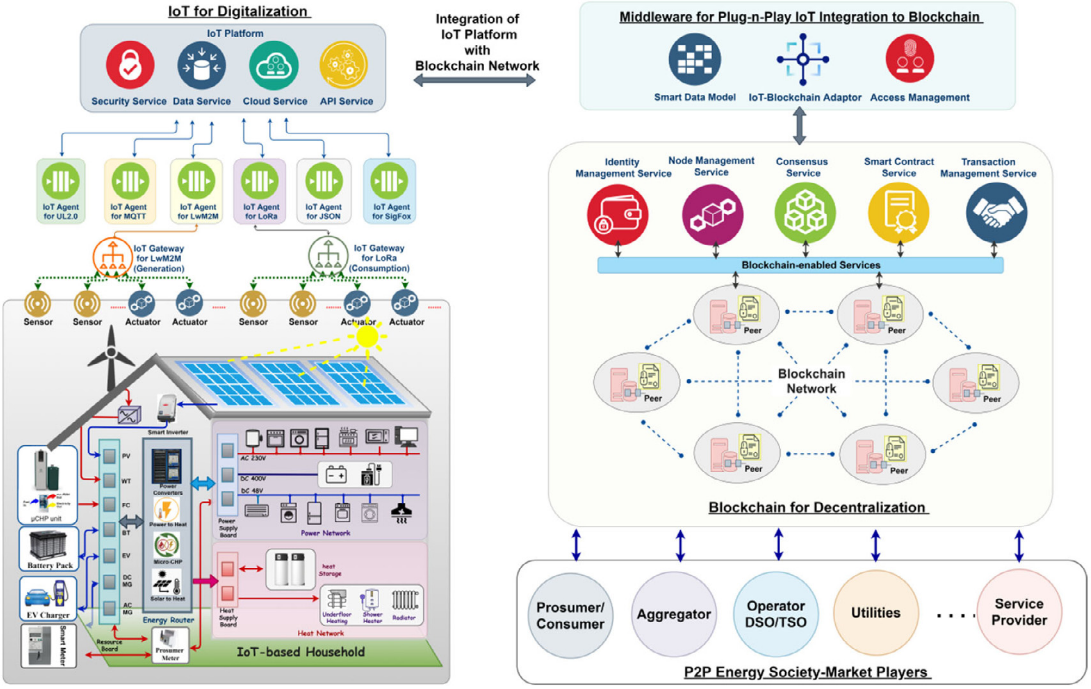


Fig. 5. Modular implementation architecture from IoT for digitalization to blockchain for decentralization.

station (SmartPort Europe, 2021). Develco IoT gateway uses UL2.0 protocol to monitor and control the consumption side via smart sensors, smart plug and smart relays (Develco Products, 2021).

- **Module 2 - middleware for plug-n-play IoT integration to blockchain**: It is responsible for providing a set of heterogeneous integration enablers, including smart data model for intensive collaboration of smart digital solutions in multiple sectors, IoT-blockchain adaptor for plug-n-play interface, and access management for data validation. These enablers serve as a bridge between the IoT-based open-source energy digitalization systems and the horizontal decentralized network, They are presented as standard software services (APIs and SDKs) used in different contexts to integrate heterogeneous IoT-enabled energy sectors.
- **Module 3 - blockchain for decentralization:** It is responsible for promoting multi-dimensional interoperability in the perspectives of technical (integration of IoT platforms), social (cooperation of market players) and economical (interoperation of marketplaces) dimensions. The targets of this module include: (1) establish a permissioned blockchain network (Wu et al., 2021) that connects grid-edge IoT platforms to form a seamless horizontal P2P energy society allowing multi-level energy market players (TSO, DSO, generators, consumers, utilities, etc.) to participant in the P2P energy trading in a transparent and non-discriminatory way. (2) provide decentralized identity management service to support the integration and extension of various roles, responsibilities and interactions of decentralized market players at different levels. Users' identities are predefined with the access rights to different trading channel resources, including data, information, business process triggered smart contract, and trading partners. (3) provide node management services to adaptively configure P2P networking topology and broadcasting protocols for more effective transactions. Blockchain network has a P2P architecture. A peer can a node that runs the smart contract, endorses transactions and stores records with distributed ledger. Blockchain nodes can be customized by developers with hardware, software and services to be more intelligent. Nodes can be easily added for network extension. Currently, blockchain node can be taken as a service "node as a service". Node service providers can offer APIs for developers to create automatic P2P networking workflows (Newman, 2021). The current popular node providers include Infura (CONSENSYS, 2021b), GetBlock (GetBlock, 2021), Alchemy (Alchemy, 2021), QuikNode (QuickNode, 2021), and Blockdaemon (Blockdaemon, 2021). (4) provide consensus service to seamlessly integrate innovative multilateral marketplaces in an opening and democratizing way. Currently, EV charger triggered mobile energy market can be easily integrated with the existing P2P energy marketplaces to form new P2P trading models with automated consensus ledger from different market players. (5) provide smart contract services to increase flexibility over different energy markets, achieving automation of multi-level and -timescale energy flexibility services defined in Section 4. It allows shared automatic control of data and energy flow within networks in a replicable, secure, verifiable and trustworthy way. It also includes a clarification of roles and responsibilities of service providers and their position as market facilitators. (6) provide transaction management services to facilitate multi-level P2P energy transaction. P2P energy trading can occur in a distributed retailer level or regional wholesale level. Household level enables prosumers/consumers to trade their surplus energy with their neighbors. They can register or access to available energy in P2P trading network with reduced cost of utility bills. Microgrids level enables wholesale trading through regional microgrids (Takyar, 2021). It can not only reduce the transaction costs but also provide enhanced flexibility for grid to fast balance supply and demand across cooperation of decentralized marketplaces.
- **Module 4 - P2P energy society with different market players:** It is responsible to provide a trusted cooperation atmosphere for cross-border energy market players and multi-level stakeholders to exchange energy, information and services. It enables specific roles to interact with each other in P2P energy society. The provided services include sector-coupling flexibility, cross-regional energy community flexibility, multi-level aggregators' collaboration with procurement of grid services by TSOs and DSOs, etc. The pluggable services, which provide distribution of roles and rights implemented over the blockchain network, can

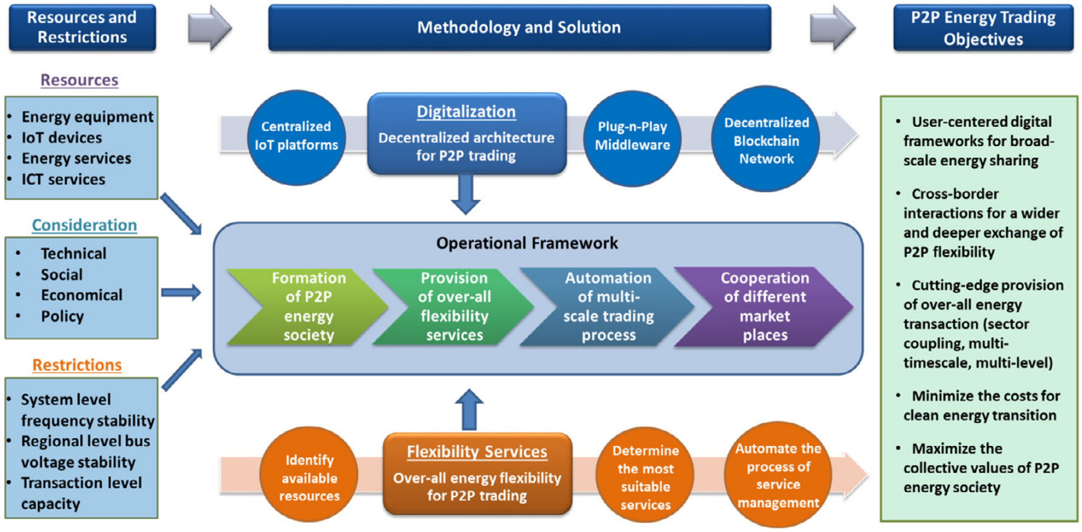


Fig. 6. Three stages of P2P energy trading implementation.

support the formation of innovative energy social networks. However, in the meantime, the legacy responsibility of the decision makers should be well considered, such as DSO, TSO and utilities with their own authentication, authorization, access control, data privacy and automation of level-oriented energy services.

5.2. Flexibility implementation for P2P energy trading

Large-scale integration of distributed renewables, transportation and electrification processes increases the need for various flexibility services for promoting the capacities of sector coupling, storage and Power-to-X conversion solutions with different time-scales. It envisions Energy Internet, an advanced energy-sharing network to implement P2P energy trading. On the other hand, solutions for flexibility realization require increased the involvement of new active players for the provision of these flexibility services. These market players become new flexibility providers over the different trading level from the trading between households to the trading between microgrids. Therefore, the implementation of flexibility for P2P energy trading needs to: (1) identify the available energy resources which can provide the flexibility, and consider the type of loads, generators, storages, AC/DC connections to other systems (Hillberg Antony Zegers et al., 0000a), (2) determine the flexibility requirements and the most suitable flexibility services according to situational restrictions and regulations, (3) automate the management process of multi-timescale and multi-level energy flexibility services with support of ICT solutions, (4) coordinate different marketplaces for the over-all P2P energy trading. Fig. 6 shows the three stages of service-driven implementation of P2P energy trading. It presents how to select suitable flexibility solutions to achieve the objectives of P2P energy trading considering the resources and restrictions, and what methods are used to support the achievement of the operations framework.

The first stage is about the resources and restrictions. Consideration needs to be taken from several aspects, including technical, social, economic concerns and national/international policy to support local/regional or operational level energy trading. In May 2019, EU in its CEP gave the legislative definition of energy community and stressed the significant role of energy community in helping EU meet its climate and energy objectives in 2030 (Eu, 0000). Energy community and P2P energy trading are two complementary models to promote clean energy transition. Energy community provides established relationships between utilities and individual prosumers, which provides the regulated energy transaction law to promote the balancing of supply and demand at the local level via P2P energy trading (De Almeida et al., 2021). For resources, the determination of flexibility capacity needs to identify the available energy equipment and IoT devices in an energy community. The deployment of advanced ICT services for the monitoring and management of the energy networks enables efficient and reliable utilization of flexibility services on real-time state estimation and advanced supply/demand forecasting at different levels. For restrictions, the management of frequency and voltage stability is essential for energy security. The operation of flexibility services needs to consider the energy security not only from the system perspective but also from the local/regional perspective. A stable system frequency needs to be maintained and the variation of bus voltage needs to be guaranteed in the required limitations. In the meantime, transaction capacity should be designed at different levels to determine the dispatchability of flexibility.

The second stage is methodology and solution adopted on the P2P trading operational framework for the final objectives. Two lines are covered: the first one is digitalization to establish decentralized architecture for P2P trading and the second one is flexibility services to automate the P2P trading processing across the over-all energy network. The line of digitalization is starting from the centralized IoT platforms, which enables cross-device, cross-network, cross-data, cross-service, and even cross-domain integration and interoperability, enhancing the ability of distributed energy resources from ubiquitous connection to distributed automation (Wu et al., 2020). Popular used IoT platforms include FIWARE (FIWARE Foundation, 2021), Inter-IoT (INTER-IOT, 2021), AWS IoT (AWS, 2021), IBM Watson IoT (IBM, 2021), Microsoft Azure IoT hub (Microsoft, 2021), Oracle IoT (Oracle, 2021), and ThingWorx (PTC, 2021). Then the development of middleware provides plug-n-play interface to enable distributed various IoT platforms to connect with blockchain network for the large-scale integration and the cross-border transaction. The design of standard data model should consider the heterogeneous communication, such as IoT agent for integration with IoT platform, and blockchain gateway for integration into blockchain network. The last block of this line is the decentralized blockchain network, which not only securely integrates different open-source or commercial IoT-enabled grid-edge networks, but also supports the establishment of the trusted P2P energy society for maximizing the participation of decentralized market players with different roles and responsibilities. Smart contract benefits the automation of flexibility services management, allowing shared data and energy flow automatically identified and distributed based on the pre-defined roles and responsibilities in P2P trading market. The popular blockchain network used in P2P energy trading includes Ethereum (Ethereum, 2020), Hyperledger fabric (Hyperledger Foundation, 2021), Quorum (ConsenSys, 2021), and R3 Corda (R3, 2021). Comparisons of features and solutions of these blockchain networks in commercial and research applications are summarized in Wu et al. (2021). With the decentralized P2P trading architecture, flexibility services are implemented along the other line from the identification of available resources to automation of management process at different trading levels.

The third stage is what objectives and results P2P energy trading can achieve, including: (1) User-centered digital frameworks integration and interaction for broad-scale energy sharing, (2) Cross-border interactions for a wider and deeper exchange of P2P flexibility of different levels, (3) Cutting-edge provision of over-all energy transaction across inter- and intra-sectoral energy flows, short- and long-term time scales, and inner- and cross-community region levels, (4) Minimize the costs for clean energy transition, (5) Maximize the collective values of P2P energy society.

6. Discussion

There is no doubt that a new energy transaction world is opened by the engagement of active new players and integration of innovative activates carried out in front of- and behind-the meter (Glachant and Rossetto, 2021). As discussed above, the advanced digitalization technology and energy services enable different market players to take initiatives to create new transaction models, options, tools and rules for combination of innovative digital and energy services (Jean-Michel Glachant, 0000). However, P2P is still not mainstream, not yet fully commercialized and not yet have a uniform definition of how P2P works, especially in energy world. Compared with other P2P trading, regulation plays a key role in energy system with definite rights and obligations for different actors in a regulated energy market. P2P energy trading involves not only small size and non-professional distributed players, but also the big and fully professional players. They are the decision makers in traditional energy system and there are already many regulated parts in energy trading market with B2B and B2C market design. Therefore, it is not easy for P2P energy trading to coordinate the non-professional distributed players and professional regulators. In this section, the regulation challenges in P2P energy trading are discussed from two perspectives: (1) Hybrid P2P energy trading models triggered by roles of players and (2) Cooperation of behind-the-meter activities and in-front-of-the-meter activities.

6.1. Hybrid P2P trading models triggered by roles of players

With the engagement of multiple players from different transactional levels, 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. P2P trading is in fact extended into peer-to-X trading (Glachant and Rossetto, 0000). Various trading types form hybrid P2P trading models, which can bring many uncertainties and variants to the energy system. Popular P2P trading types are discussed below (Glachant and Rossetto, 0000; Morstyn and McCulloch, 2020a) :

- **Behind-the-meter trading:** With installation of energy assets in households, consumers started to become prosumers to investigate more activities ‘behind the meter’ in their life. Potential retail electricity markets are boosting the utilization and efficiency of local renewable energy, but this prosumer-to-prosumer energy transaction has very high intermittent nature. The supply side is intermittent determined by weather, and the demand side is also intermittent determined by its own status of self-consumption. User cases in this trading mode can be referred to Brooklyn Microgrid (Brooklyn, 2021), Quartierstrom (Schopfer, 2021), and RENeW Nexus (Synergy, 2021).
- **Local flexibility trading:** P2P trading takes place in an organized community. Unlike the first trading type, it should be regulated with local demand constraints. Community operators can manage the local P2P energy market with communication of other system operators. They can make decisions to import/export energy with other operators according to the demand requirements and constraints to maintain system voltage and frequency stability. It can not only provide local market flexibility but also improve the energy security of supply. However, compared with distributed non-professional players, energy community has to perform complex activities. It needs to not only ensure P2P trading internal a community, but also cooperate with external players for big trading. Therefore, it is vital to identify its obligations to balance both local side and grid side (SIAPARTNERS, 2021). User cases in this trading mode can be referred to Beehive project (Enova Community, 2021) and Partagélec (Smartgrids, 2021).
- **Multi-Class energy trading:** Besides the above trading modes of individual peers, distributed non-professional players can also sell energy to the big players. It offers flexibility for prosumers to select where their surplus energy is transacted to or even where the energy comes from if they want to buy some energy. Therefore, P2P trading can occur in multiple dimensions from retail supplies to wholesale suppliers. Customers can select their preferred energy flow, but all the power injections should be managed by a system operator. The operator is responsible for monitoring multi-lateral power flows, collecting and integrating them into grid as well as guaranteeing the system stability and security. It is not easy to define the obligations of such a role. Multi-class energy trading needs to consider multi-level players, multi-geographical and multi-timescale transactions. User cases in this trading mode can be referred to Vandebron in Netherlands (Vandebron, 2021) and Piclo in UK (PICLO, 2021).
- **Federated power plant formation trading**: It is a new trading mechanism to integrate peers as trading coalition to operate together. Prosumers are incentivized to form a cooperative entity to provide flexibility services over frequency regulation, local voltage constraints management, and balancing support on TSO level. It can facilitate the regulated cooperation of different roles in energy market. Non-professional prosumers can trade energy with grid directly in a safe and regulated way. However, it is not easy to directly deal with the intermittent injection of such multi-lateral power flows. Ancillary energy services needed to be developed and implemented on the end-user side to solve the issues caused by local congestion and voltage fluctuations. User cases in this trading mode can be referred to GOPACS (GOPACS, 2021), Enera (BMWK, 2021) and NODES (NODES, 2021).

6.2. Cooperation of behind-the-meter activities and in-front-of-the-meter activities

Multiple market players trigger the hybrid P2P trading models as discussed above. More and more behind-the-meter activities are integrated into the trading models to exploit the power of non-professional players via P2P trading market. They are new to the energy system and bring regulation challenges to the existing wholesale and retail markets with regulated in-front-of-meter activities. Therefore, it is necessary to cooperate the behind-the-meter and in-front-of-the-meter activities to achieve a win–win market situation for all involved players. Three components are essential for cooperation, which are Jean-Michel Glachant (0000), Glachant and Rossetto (0000):

- **Pricing mechanism**: P2P trading is initially a business model to match trading between small players, which should provide good incentives to make a deal between small buyers and small sellers. Price is the best incentive. When energy becomes goods, its fluctuating nature can dynamically affect the pricing mechanism and its random supply and demand with very small units (kWh) can break the scheduled balance in terms of time and location. Therefore, a suitable pricing mechanism has to be intelligent enough to dynamically balance the local and wholesale market by dealing with the varying value of supply and demand at different times and locations. It also has to consider buyers feeling to incentive them to buy the energy at the specific time and from the specific location, which might not be easy. P2P pricing mechanism is still an open field for research and experiment (Jean-Michel Glachant, 0000).
- **Digital transaction loop**: Energy trading has its own dimensions in 'digital transaction loop'. It not only facilitates the transaction process by finding ways to lower the trading costs between 'small-to-small' trading, but also provides precise and effective governance to match the transaction capacities from time and location dimensions. It is because the non-professional small players cannot completely establish their own digital transaction loop by themselves. Although they can publish their required buying/selling energy on blockchain network with bidding/offering prices, final transaction should be settled by professional players and decision makers. They can use particular rules to regulate the energy system and promote the cooperation of small players.
- **Delivery loop:** It is a twin to transaction loop to satisfy the buyers' expectations. It is implemented with innovative regulations in local grid for P2P energy trading. The in-front-the-meter regulations are already mature with all the rules of connection, operation, charging, metering and billing for big players trading (Jean-Michel Glachant, 0000). The digital transaction loop mentioned above is working closely with the in-front-the-meter regulations to cooperate with the delivery loop. Therefore, it is not anymore that energy delivery loop is only operating internally with a single building or an islanded microgrid. It is operating among the connected individuals with the public regulated grid network. The interaction can cause several issues such as the settlement issue. It is not easy to do P2P settlement in an internal community with public meters even installing the private meters upon the public meters. It is also difficult for the local grid to manage congestion, secure the random transaction flows, govern the real-time network state and finally achieve the physical delivery loop according to its own constraints on injections and withdrawals.

7. Conclusion

With increasing engagement of new distributed players and deployment of innovative behind-the-meter activities, P2P energy trading has been acting as the next generation energy management mechanism to foster interaction of multi-level market players for energy sharing, transferring, exchanging and trading in a more flat way. This paper investigates the internal mechanism of P2P energy trading in the perspectives of co-creation of technical, economic and social methodologies for establishment of P2P energy society and coordination of multi-level marketplaces. Firstly, a systematic overview of building blocks to form P2P energy society for inter-operative marketplaces is provided. Two lines are covered: one is energy digitalization with IoT-based P2P interoperability and blockchain-enabled customer-centric trading privacy and security. The other is over-all energy flexibility exchange across energy sectors in multi-scale dimensions. Secondly, the roles of IoT, blockchain and flexibility services as the core pillars in P2P trading are discussed in the perspectives of necessity, feasibility and effectiveness to guarantee the operation of this new structured energy system in a secure and reliable condition with injection of new roles, new utilization patterns and new markets. Thirdly, three operational stages of P2P energy are presented from the implementation perspectives to expose the operational framework to maximize the collective values of P2P energy trading. Finally, regulation challenges are discussed on cooperation of new roles with innovative behind-the-meter activities and regulated roles with existing in-front-of-the meter activities for the guide of future work.

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.

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