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Designing microgrid energy markets
A case study: The Brooklyn Microgrid

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HIGHLIGHTS

- State-of-the-art overview of blockchain-based local energy trading.
- 7 required components are derived for the design of microgrid energy markets.
- A case study, the Brooklyn Microgrid, is evaluated according to the 7 components.

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ABSTRACT

Generation from distributed renewable energy sources is constantly increasing. Due to its volatility, the integration of this non-controllable generation poses severe challenges to the current energy system. Thus, ensuring a reliable balance of energy generation and consumption becomes increasingly demanding. In our approach to tackle these challenges, we suggest that consumers and prosumers can trade self-produced energy in a peer-to-peer fashion on microgrid energy markets. Thus, consumers and prosumers can keep profits from energy trading within their community. This provides incentives for investments in renewable generation plants and for locally balancing supply and demand. Hence, both financial as well as socio-economic incentives for the integration and expansion of locally produced renewable energy are provided. The efficient operation of these microgrid energy markets requires innovative information systems for integrating the market participants in a user-friendly and comprehensive way. To this end, we present the concept of a blockchain-based microgrid energy market without the need for central intermediaries. We derive seven market components as a framework for building efficient microgrid energy markets. Then, we evaluate the Brooklyn Microgrid project as a case study of such a market according to the required components. We show that the Brooklyn Microgrid fully satisfies three and partially fulfills an additional three of the seven components. Furthermore, the case study demonstrates that blockchains are an eligible technology to operate decentralized microgrid energy markets. However, current regulation does not allow to run local peer-to-peer energy markets in most countries and, hence, the seventh component cannot be satisfied yet.

1. Introduction

To date, power has mainly been generated by large centralized power plants run by non-renewable fossil fuels [1]. This directly causes environmental degeneration and energy losses in power transmission due to long physical distances between generation and consumption sites [2]. The increasing integration of renewable energy sources (RES) into the energy system provides a solution to this environmental energy dilemma [3]. Nevertheless, uncertainty and fluctuation in renewable generation need to be taken into account [4]. Existing wholesale markets lack the ability to react in (near) real time to the volatile and intermittent generation from RES [5]. Furthermore, market prices are often determined on a national level which does not reflect (local) energy scarcity or surplus of supply. However, to support the integration of distributed RES into the energy system, new market approaches should mirror the locality of their services [6].

Microgrid energy markets allow small-scale participants, i.e. consumers and prosumers (consumers that also produce energy),

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to actively trade energy within their community in (near) real time. Thus, they facilitate a sustainable, reliable, and local balance of generation and consumption. Hence, this represents a viable option for integrating distributed RES into the current energy system in an economic way [7,8]. Furthermore, this empowers small-scale energy consumers and prosumers, incentivizes investments in local generation, and helps to develop self-sustainable microgrid communities [9]. The implementation of microgrid markets requires innovative, secure, and smart information systems [10], which are an essential factor for their successful operation [11].

Blockchains [12], as emerging information technology, offer new opportunities for decentralized market designs and provide transparent and user-friendly applications [13] that allow energy consumers to participate in the decision on who produces their energy and by which technology it is generated. Microgrids, which are a geographically limited group of multiple generation loads and energy resources [14], can also increase the reliability of supply as they offer the potential to provide energy in case of power outages of the superordinate grid [15].

The conceptualization and implementation of blockchain-based microgrid energy markets have recently gained the attention of several researchers. Sikorski et al. [16] present a proof-of-concept implementation of a small blockchain-based machine-to-machine electricity market with two producers and one consumer in the chemical industry. Their work demonstrates that blockchain technology can establish (very) small-scale electricity markets. Green and Newman [17] analyze the development of local communities into self-sufficient, local generation utilities (so called citizen utilities). They investigate the opportunity of blockchain-based microgrid energy markets to the growth of distributed solar systems and the corresponding challenges for the traditional energy grid in Australia. They specifically state that the use of blockchain technology for electricity transactions makes microgrids more resilient by creating trust between the involved agents, especially with respect to financial payments and electricity delivery.

Building on current literature, we focus on the required components for a holistic market design and implementation of a microgrid electricity market between a significant number of residential households. Thus, we expand current literature by providing the first structured evaluation of an implemented case study on a blockchain-based microgrid energy market. The new contribution of this paper can be summarized as follows:

1. Introduction of a market design framework consisting of 7 fundamental components for designing a microgrid energy market.
2. Introduction and evaluation of blockchain technology as an information system for microgrid energy markets between residential households.
3. Presentation of the Brooklyn Microgrid (BMG), an implemented case study of a blockchain-based microgrid energy market
4. Discussion and evaluation of the case study according to the outlined 7 required market components.
5. Demonstration that a private blockchain can sustain and operate a microgrid energy market.

Subsequent to a comprehensive literature review of microgrid energy markets, blockchain technology, and their combination (i.e. blockchain-based microgrid energy markets) in Section 2, we propose a framework for designing microgrid energy markets in terms of the required components for the successful market operation in Section 3. Then, in Section 4 we present the BMG in Brooklyn, New York as an implemented case study for microgrid energy markets. We evaluate and discuss the case study according to the required market components from Section 3. Finally, Section 5 provides the conclusion of our work. Fig. 1 presents a schematic overview of this paper.

2. Literature review

2.1. Microgrid energy markets

Sustainability and an efficient use of our planet's resources are inherently linked to taking advantage of (decentralized) RES. RES use the huge energy potential of sunlight, wind, water, geothermal resources, and gravitational forces [18]. The efficient integration of RES and the restructuring of the energy system into several interconnected microgrids can improve the reliability and environmental sustainability of the energy system and, simultaneously, provide economic benefits [3].

Traditional centralized energy systems can be characterized by a large number of customers located within a wide area, e.g. a country. Energy is supplied by large power plants that operate according to a centralized coordination mechanism [19]. Decentralized energy systems, one the other hand, are the opposite of centralized energy system: They consist of small-scale energy generators (up to 200 kW) "(...) that are placed in the same location with an energy consumption point and that are used by a small number of people" [19]. Microgrids can aid in ensuring this reliable supply. They operate in both grid-connected or island-mode [14]. Microgrid energy markets provide small-scale prosumers and consumers with a market platform to trade locally generated energy within their community. Hence, they promote the consumption of energy close to its generation and, therefore, foster sustainability and the efficient use of local resources. An exemplary microgrid energy market scenario of residential consumers and prosumers (consumers with photovoltaic (PV) systems) is shown in Fig. 2. Note, that market participants do not necessarily have to be physically connected. Virtual microgrids are the aggregated control of multiple energy producers, prosumers, and consumers in a virtual community. By expanding a physical microgrid to include virtual participants, its revenue potential can increase substantially.

Microgrid markets can reduce the need for expensive and inefficient energy transportation with substantial losses [20] by satisfying demand from local energy resources. Furthermore, the latency for managing congestion and distribution faults can be decreased [21]. Microgrid markets strengthen the local community in terms of self-sufficiency and provide the possibility of energy cost reduction. Local transactions keep profits within the community and encourage reinvestments in additional renewable generation [22]. Thus, microgrid energy markets provide members of a community with a new asset class as well as a previously nonexistent direct access to locally generated energy from their neighbors. Consequently, they can be linked to the recently emerging sharing economy [23].

Combining the virtual power plant approach and the community aspect, Franke et al. [24] consider the economic and ecological efficiency of peer-to-peer (P2P) microgrid energy markets. Additionally, they point out the importance of social factors. The public acceptance of local compared to national renewable generation is discussed in the empirical study of Bertsch et al. [25]. Increasing the public's acceptance of microgrid energy markets can be done by developing a shared vision with the affected community about the objectives and operation of the market [26].

The optimal operation of a microgrid regarding its energy generation has already been addressed extensively, e.g. Pascual et al. [27] and Montuori et al. [28]. Furthermore, feasible connections between multiple microgrids are recently being investigated with the aim to facilitate a more reliable balance of supply and demand than in individual microgrids [8,11]. However, research in the field of microgrid energy markets is just gaining momentum. Our paper extends the market design research by deriving and discussing required components of microgrid energy markets and by presenting and evaluating a case study, i.e. the BMG.

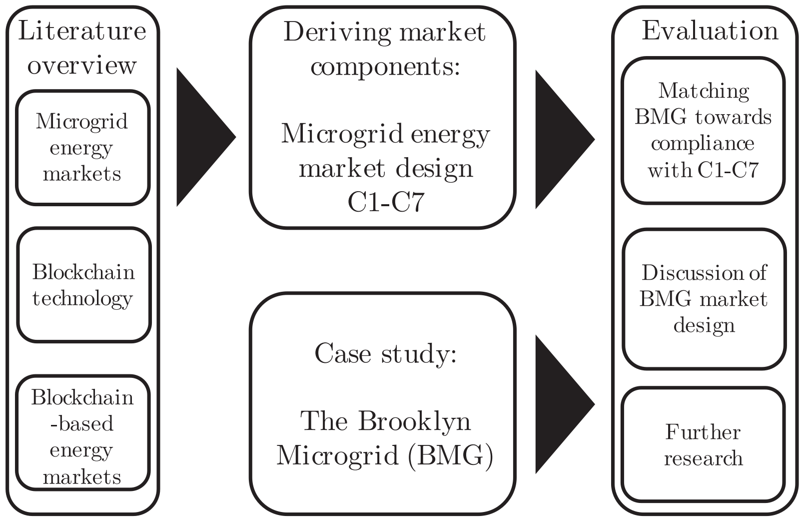


Fig. 1. Schematic overview of the paper.

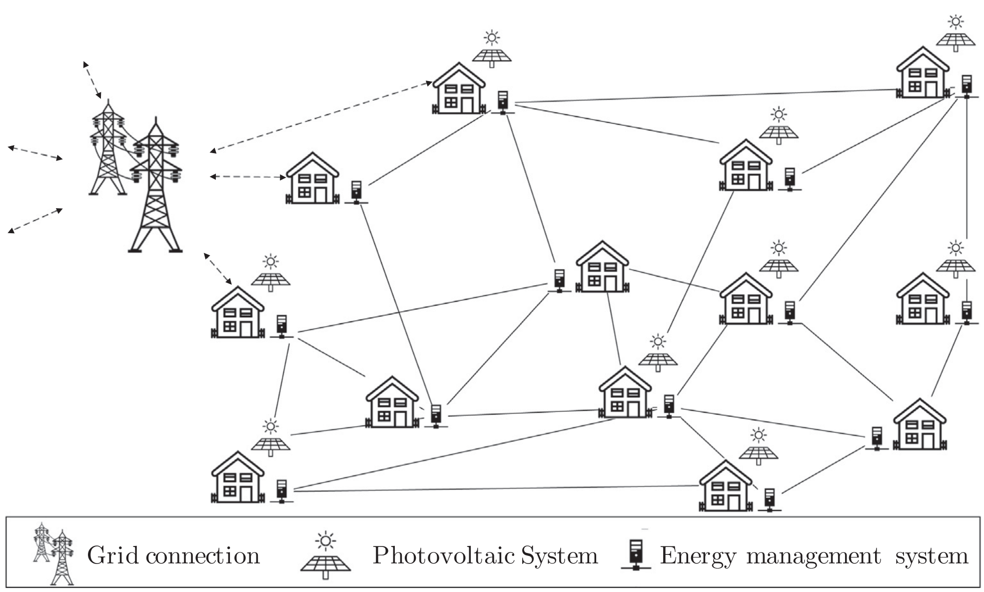


Fig. 2. Exemplary microgrid market setup.

Lamparter et al. [29] present a highly flexible market platform that allows for efficiently coordinating self-interested consumers, prosumers, and power suppliers. The detailed market mechanism on local energy markets is considered by Blouin and Serrano [30]. They propose a P2P local market with decentralized, randomized buyer and seller matching. Block et al. [31] investigate a combinatorial double auction mechanism for the pricing and allocation of locally produced energy. They establish seven requirements for local energy markets which we include in the components for microgrid energy markets in Section 3. Vytelingum et al. [32] present a continuous double auction that takes congested transmission lines into consideration by accordingly pricing the flow of energy.

2.2. Blockchain technology

Since its introduction as the underlying technology of Bitcoin [12], blockchain technology emerged from its use as a verification mechanism for cryptocurrencies and heads to a broader field of economic applications. Blockchains have the potential to benefit the economic, political, humanitarian, and legal sectors by reconfiguring the workings of society and operations, as they shift control towards distributed participants rather than central authorities [33]. Furthermore, blockchains mitigate the risk of double-spending by secure cryptography [34]. Applications show that decentralized market setups can even work in "(...) harsh environments of little, no or even negative, trust" [35].

As an information system, blockchain technology enables fully decentralized market platforms by resolving conflicts of interests and providing information symmetry [36] to all market participants. Thus, trusted cooperations can be build in a distributed system without central supervision [37]. Blockchain technology uses distributed, shared ledgers, a decentralized consensus mechanism [16], smart contracts [38], and cryptographic security to enable decentralized market platforms. It allows for cost efficient transactions of the smallest quantities [36]. The specific design of various blockchain building elements, such as the consensus mechanism, can vary with respect to the specific use case. The creation of new blocks has to incur a certain amount of (computational) costs, in order to ensure information correctness. A trade-off between high information correctness and computational costs needs to be taken into account. In a private setup, e.g. a community microgrid energy market, in which the market participants are known, a less costly hash-based user authentication mechanism, i.e. proof-of-identity [39], can be used instead of more computational costly mechanisms, e.g. proof-of-work [37]. However, proof-of-identity authentication mechanisms may not assure the level of resilience and security needed for an efficient integration of distributed energy resources.

Blockchain technology can provide a distributed software architecture [40] for energy markets. One of its main advantages for energy markets is the transparent, distributed and secure transaction log that allows for a complete and continuous tracing of even the smallest energy transactions. However, blockchains are still an emerging technology and their applications encounter numerous problems, e.g. scalability issues and limited transaction loads [36]. Furthermore, blockchain technology still poses challenges for researchers, practitioners, and users as its technical protocol and implementations are very complex [41]. Nevertheless, blockchain technology has the potential to be fundamentally disruptive by providing new ways of implementing various systems [33]. Considering the existing potential risks and drawbacks of publicly accessible distributed ledgers, a shift to hybrid solutions between existing systems and blockchain technology is plausible [34].

2.3. Blockchain-based microgrid energy markets

Extensive literature is available on microgrid energy markets and blockchain technology separately. Their combination, however, is profoundly lacking. Therefore, we aim at filling this gap in literature. Mihaylov et al. [42] are among the first researchers to specifically address the use of blockchain technology in energy markets. They introduce and present a new virtual currency. The generation and consumption of renewable energy is directly transferable into virtual coins. The currency's market value is determined centrally by the distribution system operator [43]. Al Kawasmi et al. [44] develop a local blockchain-based market model to trade carbon emissions. Their approach facilitates anonymous trading between the market participants. Similarly, anonymous trading is also considered by Aitzhan and Svetinovic [45]. They introduce a token-based, private, decentralized energy trading platform. In a scenario with P2P energy trading, the authors evaluate the attained information security and integrity, and measure the market performance of several simulation runs. They conclude that blockchains allow for implementing decentralized energy trading and that the attainable degree of privacy and security is higher than in traditional centralized trading platforms. Sikorski et al. [16] develop a small-scale blockchain-based machine-to-machine electricity market in a proof-of-concept implementation. They conclude that blockchains can successfully support electricity markets. However, a comprehensive research gap about the potential of blockchains exists. Extensive future work is necessary.

Utility companies (partly) lose their role in the energy system when independent microgrid markets ensure their own energy supply. Green and Newman [17] outline how utility duties may be taken over by local communities due to the rising blockchain support systems that facilitate decentralized markets in combination with the increasing availability of distributed PV generation. However, utilities can innovate their business models and support microgrid markets with professional know-how, by providing ancillary services and ensuring a balanced energy system [17].

Most microgrids advocate an increase in self-sufficiency, the integration of RES, sustainability, and energy demand reduction. However, the energy consumption of an implemented blockchain can be quite substantial [46]. An information technology that uses vast amounts of energy contradicts the sustainability principles of microgrid energy markets. This needs to be taken into account when designing the architecture of any blockchain-based microgrid energy market. Computationally efficient blockchains using minimal data need to be developed. We have not yet come across ground-breaking research specifically addressing this topic in the energy sector.

Besides emerging academic literature, several industrial projects focusing on blockchain-based energy markets are already underway (e.g. Powerpeers,[1] Share & Charge[2]). We choose to present and discuss the case study of the BMG as it is the first project worldwide that actually facilitated a P2P energy transaction over a blockchain. Furthermore, the BMG is installing both a physical and a virtual microgrid. This opens up the opportunity of developing different business models that would not be possible on a solely virtual microgrid, e.g. specific tariffs guaranteeing an increased security of supply over the physical microgrid.

3. Components of microgrid energy markets

Based on Block et al. [31] and Ilic et al. [26] we derive seven components for the efficient operation of blockchain-based microgrid energy markets. A schematic overview of the components making up the micromarket's framework is given in Fig. 3.

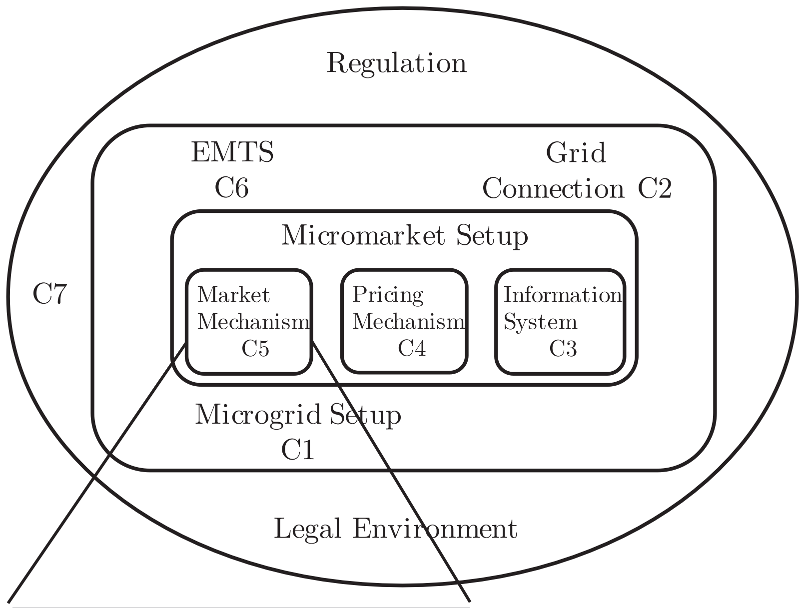
3.1. Microgrid setup (C1)

A clear objective, the definition of market participants, and the form of energy traded must be defined. Microgrids can pursue several, often conflicting objectives [27]. Exemplary objectives are the increase of the security of energy supply or the integration of local renewable generation into the energy supply system. The implementation of the objectives is especially apparent in the design of the pricing method (C4). A microgrid energy market requires a sufficient number of market participants trading energy amongst each other. A subgroup of them needs to have the ability to produce energy. In microgrids this may happen in the form of small prosumers with PV systems [31]. Market access should only be given to the communities' residents or similar defined groups of market participants. The form of energy traded in the microgrid needs to be defined, e.g. electricity, heat, or a combination thereof. Agents are usually assumed to be self-interested and rational [29]. Additionally, the microgrid setup needs to define whether the traditional energy grid is used for energy transport or a physical microgrid is build.

3.2. Grid connection (C2)

One or several connection points towards the superordinate grid are a key component [31] and must be well defined for balancing energy generation and demand within the microgrid with the help of the superordinate grid. At these points, energy flows towards the respective superordinate grid can be metered to accurately measure the microgrid's performance. A distinctive difference exists between a physical microgrid, which consists of an actual power distribution microgrid, and a virtual microgrid, which simply links the microgrid participants over an information system (C3). Contrary to a physical microgrid, virtual microgrids cannot physically decouple from the superordinate grid. Physical microgrids typically have a limited number of connection points to

[1] https://www.powerpeers.nl/.
[2] https://www.shareandcharge.com/.



Sell Orders		Buy Order	
Price (MU/kWh)	Quantity (kWh)	Price (MU/kWh)	Quantity (kWh)
26.00	1	28.23	1
26.98	1	27.71	1
27.05	1	26.00	1
27.75	1	25.95	1
28.00	1	25.50	1

Fig. 3. A schematic overview of the seven market components. The upper two orders in the order book would be matched. The transaction price will be determined by the pricing mechanism and paid in monetary units (MU).

ensure an efficient grid connection but also to swiftly decouple from the grid in case of power outages.

For extended decoupling and island-mode operation, microgrids need a large amount of their own energy generation capacity and flexibility to ensure an appropriate level of supply security and resiliency. Flexibility can be provided in form of demand or generation flexibility and storage capacities [47]. As energy is a physical good and transmitted on constrained grids, energy flow problems, e.g. grid congestion [48], need to be taken into account.

3.3. Information system (C3)

A high-performing information system [10] is needed to connect all market participants, provide the market platform, provide market access, and monitor the market operations. This requires an efficient and reliable information system working in an adequate temporal resolution. It needs to be implemented in a way that every market participant has equal access to avoid discrimination. A blockchain protocol based on smart contracts can meet these requirements. Such a blockchain protocol can be seen as a shared global infrastructure for decentralized applications that enables the implementation of full-scale software applications (smart contracts) without a central platform. While data consistency and security are inherent traits of blockchain technology [49], a secure connection from the market participants' smart meters, which measure and monitor energy generation and demand, to the blockchain is necessary. Secure smart meters can then write the required energy data directly into the corresponding blockchain accounts.

The blockchain's verification mechanism depends on the microgrid's setup (C1). If only trusted community members participate in the market, an identity-based consensus mechanism can be sufficiently secure. Identity-based consensus mechanisms are hash-based user authentication mechanisms that rely on every agent having a single identity that is confirmed. It is assumed that no agent can register additional identities. Thus, instead of using computational costly consensus mechanisms relying on complex cryptographic problems to prevent the dissemination of corrupted information, identity mechanisms use the simple, although hash-based, verification of the agent's identity to prevent corrupted agents from entering the system [39]. In a microgrid market, identities could be verified and assigned by a centralized entity (e.g. government) before providing agents with the required market access. Re-verification by the consensus mechanism then relies on the assigned identities.

3.4. Market mechanism (C4)

The market mechanism comprises the market's allocation and payment rules, and provides an employable bidding language and a clearly defined bidding format [50]. The market mechanism is implemented by the information system (C3). Its main objective is to provide an efficient allocation of the traded energy by matching the market participants' buy and sell orders [31]. This should best be done in (near) real time granularity [31]. Furthermore, constraints should exist for the minimum and maximum allocation of energy. These are especially caused by generation constraints of the microgrids' prosumers. Ideally, different market time horizons need to be implemented to cover the various stages of electricity markets (e.g. day-ahead, intraday). The allocation mechanisms must be specifically tailored to result in an efficient allocation for every stage. We focus on intraday trading and, thus, on designing a market mechanism for this market stage concerning the actual fulfillment of energy demand, as it is the prominent stage discussed in the case study in Section 4. A simple closed order book cleared at distinct time slots, is presented as a feasible market mechanism in Fig. 3. While auctions are suitable for fast intraday trading times, a P2P bilateral negotiation market, in which two parties negotiate the price and amount for extended future time horizons, may be better suited for over-the-counter trades between specific agents.

3.5. Pricing mechanism (C5)

The pricing mechanism is implemented via the market mechanism (C4) and aims at efficiently allocating energy supply and demand. Auctions with uniform or individual clearing prices often serve as pricing mechanisms for energy markets [51]. While a large part of the traditional energy price consists of taxes and surcharges, a microgrid may have different fees than the traditional grid, e.g. in case of a physical microgrid. As renewable energies typically have close to zero marginal cost [52], prosumers can generate profits by pricing their energy above all applicable taxes and fees. Price signals should be used to indicate energy scarcity or surplus [31]. Accordingly, a surplus of energy should lower the microgrid's energy price while a lack of local energy increases the market price. Economically speaking, local markets are beneficial to their participants as long as the average energy price is lower than the external grid price. However, if socio-economic reasons (e.g. supporting local renewable energy) are considered, the local energy price may even surpass the grid price.

3.6. Energy management trading system (EMTS) (C6)

The EMTS's main objective is to automatically secure the energy supply for a market participant while implementing a specific bidding strategy. The EMTS needs access to the (real time) demand and supply data of its market participant. Based on this data the EMTS forecasts consumption and generation, and develops its bidding strategy accordingly. Furthermore, it trades the predicted amounts on the market platform and may react to variable prices via demand side management [53]. Self-interested rational market participants maximize their revenue and minimize their energy costs. A simple EMTS would always buy energy at the microgrid market when the price falls below its maximum price limit. However, individual agents' intelligent bidding strategies shall employ varying prices at different times and are one of the core components of active local markets.

Socio-economic factors should also be considered by the EMTS (e.g. preferred buying from local renewable generation). As EMTS take over the energy management and decrease the burden of energy trading, they simultaneously increase the social acceptance of the community energy market [26]. The EMTS need to have access to their market participant's blockchain account to automatically facilitate energy transactions.

3.7. Regulation (C7)

The regulation determines how microgrid energy markets fit into the current energy policy. Thus, legislative rules determine which market design is allowed, how taxes and fees are distributed and in which way the market is integrated into the traditional energy market and energy supply system. Hence, governments can easily support microgrid energy markets to further the efficient utilization of local resources and to decrease environmental degeneration by regulatory changes, e.g. the introduction of subsidies. Then again, they may also discourage the implementation of microgrid markets if these result in negative impacts on the traditional energy system [54].

The operation of a microgrid energy market most importantly depends on an efficient information system (C3), market mechanism (C4) and pricing mechanism (C5). These three components can create an operational local energy market in its purest form and provide market access to its participants. Thus, they are the innermost and, therefore, most important market components in Fig. 3. C3 may be implemented as any information system as long as the market access and market mechanism including the pricing method are ensured. Additionally integrating EMTS (C6) automatizes the bidding process, yet it is not necessary for the basic market operation. Without C6 participants would likely trade in longer rather than shorter time intervals as automated trading largely reduces the personal effort of any transactions.

Disregarding the microgrid setup (C1) results in providing a market platform without specific objectives. The market would be open to anyone, thus looses its locality, and the transactional object remained largely undefined. If the traditional grid is used, the design of the grid connection (C2) can be largely disregarded. Thus, C1, C2 and C6 may further specify the market setup. Yet even without them, an operational market can be implemented. However, we emphasize that regulation (C7) is needed to legalize any market transactions and classify the market into the overall energy system. Thus, it sets the legal environment of the microgrid market which must be obeyed in any market implementations. For real-life implementation projects C7 is most important. However, it is often abstracted from the legal environment in academic studies as special conditions for research projects may apply.

Socio-economic incentives as mentioned in C5 and C6 include not economically justifiable reasons [55] to purchase local generation based on personal preferences. In a microgrid energy market, this especially includes personal preferences for local renewable energy and community products. If residents are only economically interested in participating in a microgrid market, the traditional grid price sets their upper price limit for procuring, and the feed-in tariff for selling energy. However, if they value local renewable energy higher than non-specific brown energy and, thus, see local energy as a premium product, their willingness to pay should be higher than the traditional grid price. Especially community incentives may lead to consumers' increased willingness to pay higher prices for local energy.

An economically profitable, active microgrid market encourages more renewable generation to be build in a community. Thus, local employment can rise through employment opportunities for building and maintaining additional local generation. The local economy can be increased as more profits stay within the community [19]. Thus, socio-economic incentives (e.g. employment rates and the security of energy supply) should be given equal consideration as any economic factors [55].

4. Case study: The Brooklyn Microgrid

4.1. Project overview

The BMG project, run by LO3 Energy,[3] consists of a microgrid energy market in Brooklyn, New York. Currently, participants in the BMG are located across three distribution grid networks in the BMG's region as shown in Fig. 4(a). Severe weather events (e.g. hurricanes, heat waves, etc.) increase, which raises operation issues of

[3] LO3 Energy was founded in 2012 by Lawrence Orsini and incorporated as a Delaware C corporation by Lawrence Orsini and Bill Collins in 2015. It focuses on disruptive trends in energy markets. The BMG is LO3 Energy's most prestigious project and receives huge attention evoked by the realization of the very first blockchain-based P2P electricity transaction [56].

the (already) outdated electrical grids in Brooklyn. A physical microgrid can reduce the impact of grid issues through complete decoupling and control the energy supply within the community. Furthermore, the electrical grid already struggles to accommodate the growing amount of renewable generation (mostly residential PV) and the characteristics of new appliances (e.g. electric vehicles or energy storage systems). The area of the BMG is especially vulnerable to grid failures as its rate of electric capacity utilization already approaches its limits. Particularly the Borough Hall distribution network is frequently congested.

The BMG addresses these challenges and provides a local energy market on which community members can trade (locally generated) energy P2P with their neighbors. The project consists of two main components:

1. **The virtual community energy market platform:** This platform provides the technical infrastructure for the local electricity market. It is based on a private blockchain using the Tendermint protocol.[4] The TransActive Grid blockchain architecture [57] and TransActive Grid smart meter (see Fig. 4(b)) are implemented. Note, that the TransActive Grid meter is installed in addition to the analogue meter. Thus, measurements of the TransActive Grid meter can be verified by the analogous meter during the early project stages.
2. **The physical microgrid:** An electrical microgrid is build in addition to the existing distribution grid. The physical microgrid acts as back-up to prevent power outages. By uncoupling from the traditional grid, it can operate in island mode. Then, critical facilities (e.g. hospitals) receive energy at fixed rates. Residences and businesses have to bid on the microgrid's remaining power. The physical microgrid currently comprises 10-by-10 housing blocks and will be extended.

Fig. 5 shows the topology of the BMG. It contains the physical layer consisting of the grid infrastructure and the virtual layer, i.e. the virtual energy market platform that is run on the blockchain protocol. Note, that the physical microgrid is only a part of the grid infrastructure that the BMG uses. Majorly, the BMG uses the traditional grid run by the independent system operator, Con Edison, Inc.,[5] to supply the physical energy flow and only decouples the physical microgrid in emergency situations. While all energy flows occur on the grid infrastructure, information is transferred over the virtual layer. Thus, consumption and generation data is transferred from the participants' Transactive Grid smart meters to their blockchain accounts. Buy and ask orders are created according to this information, and orders are send to the market mechanism (C4) that is sustained by a smart contract. Once the matching is completed, payment is carried out and a new block (here Block iv) is added to the blockchain. This block includes all current market information. The required information (i.e. conducted transactions) is also send to the involved agents via their blockchain accounts.

The success of the BMG project aims at supporting the systematic introduction of community microgrids. It is currently providing local and hyper-local energy (energy from the surrounding area) to the community, actively increasing local generation and building the physical microgrid. A preliminary three month trial run of P2P transactions between two participants was conducted. Simultaneously, required regulatory and legal changes are investigated. The BMG will also offer ancillary services within the physical microgrid.

4.2. Market mechanism

The physical and virtual layer of the BMG are clearly separated. The physical (radial distribution) grid between the set of prosumers $P = \{P_\eta | \eta = 1, \ldots, |P|\}$, the set of consumers $C = \{C_\alpha | \alpha = 1, \ldots, |C|\}$, and the grid connection points are given by the implemented infrastructure already in place in the BMG's area.[6]

The virtual microgrid market is implemented on top of the existing physical grid infrastructure. It aims at increasing the local security of power supply by integrating renewable generation. Furthermore, it empowers the community to take over responsibility for their power supply. Market participants are local consumers and prosumers (C1). Hyper-local participation is also feasible. While only electricity may be traded for now, heat will be included in the future. The connection between the microgrid setup (C1) and the grid infrastructure (C2) is facilitated by infrastructural units (e.g. TransActive Grid meter) measuring the electricity supply and demand as well as settling the billing transactions over the information system (C3), i.e. the blockchain.

Currently, the connection of the BMG's distribution grid to the traditional grid is used for balancing supply and demand on the microgrid market (C2) in case local generation under- or oversupplies the community's demand. This is the normal market situation. However, the additional physical microgrid may decouple completely from the traditional grid in emergency situations. In that case, a balance of local supply and demand must be facilitated within the physical microgrid with the help of the existing generation. As the physical microgrid does not encompass the entire virtual microgrid, the supply of the remaining customers cannot be ensured without the traditional grid.

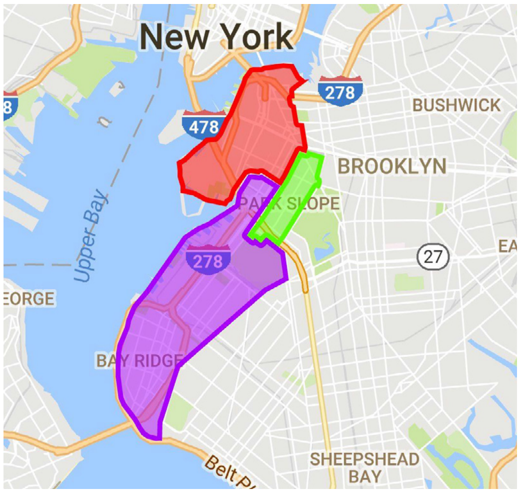
The BMG's market mechanism is implemented on the TransActive Grid private blockchain protocol (C3). Thus, the characteristics of data consistency, security, and verification are covered by the TransActive Grid platform and are inherited traits from the blockchain protocol. Based on measurements of demand and supply as well as market information, the platform tracks and displays local (near) real time energy prices on an intuitive interface. Thus, market participants may gather generation, consumption and market information, and trade energy needs accordingly. Trading is mostly done automatically by the EMTS (C6) and just requires several preferences of its market participants, e.g. the preferred energy sources and price limits.

Fig. 6 depicts the conduction of typical local electricity transactions. Any prosumer P_η and consumer C_α willing to trade electricity in the next time slot, can submit buy or sell orders via their EMTS (C6) to the market. Any order includes an order quantity and price. The market mechanism (C4) is a closed order book with a time discrete double auction in 15 min time slots. For now, consumers constantly bid their maximum price limit for their preferred energy sources (e.g. local renewable energy). Prosumers bid the minimum price limit that they request for selling their generation on the microgrid market. For example, consumer C_1 bids a maximum price x_1 for quantity y_1, prosumer P_{24} offers quantity y_{24} for a minimum price of x_{24}. Similar to a merit-order dispatch, the highest bidder is allocated first, then the lower bidders are allocated. The last allocated bid price represents the market clearing price for this time slot (C5). Consumers that do not undercut the clearing price will be supplied by additional energy sources (i.e. hyper-local energy or traditional "brown" energy) allocated over a similar bidding mechanism or predefined prices. This is well in line with the market mechanism presented by Ilic et al. [26]. In addition to the

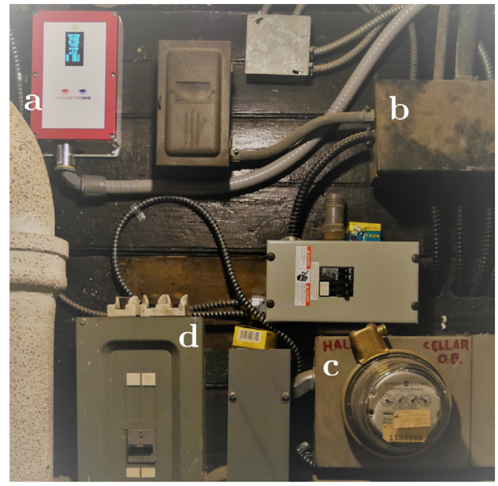
[4] https://www.tendermint.com/.

[5] Consolidated Edison, Inc., (commonly called Con Edison): https://www.coned.com/en.

[6] The physical microgrid extensions may change the grid lines, however, these are long-term investments that only concern the market mechanism after implementation.



(a) The BMG connects participants from three distribution grids: the Borough Hall (red), the Park Slope (green), and the Bay Ridge (purple) network.



(b) Installation of a TransActive Grid smart meter (a) next to the distribution box (b), existing (analogue) utility meter (c) and the domestic fuse box (d).

Fig. 4. Impressions of the BMG.

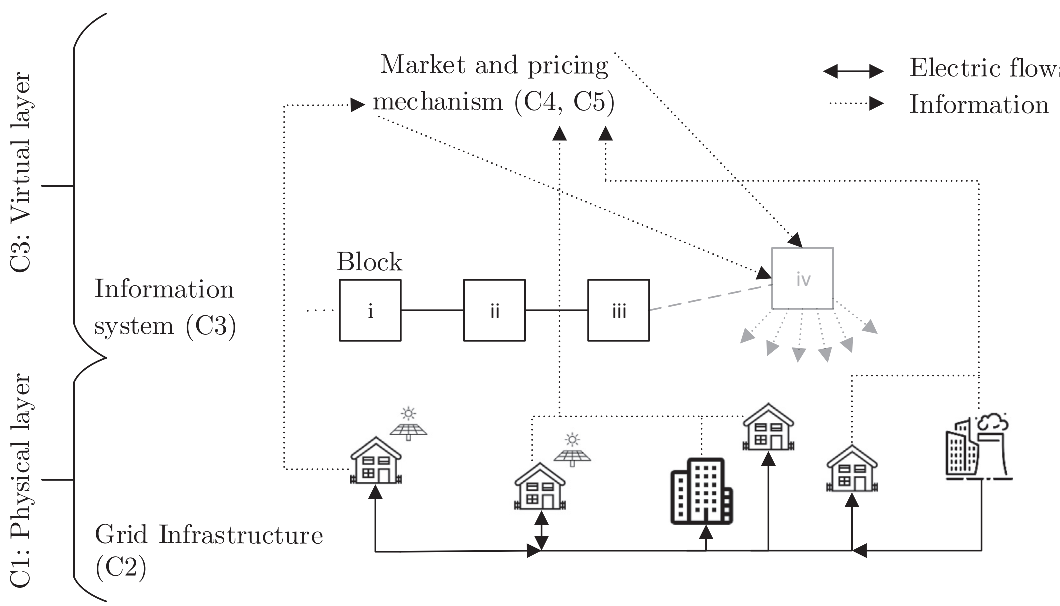


Fig. 5. High-level topology of the BMG.

currently implemented market mechanism, the BMG will try out further market mechanisms, including a pay-as-you bid order book in which each transaction may have an individual transaction price. The market mechanisms will be analyzed and evaluated according to their allocation efficiency before determining the final market mechanism.

Financial transactions are carried out between the allocated market participants according to predefined payment rules that are also part of the market mechanism (C4). On the virtual layer, local trading is now realized and the respective funds are transferred. Yet, considered from the physical layer, consumers just pay their producing neighbors for feeding-in renewable generation into the distribution grid. These, thereby, increase the share of locally produced renewable energy in the community. Any local trading is only conducted virtually, i.e. conducted on the blockchain. It has no influence on the physical delivery of electricity. Nevertheless, the share of local renewable energy satisfying the community's demand grows as more local generation is incentivized by the favorable (local) market prices. Thus, the probability of actually receiving locally produced renewable energy increases.

The legal environment (C7) sets the regulatory framework for local energy trading. To date, local P2P electricity trading without any utility involvement is not covered by regulation in the BMG's area. The BMG is actively working closely with utilities to refine the legal framework and is currently on its way to being licensed as an energy retailer.

The BMG will be beneficial for its community in several ways. Besides being able to trade energy locally at varying prices,

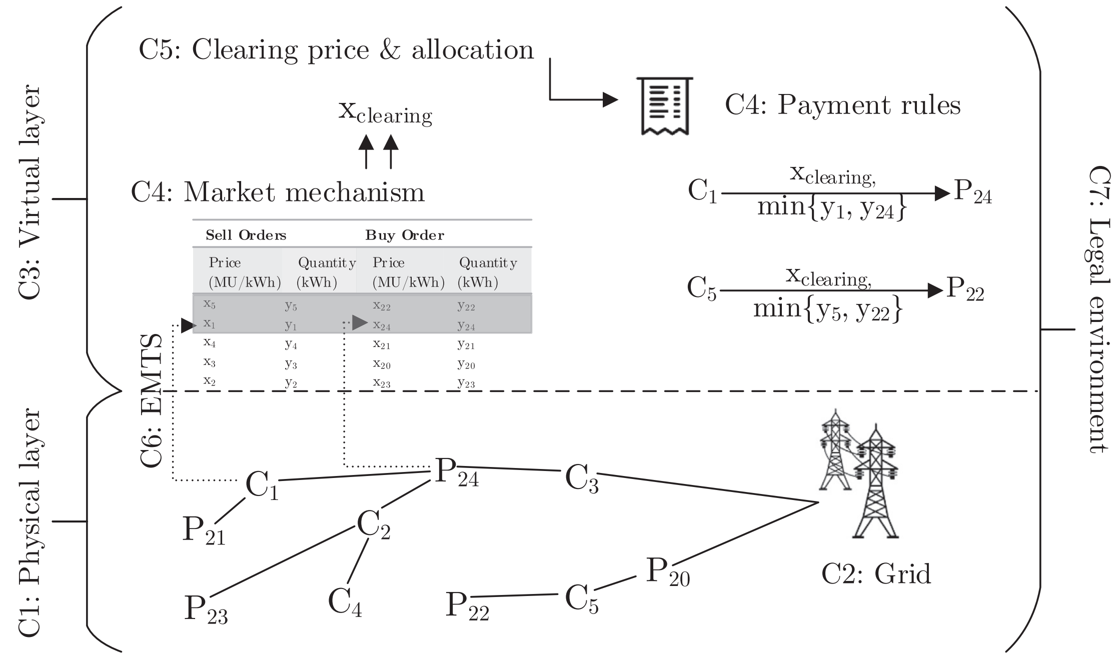


Fig. 6. A schematic representation of local electricity transactions conducted in the BMG. The different phases are attributed to the market components C1–C7.

employment opportunities will be created to satisfy the demand for renewable system installations and maintenance as well as to oversee the operation of the project. The local economy benefits from the project as profits from electricity trades stay within the community instead of entirely benefiting utility companies outside of the community. This empowers the community and helps to acquire the community's support. The BMG intends to prove that a substantial market for renewable and local energy exists. It already demonstrates that blockchain-based information systems can effectively control a microgrid energy market. Additionally, the BMG aims to prove that regulatory challenges can be overcome by working with utilities and energy providers.

4.3. Evaluation and discussion

Table 1 maps the characteristics of the BMG as presented in Sections 4.1 and 4.2 against the microgrid energy market components (C) introduced in Section 3.

We derive that the first three components C1, C2, and C3 are fully addressed by the BMG. The microgrid setup (C1) is clearly defined and aims at increasing the security of power supply for the local community, integrating local generation into the energy system, and empowering the community. Market participants are defined as local prosumers (mostly with PV systems), consumers, and hyper-local participants (consumers, prosumers, and (possibly) producers). In addition to trading electricity, heat will be integrated in the future. The grid connection (C2) is well defined. Currently, the traditional grid is used for balancing the microgrid's supply and demand. The physical microgrid adds the option of decoupling in case of grid instabilities or outages and ensures the energy supply for important facilities (e.g. hospitals). In case of island-mode operation, the physical microgrid relies on the existing generation within the physical microgrid. Currently, the existing generation capacity cannot yet ensure a reliable balance of energy supply and demand for an extended period of time. Storage capacities need to be added to increase the flexibility. The information system (C3) is implemented via a private blockchain based on the Tendermint protocol. The blockchain's inherent characteristics of security, privacy, as well as efficient and secure micro transactions are inherited. The blockchain protocol can sufficiently connect all market participants and provide an operational market platform.

Table 1
Matching the BMG against the required components of microgrid energy markets.

C	Execution	Comment
C1	✓	The BMG clearly aims at increasing the local security of energy supply and at strengthening the community and the integration of local RES. The market participants are local and hyper-local consumers and prosumers.
C2	✓	The superordinate grid balances demand and supply.
C3	✓	The blockchain-based, cryptographically secure platform TransActive Grid is used.
C4	(✓)	The initial mechanism is a double auction mechanism.
C5	(✓)	A clearing price will be determined in every time slot. Prices will vary according to demand and supply as well as socio-economic characteristics.
C6	(✓)	Residents set their price limits for local renewable energy and choose their generation mix.
C7	✗	The BMG is closely working with the utility company Con Edison, Inc., that is responsible for the BMG's region, to determine the necessary regulatory framework to legalize a P2P local microgrid energy market.

Nevertheless, the implementation of the further market components, i.e. C4, C5, and C6, is only partly realized, although actively addressed by the BMG. The double auction market mechanism (C4) is cleared at discrete time intervals at uniform clearing prices. This allocation and the pricing mechanism (C5) are already implemented. Hence, C4 and C5 are sufficiently addressed for operation. Still, the three month trial period did not actively use the market mechanism as only one consumer and one prosumer were trading and the electricity price was predetermined and fixed at the traditional price for renewable energy in Brooklyn. Thus, a very simple pricing mechanism, i.e. a fixed price, was implemented. Hence, although the market and pricing mechanism are implemented and operational, they have not yet been tested in extended real-life trial runs. In conclusion, we judge C4 and C5 to be only partly addressed by the BMG. We strongly emphasize that C5 needs to be tested for allocation efficiency as participants are able to adjust their price limits to realize the preferred mix of generation.

Automatic EMTS (C6) are implemented on the TransActive Grid smart meters. Customers set their preferences (price limits) for energy demand or excess production. They can choose the source mix (e.g. solar, wind, coal) of their preferred generation by including or excluding certain types of generation from their preferred source mix. The higher their price limit, the more local renewable energy will typically be available. So far, the same bidding strategy is implemented for every customer, i.e. bidding the agents' maximum or minimum price limit for consumers and prosumers, respectively. We judge C6 to be borderline addressed as EMTS exist although they are implementing the same simplistic strategy. Advanced bidding strategies should be automatically executed in the future, e.g. according to the agents' specific risk tolerance and further preferences.

Regulatory restrictions (C7) are still being determined. So far, P2P energy trading directly between two residents without any other stakeholders involvement (e.g. utility) is not covered by the current regulation. This is part of the reasons the first trial period had to be abandoned. For now, Con Edison remains the independent system operator of the BMG's area while LO3 Energy is on its way to being licensed as an energy retailer. Con Edision will also take over operation of the physical microgrid.

In conclusion, we derive the following key findings from our analysis:

1. A private blockchain protocol can successfully implement and operate a microgrid energy market.
2. The BMG microgrid energy market is operational. Six out of the seven market components (C1, C2, C3, C4, C5, C6) are (partly) implemented in the BMG.

However:

3. The market (C4) and pricing mechanism (C5) still need to be tested and adequately adapted for allocation efficiency. The implemented EMTS (C6) are very simplistic and require further development to adequately implement intelligent bidding strategies.
4. The legal environment (C7) does not yet allow P2P electricity transactions between residents in the BMG. Thus, regulation needs to be adapted before microgrid energy markets can be commercially implemented. This seems to be an important issue in most countries.
5. Public acceptance and customer participation in the BMG are well developed due to public relations work and demographics (many early adopters in the BMG region). Yet, the socio-economic perspective of microgrid energy markets is mostly neglected in current research.

5. Conclusion

We present a state-of-the art literature review of microgrid energy markets, blockchain technology, and their combination, ie. blockchain-based microgrid energy markets. Building upon this current literature, we derive seven components (C1–C7) for the efficient design and operation of blockchain-based microgrid energy markets to locally trade distributed generation. Thus, we develop a construct to evaluate the case study of the BMG, a blockchain-based microgrid energy market in Brooklyn, New York. Our paper includes the following key findings:

1. We derive that six out of the seven required components (C1-C6) are (partly) implemented in the case study. However, to date, regulation (C7) does not allow to run local energy markets like the BMG in most countries.
2. We show that (private) blockchains are suitable information systems that can facilitate localized energy markets. The BMG has already been tested in a three month test trial (with a simplified market setup).
3. Still, the BMG's market design needs to be further evaluated. The socio-economic incentives of community members to participate in localized energy markets require further research to adapt the market design to facilitate an efficient allocation of local energy generation.

We brought forward, that there are several advantages of (decentralized) microgrid energy markets, like the active local integration of RES into the energy system. Thus, we argue that regulation should be revised to allow for leveraging these advantages. Nevertheless, the rate of participation in the BMG and the public's positive perception of the project proof that market potential for local and renewable energy exists. The requirements and the structure of blockchain-based microgrid energy markets are just beginning to be analyzed in academia. At the same time, the current hype of blockchain technology will promote various industrial and academic projects of localized energy markets. The BMG is the first projects that actually facilitated a blockchain-based electricity transaction. The projects' findings need to be further investigated to evaluate the economic and socio-economic impact of microgrid energy markets on their participants and the entire energy supply system. Thus, future research includes socio-economic studies of the preferences and needs of microgrid energy market customers. Based on these studies, efficient allocation and pricing mechanisms should be developed for microgrid energy market mechanisms that consider the market participants' utility functions and real valuation of energy assets and services. Furthermore, possible connections between microgrid markets should be investigated to facilitate energy balances between several microgrid markets over a connecting market platform. Finally, a technological evaluation of blockchains as information and communication system for microgrid energy markets needs to be conducted. We propose to focus on the scalability and robustness of blockchains as microgrid market information systems and to evaluate the (energy) resources and transaction costs of conducting blockchain-based energy transactions.

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