Exploring blockchain and new ways forward in the energy sector: A case study in Japan

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Abstract— Under pressures to reach net zero emissions by 2050, there is an ongoing transition of energy decarbonization, decentralization and digitalization. Physical and information flows in energy systems are increasingly complex and distributed, leaving centralized structures inefficient. Blockchain technology is suggested as part of the next step in this transition. Blockchain has potential to facilitate distributed, peer-to-peer trading with reduced transaction costs, increased security via cryptography, and prosumer choice. However, there are as of yet multiple challenges to the expansion of blockchain in the energy sector. This paper argues that analysis of these challenges requires a multi-angled approach incorporating technological, economic, social, environmental, and institutional dimensions. First, each dimension is explored, substantiated based on a blockchain-based energy system case in Japan. Concrete challenges of scaling this case toward 2050 and potential opportunities in overcoming these challenges are discussed, leveraging extensive literature review. Finally, an overview of strategic indications is suggested. The findings of this paper present initial indications on challenges and opportunities to overcome them based on a multi-dimensional overview. It is suggested that the factors identified across the dimensions are interrelated. This would in turn call for coherent innovation management and multi-stakeholder innovation ecosystems. At large, it is suggested that a holistic and pragmatic approach can benefit the application and scalability of blockchain in the energy transition.

Keywords—blockchain, energy transition, renewable energy, prosumers, innovation ecosystem

I. Introduction

If human-produced carbon emissions reach net zero by 2050, global warming may be limited to 1.5 degrees and climate risks evaded [1]. In this scenario, renewable energy would supply 70-85% of electricity globally [1]. The majority of greenhouse gas (GHG) emissions are linked to energy production and use, which need to be in core efforts to combat climate change [2]. These pressures have steered an energy trilemma, meaning a need to facilitate emissions reduction while maintaining energy affordability and security [3, 4]. This has set off a sweeping energy transition toward decarbonization, decentralization and digitalization [5, 6]. In 2017, 257 GW of renewable power capacity was added globally, outpacing the 70 GW net addition of fossil fuels [7]. Several nations target a 100% renewable electricity share by 2050, such as Spain [8], Germany [9], and Denmark [10]. Costs of renewable energy technology are expected to continue decreasing [11] enabling a fundamental shift to distributed energy systems, such as microgrids [4, 12-15].

The increasing complexity of physical and information flows in the distribution network is a challenge in this shift [2, 16]. This is related to the smaller scales and intermittency of distributed renewables, affecting power grids [16, 17] and markets [18]. Technological innovation is a vital driver in energy transitions [2, 3]. The smart grid is one such innovation. By integrating information and communication technologies (ICT) with energy networks [19, 20] bi-directional control of physical and financial flows in smart grids has increasingly facilitated system efficiency and resource coordination [16, 21]. Various systems are evolving via smart grids, such as virtual power plants (VPPs) and vehicle to grid (V2G) [2, 6]. For example, V2G complexity increases the difficulty of maintaining grid stability as well as managing financial flows. In this context, ICT can contribute to both physical and financial management.

In addition to technology, market policies can support renewable energy expansion. For example, fixed price feed-in-tariffs (FITs) can encourage initial low-risk deployment of renewable energy, followed by further integration in liberalized electricity markets subject to dynamic pricing [22]. However, even in liberalized energy markets, small-scale trading is inhibited by regulatory requirements and transaction costs that offset benefits [4, 15]. For example, while the Dutch energy market was liberalized in 1998 [23], license requirements are as of yet a challenge for small-scale prosumer market participation [24]. Prosumers are likely to increase, and this would require advancements in exchange mechanisms, market access, and grid stability [5].

What is the next step in the energy transition? To answer this, it is useful to turn to digital industry trends. As put by Bheemiah [25], “The information revolution is reversing the industrial revolution and changing the structure of markets in this process.” The structure of payment and money is undergoing tremendous change, with a rise of cashless societies, peer-to-peer (P2P) transactions, and micropayments in social networks [25, 26]. Following these trends, central banks are deliberating on the backing of digital currencies, such as Sweden, Norway, Brazil, China and Canada [26]. Markets are increasingly decentralized with multiple agents among which trust influences transaction costs [25]. In the energy sector, the growth of variable data and distributed systems renders centralized approaches inefficient [6]. This calls for enhanced digital infrastructure, data management, and trustworthiness of information [21].

Several authors have discussed the next generation of the smart grid as the “Energy Internet” [14, 15, 20] which leverages connectivity, big data and cloud-computing for multi-energy coupling and interconnection [2, 14, 15, 20]. Multi-energy refers to the integrated coordination of transportation, electricity, thermal and natural gas sub-systems [14]. Such cross-sectorial integration can support energy- and cost-efficient, coherent energy systems [27]. This is mainly theoretical, with few systems running [20]. Blockchain technology may facilitate transparent, disintermediated, and distributed platforms for the Energy Internet [15, 20, 28]. It has potential to support P2P microgrids with prosumers [5], and solve issues of consensus, flexibility and security in the Energy Internet [14]. Blockchain is essentially a distributed ledger through which transactions can be carried out without a third party, based on consensus mechanisms and cryptography [29, 30]. This can reduce transaction costs, facilitate trust, and support P2P trading on multiple scales [13]. Transaction costs can be based on computation [31] and reduced with the removal of intermediary financial institutions [29]

How blockchain can contribute to the energy sector is a question which several organizations are exploring. Progress of the technology can be divided into phases of 1) cryptocurrencies, 2) smart contacts with limited applications, and 3) decentralized autonomous organizations (DAO) [5, 20, 28]. Attention was first directed to Bitcoin, but is shifting to blockchain applications at large [32]. It is suggested that the current phase is that of exploring smart contracts, systems which “automatically move digital assets according to arbitrary pre-specified rules” [32]. The final phase involves DAO: a “long-term smart contract that contains assets and encode the bylaws of an entire organization” [32]. If the current rate of blockchain development persists, it is suggested that the final phase is likely well before 2050.

Blockchain can nurture innovation by enabling small economic actors, transforming economic functions, such as P2P models, and at large contribute to sustainable societies [28, 33]. Blockchain has potential to support the energy transition toward 2050 and beyond. However, its application in the energy sector still faces multifaceted challenges, which need to be assessed [6, 34], alongside impacts on sustainable development [35, 36]. Such challenges are yet to be integratedly addressed. This is an exploratory paper aiming to identify and discuss concrete challenges which affect blockchain-based energy systems, and opportunities to overcome them. Transitions present ambiguities surrounding future technological and social changes [37]. Understanding energy transitions benefits from discussions on technological, social, economic, environmental, and institutional dimensions [3, 17, 38]. A blockchain-based P2P microgrid case in Japan is analyzed from these dimensions, and concrete challenges to scaling up toward 2050 are identified. Opportunities to overcome these challenges based on both academic and grey literature are intertwined in this discussion. Finally, indications for practitioners and researchers are suggested.

II. Case analysis: Challenges and opportunities

A. Technology

The case pilot project is in Urawa Misono, Japan, with technical details shown in Table 1 [39]. Technological challenges include blockchain resource intensity, throughput (transactions per second: tps), latency (seconds per transaction: spt), data storage, legacy system interoperability, high speed connectivity, and cybersecurity. These issues are influenced by blockchain design and consensus mechanisms. Proof-of-Work (PoW) was introduced for consensus in the Bitcoin blockchain [29] and several other blockchain platforms including in the energy sector [6]. However, PoW involves high energy intensity [40, 41], and latency [6]. Initially, PoW was mainly carried out using central processing units (CPU). However, due to their higher efficiencies for PoW and cryptocurrency mining, graphics processing units (GPU) and Application Specific Integrated Circuits (ASIC) have been increasingly adopted for such purposes [42]. CPU, GPU and ASIC nonetheless all incur a high energy consumption [35].

The current case is based on a private Ethereum blockchain, and Proof-of-Authority (PoA) consensus mechanisms. PoA adopts an authority node (a known validator) to manage bids, transactions, and completion

TABLE I SYSTEM DETAILS OF CASE PROJECT (DGC: DIGITAL GRID CONTROLLER; DGR: DIGITAL GID ROUTER)

	10 Consumers	**5 Prosumers**	**1 Mall**
Equipment	DGC, smart meter	5kW solar PV, 12 kWh Li-ion battery, 10 kW sub-grids, DGC, DGR	60kW solar PV, DGR, DGC, smart meter
	200 V AC distribution line (connects prosumers, consumers, mall), 350 V DC sub-power line (prosumers only), 6600 V HV embedded distribution line (connects prosumers/ consumers/mall & main utility grid)		

reports in the P2P network. Digital grid routers (DGR) carry our power and financial transactions based on smart contracts and by leveraging asynchronous grid connections [39]. PoA requires lower computation power, resulting in lower latency and resource consumption. Adoption of more energy efficient and scalable consensus mechanisms are expected to increase, such as of PoA and Proof-of-Stake (PoS) [6]. Ethereum, for example, maintains plans to standardize PoS on its platform, as opposed to PoW, [43] and integrate sharding [25, 28]. Sharding involves branching one blockchain into several chains, which may reduce latency and increase throughput. A technical issue related to sharding is multi-chain interaction and communication: an area for further research [43]. Ethereum is developing a framework (Plasma) for scalable, autonomous execution of smart contracts leveraging externalized multi-chain, multi-party channels connected to the blockchain root [43]. Multi-chain blockchain infrastructure may contribute to scalability.

If the case is to be scaled up, large-scale blockchain data storage would also be an issue [6, 12, 14]. The Ethereum network, for example, requires high speed large-scale databases such as solid state drives (SDDs) to support node-syncing, data transfer, and multi-tasking [44]. Storage issues can be further tackled via cloud computing [12], side-chains [6], off-chain storage [45], and other potential advancements. State channels can make blockchains more efficient and scalable by moving several processes off-chain, including storage, while maintaining system trust [46]. These developments may enhance scalability in blockchain applications, including in the energy sector.

Data security is a benefit of the distributed structure of blockchain as opposed to centralized data systems with single points of failure [13, 29, 36]. There are however still security and privacy risks such as 51% attacks, double-spending, ledger data falsification [41, 47], and smart contract bugs [48]. Security and privacy risks are especially an issue in public blockchains [49]. The development of consensus mechanisms, privacy measures such as pseudonymity and asymmetric encryption, and data fraud prevention are important next steps [13, 15, 41, 48]. In parallel, there is a need to maintain equity and balanced control in emerging autonomous systems [33]. The blockchain topology is an important consideration for security, privacy, and control.

Blockchain topology and communication would affect security and privacy, as well as throughput, resource consumption, network effects, trading capabilities, and social interaction [50]. This shows topology choice impacts several dimensions. While the case is a private network, the topology of future larger scale blockchain-based energy systems is unclear. Fig. 1 shows potential topologies, which may be based on private, public, consortium [13, 20], or semi-private blockchains. Private, semi-private, and consortium blockchains have lower energy consumption levels than public topologies as consensus mechanisms are carried out in a smaller number of nodes or by cloud solutions [50]. Semi-private structures are at the intersection of private and public blockchains, whereby a single authority node (company) runs the blockchain and manages

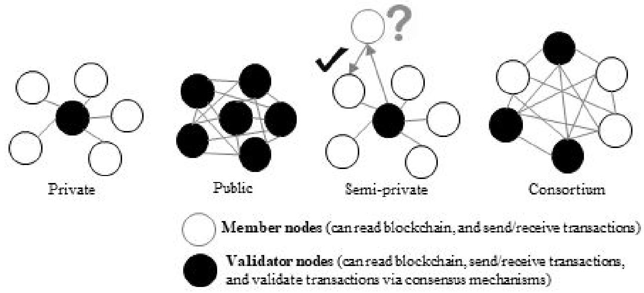

Fig 1. Overview of potential blockchain topologies

user access. In consortium blockchains, pre-selected authority nodes control access and consensus in a broader network. The consortium topology may be useful for P2P trading in microgrids with pre-selected aggregators [5]. In the future energy blockchains may be fully public, such as in the Energy Web Chain [49]. It would be important to decide on topologies not only based on blockchain-oriented technological advancements but also on the energy sector context, such as market models and power grid conditions.

While the pilot project can operate as a trial blockchain platform, interoperability with legacy smart grid and digital systems is also uncertain on a larger scale. Blockchain interoperability and integration into digital systems [33], and smart meter infrastructure would require a gradual

adjustment if P2P systems are to scale up [6]. Blockchain platforms at large, such as Ethereum, require high speed and continuous internet connection in order to support transactions and syncing [44]. Multi-chain and off-chain developments, such as state channels, would also depend on reliable and continuous internet connection [51]. It is uncertain if current systems would be able to support scalable blockchain-based energy systems.

Certainly, there is a cornucopia of other advancing, mutually reinforcing technologies also likely to affect energy in 2050. 5G networks are expected to significantly increase connectivity and autonomous operations among devices and systems [52], which would support connectivity among blockchain nodes. Light clients on devices such as smart meters can be used to couple the Internet-of-Things (IoT) with blockchain networks [49]. Smart grids will increasingly leverage IoT, machine-to-machine (M2M) communication, cloud-computing, and artificial intelligence (AI) [21]. Via 5G coupled with V2G and M2M, for example, machines may be economically independent entities acting based on smart contracts. Grid management can be automated further, including V2G grid-balancing and ancillary services [6]. With smart grid developments, there is an increasing size and complexity of data whch would need to be supported by improved communication networks [54]. Cognitive radios (CRs) may contribute to spectral efficiency and larger networks [54], including for wireless 5G.

New systems such as cognitive and neuromorphic computing will continue to increase AI efficiency and abilities [54]. For example, AI can oversee transactions and smart contracts, distinguishing vulnerabilities or suspicious activity and contributing to platform security [48]. AI solutions can also be integrated within smart contracts with auditable data trails, such as for autonomous vehicles [28]. Autonomous electric vehicles (EVs) [55], wireless electricity transmission for EVs [56], and wireless energy harvesting for electronic systems in general [57] may increasingly influence the energy transition. Leveraging AI as a "brain", blockchain-based energy systems may operate on far higher levels of automation and decentralization than previously seen in the sector. Fig. 2 illustrates a potential future platform in this context based on DAO, interconnecting and enabling P2P trading among energy producers and prosumers in digital interfaces and through physical grid infrastructure. On such platforms, energy-as-a-service (EaaS) and decentralized trading may become the new norm.

As put by Bheemiah [25], "blockchain is not a panacea. It is a tool and like any good tool, it is versatile and works better when it is part of a toolkit." Decentralized energy-trading would require the integration of several technologies, including AI and machine learning, for predictive analysis and balancing [2, 6]. However, just as new technologies can support blockchain-based energy, they can present threats to competitiveness and system security. For example, Casino et al. [28] highlighted resilience toward quantum computing, which has the potential to 'break' algorithms. Lattice and new code-based cryptographies may decrease this risk [28]. With coherent management of technological innovation, blockchain coupled with other advancements may decentralize energy grids and the energy economy.

B. Economy

For the case in Japan, identified challenges in the economic dimension include subsidy-dependence, market competition, contract interoperability, and platform market growth. In Japan, power utilities have largely been supported by public grants and subsidies, showing a need to mobilize resources and develop business models that do not depend on governmental funding [58]. The case project is mainly funded by the Ministry of Environment (MoE) of Japan. Long-term business model innovation and scalability in the event of subsidy independence is an important question. Market barriers built by incumbent companies or monopolies may inhibit decentralized blockchain-based models [13, 15, 59]. Such players are present in Japan [59]. Electricity retail was indeed liberalized in 2016, with new entrants constituting 9% of the power market at the onset [60]. Large corporations, and not prosumers, are active on the Japan Electric Power Exchange (JEPX) and dominate regional areas [61]. There is a need of new entrants, higher renewable shares, and resource transparency [61]. Wee et al. [16] similarly highlighted a lack of renewable energy information as a market barrier.

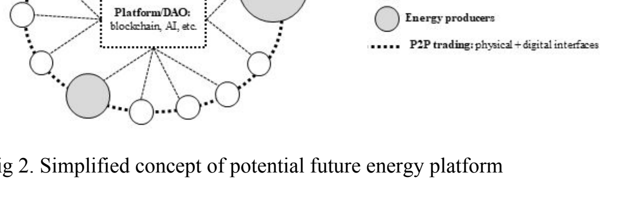

Fig 2. Simplified concept of potential future energy platform

A sustainable energy shift requires energy and smart technology advances, as well as new market designs and business models [2]. As discussed by Bheemiah [25], "fragmentation in banking is already underway in the more subtle and decorous guise of technological change". What will this mean for the energy sector? Blockchain may aid in tracking sources and sharing this information for more decentralized and transparent energy markets. Opportunities following future market developments, such as the 2020 legal unbundling of power transmission and distribution in Japan, are also important in this discussion. New wholesale markets are undergoing groundwork in Japan, including for non-fossil value, base load, balancing, and capacity trading [62, 63]. This may encourage investment in renewable energy, and benefit distributed energy in P2P networks. However, prosumers and smart contracts are not yet institutionalized in the market. In the case, prosumers trade electricity through a company, as they cannot legally do so directly on the wholesale market. It is suggested that for technical structure decentralization, design of more decentralized markets is also important. This is especially important as individual prosumers have greater incentives to realize the value of distributed energy resources, which can be leveraged in P2P prosumer markets [4].

Trading in P2P prosumer markets can be orchestrated by smart contracts. Blockchain platforms with smart contracts can cost-efficiently decentralize transactions and support P2P energy-trading even for low-value transactions [6]. In the case, automated buying, selling, and scheduling of transactions is possible via smart contracts and smart meter value readings. This is based on the Zaraba method, an auction-like process grounded on price and time to automatically match bids with flexible pricing mechanisms [64]. Bidding is done in 30-minute intervals in a day-ahead P2P market, with power control in digital grid controllers (DGCs) [39]. This facilitates concurrent electricity and financial flows, in contrast to conventional power balancing groups. While these processes function on a pilot level, interoperability with traditional contracts and on electricity wholesale markets would be important for scalability.

Spot price prediction mechanisms in contracts would also need improvement for more accurate bidding [61]. This depends on data such as solar radiation, wind speed, and other weather forecasts. Oracles, external digital agents integrated in smart contracts to monitor external parameters [13], may support collection of such data. Machine learning methods and AI can further improve accuracy in spot price predictions [65]. This may contribute to price and market mechanisms, further highlighting the complementarity among technological innovations discussed earlier.

The energy transition requires decentralization both in technical infrastructure and in energy markets which support P2P exchange [5]. Platform business models may be a key element in future energy landscapes, enabled by a stream of advancing digital technologies [2]. In markets with higher shares of distributed renewable energy, it is difficult for marginal cost-based bidding to support revenues [66]. The volatility and complex end-user roles arising with distributed renewables, alongside ICT progress, are drivers of energy platform markets [67]. A platform market involves going from marginal transaction cost- to fee-based business models [67]. It can be described as a multi-sided market in which an intermediary captures value in transactions between two user groups [67-69]. The stakeholder to provide and manage such a platform for energy-trading is open for question. This may also be highly autonomous, such as with DAOs as illustrated in Figure 2, eliminating the need to have a conventional intermediary, and thereby reducing transaction fees. This may be part of a solution to the growing demand for more frequent and small-scale electricity transactions [19].

In fee-based markets, EaaS may indeed become a norm, supporting contract and market diversity [49]. The fee-based blockchain platform can be a ledger for sharing costs of platform maintenance, distribution charges, and taxes [70]. Not only how people buy and sell energy, but investment platforms may change [6, 50], such as via shared investments [50] and crowd-funding of renewable energy [71]. One example is SolarDAO, a DAO through which anyone can invest in solar PV projects worldwide [72]. A platform market is also dependent on the creation of network effects [67], as the value to one user is dependent on the number of users in the network [73]. This is significant considering that "social structure assists or impedes economic performance" [74]. This fringes with discussion on the social dimension.

C. Society

Key issues identified in the social dimension include uncertainties in behavioral change, public acceptance, stakeholder management, and skill development. Scaling up P2P platform markets would depend on residential user interest to become prosumers and actively engage in energy markets [75]. According to green marketing theory, people are more likely to purchase renewable energy if assured of its origins [36]. This confidence can be increased with transparency, certificates of origin, and data immutability on blockchain platforms [28, 36]. Users in the case (consumers/prosumers) can access electricity source information. Users cannot yet select specific parameters, but can form smart contracts based on archetypes: 1) Cost-conscious, 2) Moderate, and 3) Renewable energy-conscious. This affects smart contract price ceilings/floors, energy source, storage, and bidding strategies. In the long term, blockchain and enhanced traceability can support user choice. However, increased choice may not necessarily lead to behavioral change [75].

How can coordination among prosumers, which have varying characteristics and objectives, be incentivized [4]? User interests and socioeconomic incentives needed for P2P market participation is a key area for further investigation if the case would be scaled up. The case pilot involves 15 households, which may be classifiable as interested early adopters as opposed to mainstream residents. How may user behavior be on a larger scale? In Japan, a recent study showed that utility customers are often either uninterested in digitally engaging with power utilities, or are uninformed of how to do so [76]. Concerns on data security issues were also found [76]. Security and privacy concerns would be applicable both to the power grid and to autonomous IoT-connected devices and EVs [6, 50]. With such concerns, large-scale behavioral change may be difficult, despite financial benefits in P2P markets [75].

Convenience and public acceptance may be key factors in facilitating behavior change [18, 20], potentially driven by incentives such as information transparency and user friendliness [15, 75]. For example, blockchain can contribute to transparent information and platform credibility in VPPs, thereby potentially increasing users' motivation to participate [15]. It is suggested that prosumer/consumer interaction is a key element to be further integrated into the energy value chain. Partnering with companies with a strong foothold in platform markets, such as today's Amazon and Alibaba, may also contribute to overcoming customer engagement issues [75] and supporting convenience. In addition, the incorporation of AI into digital platforms can facilitate the instant responses and services that are in increasing demand across all sectors [77]. Trust in the technology is an important consideration for public acceptance, especially if blockchain is to be incorporated into IoT systems and smart homes [50]. Both trust and user-friendliness may be increased via enhanced searchability among nodes: a feature which both startups and companies such as Google are exploring [78].

In addition to users, stakeholders in the case include corporations, startups, government officials, and researchers. In this group, there are varying expectations, company cultures, and communication channels. For example, the speed of decision-making tends to be higher among startups in the case. In addition, the degree of documentation required by large corporations is typically higher. As a solution, a partner was assigned an administrative role in the group to facilitate management and communication. Inter-organizational factors, such as lack of standards for information-sharing and competitiveness concerns [34] may be a challenge if the project is scaled. Intra-organizational elements, such as management support and company policies, are also challenges of blockchain in general [12, 34]. Effective stakeholder coordination and conflict management both within and among organizations would be important. To facilitate low carbon systems and associated policies, these systems must integrate stakeholder objectives and dynamics in addition to technological innovation [37].

If the case pilot project is to be scaled, effective stakeholder interest management would be a vital bridge between technological innovation, application, commercialization, and expansion. There is also a talent shortage and lacking expertise related to blockchain [20] as well as other digital technologies such as machine learning [25]. This is likely to be an issue for system development, scaling, and maintenance. It is suggested that intra-organizational management support can contribute to blockchain skill development. Furthermore, several universities are setting up blockchain-related programs, such as Cornell University, ETH Zurich [79], Duke University [80], and MIT [81]. This is similarly the case in Japan, such as at the University of Tokyo [82], and Keio University [83].

Such efforts for skill development, in the private sector and among universities, may be leveraged further in projects and programs guiding the energy transition.

D. Environment

The environmental dimension is discussed in the context of emissions and pollution in the case, especially if scaled up. Important issues in this discussion are uncertainties in emissions reduction schemes, environmental regulation integration in smart contacts, and microgrid equipment end-of-life management. In the case, the digital grid router (DGR) tracks and records all energy sources and carbon emissions. This can provide data supporting renewables-trading, especially if reinforced with governmental policies. The Japanese target for electricity emissions reduction from 2013 is 26% by 2030 and 80% by 2050 [84]. A non-fossil value market (including nuclear power) for FIT-certified generators is ongoing as of 2018 in JEPX [63], with a price ceiling at 4 JPY/kWh (0.036 USD/kWh) and floor at 1.3 JPY/kWh (0.012 USD/kWh) [85]. Transactions fell on average at the price floor in August 2018 [85]. The trade volume was 2.24 MWh in 2018 [85], which is small compared to JEPX sales contracts of 27,861 MWh April-June 2018 [86]. The market's ability to benefit renewables is uncertain and may require further stimulus.

There is a need of improved incentives for clean energy in Japan [87] and worldwide [88]. Blockchain can contribute in this context, for example, by simplifying trading environments and supporting instantaneous monetization of credits upon clean energy generation [88]. Effective validation of rights and metering is a key opportunity of blockchain, relevant for emissions-tracking and -trading schemes [5, 15, 28]. Smart meter interval data can be recorded to cloud databases, with blockchain timestamps automatically recording due credit [88] and facilitating fraud prevention [6]. Environmental metrics such as carbon emissions and energy consumption, as well as water use, waste, and toxic substances can be monitored and shared [12]. The end-of-life management and recycling of microgrid equipment such as batteries [89] and solar panels [90] is also an important discussion. The ability of blockchain to promote end-to-end supply chain traceability in supply chains when coupled with IoT systems [91] may contribute to this issue, and is also yet to be integrated in the case. Indeed, enhanced traceability would be useful on several fronts, from carbon asset markets to holistic environmental management schemes.

The MoE of Japan supports a carbon-pricing scheme [92], whereas the Ministry of Economy, Trade and Industry (METI) stands in opposition chiefly due to concerns of detrimental economic impacts on Japanese industry [93]. There seems to be need of unison and silo reduction in the government with regard to environmental programs. Agreement on market mechanisms such as carbon-trading are also a challenge worldwide, seen for example in COP24 in 2018 [94]. In the case, environmental schemes, regulatory opportunities, and emissions reduction targets are not yet included in smart contracts.

The spread and diversification of renewable energy is also an important puzzle piece in reducing carbon emissions and pollution. There are several widespread and expanding technologies for distributed generation, such as rooftop solar PV. However, the landscape of renewables is likely to look different in 2050. Ongoing and potential future developments would be important to consider in this long-term perspective. Just a few examples of such advances include the harvesting of photosynthetic energy from plants for electricity [95] which is already being tested commercially [96, 97], perovskite solar PV facades [98], and liquid fuels that store solar energy [99]. It would be important to follow energy technology advancements and maintain flexibility to integrate them. In this way, coherent innovation management may bolster environmental sustainability.

E. Institutions

Identified challenges in the institutional dimension include low renewable energy targets, grid interconnection, network consignment fees, uncertain stakeholder roles, prosumer licenses, smart meter measurement acts, and centralized decision-making. Japan's FIT scheme was launched in 2012 to increase renewable power [100]. Rather than resulting in energy diversity, however, solar PV accounted for 95% of 2012-2017 renewable energy surges [101]. In 2016, liberalization of the Japanese power retail market commenced, with full unbundling of distribution and transmission by 2020. The current levels of renewable energy are also relatively low, at 7% of primary energy supply [102]. Government plans emphasize distributed energy, battery storage [103], as well as regional and interregional grids [58]. While this shows progress, Japan's renewable energy shares and future targets are low compared to other nations [104]. Seen in the 2014 Strategic Energy Plan, METI targets a 2030 renewable electricity share of 22-24% [84]. It is uncertain if the current institutions affecting renewable energy would support P2P microgrid expansion.

The low proportion of renewables is partly attributable to limited grid connection ensuing from concerns on intermittency and grid capacity among incumbent utilities [58]. The institutions surrounding the transmission grid, developed by ten power utilities on two differing frequencies in the East and West, limit interconnection [62]. This occasionally leads to split wholesale markets [62], reducing liquidity and trading efficiency. Grid connection via both physical and virtual interfaces would be an important component of blockchain-based microgrids [18]. Difficulties in interconnection in Japan is likely to inhibit the scalability of blockchain-based energy platforms. Nonetheless, interconnection efforts are being expanded in the country, focusing on integrating more renewable sources while maintaining stable supplies [62, 104]. Grid interconnection went from a first-come-first-served basis to implicit auction in April 2018 [62, 63], meaning that day-ahead transmission capacity trading is integrated in the power spot market. The 2020 unbundling may also contribute to a gradual increase of competition and in overcoming the interconnection issue.

These developments seem to indicate positive prospects for prosumer participation, renewable energy, and P2P microgrid interconnection. However, it is suggested that network consignment fees would also need to be updated to facilitate P2P trading. In Japan, these fees are the highest for low voltages, at approximately 7.8-9.9 JPY/kWh (0.07-0.09 USD/kWh; 2019-02-5), as compared to high voltages at 3.5-5.2 JPY/kWh (0.03-0.05 USD/kWh; 2019-02-05) [105]. These network consignment fees constitute approximately 30-40% of electricity charges to end-consumers [105]. P2P trading would be carried out based on low voltages [106, 107], for which the network fee system would incur higher costs as it assumes transmission over long distances, as opposed to proximate P2P trading [108]. The network fee structure for prosumers would necessitate further review for feasibility of P2P power trading and interconnection.

Energy transitions also involve shifting roles in governments, markets, and civil society [108]. There is a need to define future roles, including prosumers as well as distribution network and system operators (DNOs and DSOs) [4, 75]. Energy-matching, decreased uncertainty via information transparency, and preference fulfilment would need to be achieved through coordinated use of distributed energy resources in the downstream energy value chain [4]. Blockchain can contribute in this context for resource coordination and energy flexibility at any scale [50] especially if smart contracts can enable these resources to be aggregated in flexible markets and provide ancillary services [109]. Traditionally, DNOs have been the entities with details on the distribution network and its constraints [110]. The role of DNOs would also need to be evolved for an electricity sector with prosumers and P2P trading in blockchain platforms [70]. A DSO, in contrast, takes a more active role in operating the system as a whole, such as adjusting voltage targets in distribution networks [110]. At present these roles are not well-established in Japan and would be a key issue moving forward [111]. The DSO may hold an active role in the aggregation of distributed energy resources and facilitate activity on the prosumer side [109]. Following the 2020 market unbundling in Japan, DSOs as platform providers and more unbiased facilitators may be an opportunity to consider.

The prosumer role would also be important to institutionalize. Prosumers are as of yet not included in the Japanese Electricity Business Act. Based on the content in this act, a license is needed to buy and sell electricity [112]. One option is a retail license, which requires continuous supplies meeting counterparty loads [112] and customer protection [113]. This system appears impractical for smaller-scale prosumers. The Act also allows for "Specific Supply" licenses, through which an entity does not need to register as a utility business and can supply power to pre-specified entities [112]. In order to do so, however, the supplier would need to also register information on each consumer, such as location and name [112]. The license also assumes large-scale producers and consumers [107], also appearing unfeasible for distributed prosumers and consumers. To overcome this license issue, the case prosumers acquire a "Specific Supply" license and sell electricity through a designated company, receiving digital tokens. This company can manage balancing requirements as a "Retail Electricity Supplier" in the power market. Thereby, the license requirements of today can be managed until specific prosumer licensing may be developed. Prosumers can gain economic benefits with the ability to also trade at wholesale market prices [114]. It has also been highlighted by other authors that new contract types [6] and prosumer licenses [70] need development to support P2P trading

In managing the financial, information and electrical flows in potential P2P networks, the development of smart meter infrastructure is imperative. In Tokyo, smart meter installations are targeted for all low voltage entities, such as households, by 2020 and in Japan by 2024 [115]. This target aims for prospects of demand response, energy management, new services, and innovative business models [115]. This presents a positive outlook for prosumer markets, as smart meters provide an important basis for associated energy management and trading systems. In Japan, all smart meters are subject to the requirements of the Measurement Act, which includes certification from the Japan Electric Meters Inspection Corporation (JEMIC) [111]. Currently, the certifiable meters are on a Watt-hour (Wh) basis for electricity transactions [111]. In the case, the DGC communicates with a Measurement Act-certified smart meter, in which blockchain is not yet integrated. A challenge here is the development of smart meter infrastructure by integrating blockchain, which currently lacks regulation and standards both in Japan and worldwide [6]. Smart meters enable decentralized energy systems, but data can indeed still be tampered with [13]. Blockchain can contribute to immutability, traceability, and automation among smart meters [13, 88]. Furthermore, additional energy services, such as gas and heating, would need to be integrated in the act if blockchain multi-energy platforms, as advocated for 'Energy Internet' efficiency by several authors [14, 15, 20], were to be developed.

There are governmental programs in Japan supporting the advancement of smart meters and ICT infrastructures at large. In its 5th Science and Technology Basic Plan (2016-2020), the Japanese government developed a "Super Smart Society" agenda for new service systems and businesses leveraging ICT [116]. Grid connection technologies for renewable energy, power quality, and microgrids have been key government-driven areas [58]. While developments have been in collaboration with Japanese industry and local administrations [58, 117], the central government remains the key decision-maker [100]. Entrepreneurial experimentation is a valuable factor in energy innovation [58] by both the public and private sectors. This may be inhibited in centralized forms of governance. Especially considering that blockchain is a new technology of which applications are still being explored worldwide, it is suggested that institutional change would also need to be flexibly directed based on multi-stakeholder knowledge-sharing, co-learning, and collaboration.

There is an increasing number and diversity of stakeholders in decentralizing energy systems [3, 17]. It is suggested that keeping both short- and long-term outlooks with multi-perspective approaches is vital in identifying blockchain applications in the energy sector. This is especially essential with the strong sociotechnical lock-ins in the sector, for which change would necessitate joint efforts of multiple stakeholders [37]. Technological systems "are both socially constructed and society shaping" [118]. Blockchain platforms would need to gradually scale up, ensuring sufficient value for people and generating network effects. Collaborative innovation ecosystems with stakeholders from multiple sectors, including end-users, would be important to garner knowledge on success factors and issues [49]. Opportunities of blockchain in the energy transition depend on business model innovation as well as flexible change of policies and regulations [5]. In understanding and managing energy transitions, interdisciplinary teams are also vital due to the multiple dimensions involved [3, 34, 38, 49]. There is a need to develop the Energy Internet elements, such as blockchain consensus mechanisms, in cooperative industry-academia setups [15]. Governmental bodies would also be important players, as their involvement can facilitate informed policy development [16, 38]. A "transition assemblage" including policy, regulation, and R&D strategies may guide energy transitions based on collaborative schemes [119].

Such cooperation can support exploring smart contracts in the energy sector with fewer regulatory barriers, to benefit from observations and lessons learned [13]. Rigid regulations inhibit holistic overview and the expansion of business model and technological innovation [25]. In this way, governmental inaction may inhibit fully leveraging blockchain [25]. The technology has potential to contribute to smart grids and P2P trading, but there is a need of more use cases to sway industry standards and government-backing [19]. Policy-makers should be more proactive as opposed to reactive by exploring how agents react to policies, such as via system dynamics simulations [17, 25, 109]. Bale et al. [38] suggested complexity models, such as agent-based modeling, to aid in addressing issues of technology, policy, and behavior in a holistic way in energy transitions. Regulatory alignment with multiple objectives in P2P networks, such as of DSOs and prosumers, would require gradual development [4, 109]. This would benefit from modeling as well as field studies and performance tests in order to evade adverse outcomes [109].

Institutional, economic and social dimensions are dependent on local context. Living Labs and regulatory sandboxes may be of interest for interdisciplinary and proactive approaches. Living Labs can be defined as "physical regions or virtual realities, or interaction spaces, in which stakeholders form public-private-people partnerships (4Ps) of companies, public agencies, universities, users, and other stakeholders, all collaborating for creation, prototyping, validating, and testing of new technologies, services, products, and systems in real-life contexts" [120]. For example, Austrian Living Lab Act4Energy was founded in 2018 to support research and development of decentralized energy networks, including blockchain applications, in a regional user community [121]. In addition, a regulatory sandbox is space in which businesses can test new products and services with a degree of regulatory freedom, based on coordination with government [122]. Especially considering the regulatory uncertainty of blockchain in the energy sector, this approach may be useful in order to experiment without clashing with regulations. Living Labs and regulatory sandboxes would be useful, for example, in creating smart contracts that are interoperable with a jurisdiction's contract laws [123], exploring market mechanisms, and understanding public acceptance. This can allow corporations and startups to test technologies in real environments, and support the public sector in crafting new regulatory systems.

III. CONCLUSIONS

This paper set out to explore concrete challenges of blockchain in the energy sector based on a case in Japan, to discuss opportunities to overcome these challenges, and to present strategic indications for academia and practitioners. Table 2 summarizes the challenges and opportunities discussed across five dimensions. The findings are not empirically tested, but it is suggested that the identified factors are a useful starting point with indications for scaling blockchain applications in the energy sector. It is suggested that the dimensions are co-evolutionary, and do not develop in isolation. Both varying and similar opportunities can be seen across multiple dimensions, such as transparency and AI integration. This would suggest that strategies to scale blockchain-based energy systems would require a multi-dimensional, co-evolutionary approach. Coherent innovation management and multi-stakeholder innovation ecosystems may contribute to this approach. Living Labs and regulatory sandboxes are potential institutional foundations to support such ecosystems. It is suggested that with a holistic approach to blockchain in the energy sector, it may contribute to digitalization, decentralization and decarbonization in the future. Overcoming challenges and taking advantage of opportunities in this realm may be a central prospect for practitioners, academics, as well as academic-practitioner collaboration in the energy sector.

Challenges and opportunities identified across multiple dimensions in the blockchain-based microgrid case in japan (CR: cognitive radio, IoT: internet of things, M2M: machine to machine, DAO: distributed autonomous organization, EaaS: energy as a service, DNO: distribution network operator, DSO: distribution system operator)

	Challenges	**Opportunities**
Technology	Resource intensity, throughput, latency, data storage, high speed connectivity, interoperability, cybersecurity	Consensus mechanism development, sharding, multi-chain communication, off-chain storage, state channels, 5G internet, CR, AI solutions, machine learning, smart meter blockchain integration (such as via light clients), IoT, M2M, privacy measures, quantum resilience, AI solutions
Economics	Subsidy-dependence, lacking market competition, contract interoperability, platform market growth	Business model innovation, market transparency, wholesale trading, pricing mechanism development, AI solutions, machine learning, DAO- and fee-based platforms for trading and infrastructure cost-sharing, EaaS.
Society	Behavioral change, public acceptance, stakeholder management, skill development	Platform transparency and user-friendliness, digital platform company partnerships, convenience, user interaction, AI solutions, blockchain searchability, expanded consumer/prosumer choice, university blockchain training and programs.
Environment	Emissions reduction scheme uncertainty, environmental regulation in smart contracts, grid equipment end-of-life management	Transparency and traceability in renewable energy trading, green wholesale market opportunities such as ancillary markets, emissions-tracking and trading, carbon taxation, validation of rights and meter data, environmental metric fraud prevention, end-to-end supply chain traceability, IoT, coherent technology management
Institutions	Low renewable energy targets, uncertain stakeholder roles, prosumer licenses, grid interconnection codes, network consignment fees, smart meter measurement act, centralized decision-making.	Market unbundling and competition, network consignment fee structure update, DNO and DSO role establishment, prosumer contract and license development, smart meter act and standard development for blockchain integration, smart meter security and data traceability, Living Labs, regulatory sandboxes, interdisciplinary teams.

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