Peer-to-Peer energy trading in a Microgrid☆

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ABSTRACT Peer-to-Peer (P2P) energy trading represents direct energy trading between peers, where energy from small-scale Distributed Energy Resources (DERs) in dwellings, offices, factories, etc, is traded among local energy prosumers and consumers. A hierarchical system architecture model was proposed to identify and categorize the key elements and technologies involved in P2P energy trading. A P2P energy trading platform was designed and P2P energy trading was simulated using game theory. Test results in a LV grid-connected Microgrid show that P2P energy trading is able to improve the local balance of energy generation and consumption. Moreover, the increased diversity of generation and load profiles of peers is able to further facilitate the balance.

Introduction:

With the increasing connection of Distributed Energy Resources (DERs), traditional energy consumers are becoming prosumers, who can both consume and generate energy [1]. Electricity generation of DERs is usually intermittent and difficult to predict. When prosumers have surplus electricity, they can curtail it, store it with energy storage devices, export it back to the power grid, or sell it to other energy consumers. The direct energy trading among consumers and prosumers is called Peer-to-Peer (P2P) energy trading, which is developed based on the “P2P economy” concept (also known as sharing economy) [2], and is usually implemented within a local electricity distribution system. A peer in the P2P energy trading refers to one or a group of local energy customers, including generators, consumers and prosumers. The peers buy or sell energy directly with each other without intermediation by conventional energy suppliers [3]. P2P energy trading is usually enabled by Information and Communication Technologies (ICT) -based online services [2].Conventional energy trading is mainly unidirectional. Electricity is usually transmitted from large-scale generators to consumers over long distances, while the cash flow goes the opposite way. In contrast, the P2P energy trading encourages multidirectional trading within a local geographical area. Trials of energy trading based on the “P2P economy” concept have already been carried out across the globe, for example, Piclo in the UK [4], Vandebron in Netherlands [5], and sonnenCommunity in Germany [6]. These trials mainly focused on providing incentive tariffs to electricity customers from the energy suppliers’ perspective. Piclo is an online platform that performs peer-to-peer energy trading for generators and business consumers. It uses a matching algorithm to match local generation and consumption. Data visualizations and analytics are provided to customers. The meter data, generator pricing and consumer preference information are used to match electricity demand and supply every half hour. Generators have control and visibility over who buys electricity from them. Consumers can select and prioritize from which generators to buy electricity [4].Vandebron is an online platform in Netherland where energy consumers can buy electricity directly from independent producers, such as farmers with wind turbines. Similar to Piclo, Vandebron acts as an energy supplier who provides incentive tariffs for consumers and generators to exchange energy. Prosumers who inject surplus energy to Vandebron are able to purchase energy from Vandebron at a lower price compared with other suppliers [5]. SonnenCommunity was developed by SonnenBatterie, which is a battery storage manufacturer in Germany. It is a community of SonnenBatterie owners who share self-produced energy with others with a low-priced tariff provided by SonnenCommunity. With a SonnenBatterie system and photovoltaic panels, members can completely cover their own energy needs on sunny days, and even have surplus energy. This surplus energy is not fed into the power grid, but into battery energy storage that serves the community when they cannot produce sufficient energy due to bad weather [6]. The idea is very similar to those of Piclo and Vandebron, but sonnenCommunity highlights the importance of the storage system. In recent years, P2P energy trading has also been investigated at the distribution network level. In [7], a paradigm of P2P energy sharing among neighboring Microgrids was proposed for improving the utilization of local DERs and saving the energy bills for all Microgrids. Alam et al. [8] integrated a demand side management system coordinated with P2P energy trading among the households in the smart grid in order to minimize energy cost. In [9], an energy sharing model with price-based demand response was proposed. In [10], a non-cooperative game-theoretical model of the competition between demand response aggregators for selling energy stored in energy storage was illustrated. The operation of Microgrids and multi-agent energy management systems in liberalized electricity has been widely discussed in recent years. Roche et al. [11] provided a review of several multi-agent systems which were used for grid energy management. A number of concepts and experiments were compared and analysed. In [12], a selection of available models for distributed generation planning and design was presented and analysed in the perspective of gathering their capabilities in an optimization framework to support a paradigm shift in urban energy systems. In [13], a retailing spot market of electric energy was proposed. Its interoperability with other stakeholders in the electric power infrastructure, which was modelled as a cooperating multi-agent system was elaborated. Mashhour et al. [14] presented a novel hourlyahead profit model for an active distribution company, which had high capacity level of connected Distributed Generators (DGs) that could make selling proposals for the markets in a pool-based system. Besides, a profit-based network reconfiguration methodology for a multi-substation multi-feeder distribution company was also introduced and analysed. Vergados et al. [15] studied the problem of orchestrating the energy prosumers into virtual clusters, in order to participate in the market as a single entity and to reduce the total energy cost through the reduction of the total relative forecasting inaccuracies. In [16], a general framework for implementing a retail energy market based on the Nikaido-Isoda relaxation algorithm was proposed as an electricity market structure with large DERs penetration and demand side management of consumers. By considering the related uncertainties, the DERs were able to maximise their expected payoff or profit by undertaking strategies through the price bidding strategy considering Nash equilibrium. Coelho et al. [17] discussed the major issues and challenges in multi-agent system and smart Microgrids, presented a review of state-of-the-art applications and trends, and suggested future applications with attention to renewable energy resources integration in emerging scenarios, which would be able to decentralise the high complex energy system, allowing users to participate in the system more actively. The work presented in this paper contains prominent novelty and contributions compared to the above listed literature. First of all, although many of the above listed papers (including [11,13,15–17]) considered liberalized markets in the forms of bilateral contracts, auctions or energy pools, the entities in the markets were all modelled as either generators or consumers. However, prosumers who are able to both generate and consume electricity are an important type of market entities, and they are not supposed to be modelled as pure generators or pure consumers. In this paper, the prosumers were modelled as entities that are able to shift their roles between generators and consumers. As a result, the ways of dealing with the energy trading among the market entities are changed as well. Secondly, in some of the studies mentioned in [17], the multi-agent systems were used for supporting Microgrid operation and management, or for improving supply reliability and stability. Those are different from the P2P energy trading discussed in this paper, in which the major objective of each peer is to maximise its own economic benefits. Thirdly, this paper establishes a four-layer system architecture model for P2P energy trading and proposes an associated bidding system for the P2P energy trading among consumers and prosumers in a grid-connected Microgrid for the first time, both of which were not addressed in existing studies. Last but not the least, this paper also provides more results on the benefits of P2P energy trading, which were not fully investigated in existing literature. The structure of this paper is summarized as follows. In Section 2, a four-layer system architecture of the P2P energy trading is proposed. Section 3 discusses a business model and the design of an online trading platform ‘Elecbay’. It is an example of the possible implementations in the business layer, based on which a P2P energy trading is carried out. In Section 4, game theory and Nash Equilibrium are used to validate how energy is traded among peers within a Microgrid during the bidding process. Case study is presented in Section 5, in which the benefits of using the P2P energy trading are demonstrated. Section 6 concludes the whole paper.

Designing microgrid energy markets A case study: The Brooklyn Microgrid Esther Mengelkamp a,⇑ , Johannes Gärttner a , Kerstin Rock b , Scott Kessler b , Lawrence Orsini b , Christof Weinhardt a

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 selfproduced 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.

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),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 smallscale 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.

Conclusion: 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 socioeconomic 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.

Comparative review and discussion on P2P electricity trading

Abstract : The peer to peer (P2P) electricity trading without the need for utilities is expected to increase as the awareness of the shared economy has grown and the microgrid has spread. Furthermore, the development of renewable energy technology and the Internet technology will accelerate the dissemination of the new system. In this light, this study compares the major P2P electricity trading cases being promoted and reviews the potential development and future challenges. Since there have been little case studies of P2P electricity trading published, this study could be used as valuable information for government and corporations that are promoting or pursuing P2P electricity trading business.

Introduction:

There has been growing number of peer-to-peer electricity trading (hereinafter referred to as "P2P electricity trading") cases developed in areas especially where the electricity trading is deregulated. In 2014, Vandebron, a Netherland-based startup, opened the world's first online market for energy that enables consumers to purchase electricity directly from independent producers. In October 2015, the UK's Open Utility launched a service using an energy trading platform that allows direct trading between commercial power consumers and renewable energy producers without going through power utilities. Similar projects are being promoted in other parts of the world such as Germany and the United States. Although at the early stage, the P2P electricity trading without the need for utilities is expected to increase as the awareness of the shared economy has grown and the microgrid has spread. Furthermore, the development of renewable energy technology and the Internet technology will accelerate the spread of the new system [1–3]. Studies on P2P electricity trading have discussed generally regarding technology development. Since P2P electricity trading is still at an early stage in business, studies are focused on what technology to use in that trading. Alvaro-Hermana et al. [4] presented a novel peer-to-peer energy trading system between two sets of electric vehicles. Inam et al. [5] discussed the architecture and system analysis of microgrids with P2P electricity sharing. Kim et al. [6] proposed P2P energy loan service using block-based P2P loan process. On the other hand, there is an increasing number of studies examining the socio-economic impact of P2P electricity trading, with the expectation that P2P electricity trading will gradually spread. Giotitsas et al. [7] discussed the evolution of energy trading technologies and the impact on the global socio-economic structure. Roy et al. [8] reviewed the potential value of P2P electricity trading in the Australian national electricity market. Burger et al. [9] investigated in some cases using the blockchain technology in the electricity trading. However, overall, from a business model point of view, there was no comprehensive review. In this light, the aim of this study is to compare the major P2P electricity trading cases being promoted and to review the potential development and future challenges. Since there have been little case studies of P2P electricity trading published, this study could be used as valuable information for government and corporations that are promoting or pursuing P2P electricity trading business.

Discussions and Conclusions: As we have observed in the above cases, the P2P electricity trading has been promoted in various forms, starting in the Netherlands, then Germany, the United Kingdom, and the United States. The cases vary as we have seen in the Piclo; an IT company operating P2P electricity trading online windows, a cooperative model of the power companies dealing with transactions, contracts, and billing, a P2P electricity trading using energy storage devices like sonnenCommunity, and a case applying new technology used in Bitcoin transactions while directly supporting transactions within the microgrid like Microgrid Sandbox. Additional business models are expected to emerge in the future, and the convergence type of other operators' business models will increase. P2P electricity trading is supposed to contribute to expanding small-scale distributed resources and creating new markets. The main advantages of this system are the energy they generate on their own can be linked to the profit not 8 Chankook Park et al. / Energy Procedia 128 (2017) 3–9 6 Author name / Energy Procedia 00 (2017) 000–000 discarding it; the power generation can be made meeting the requirements of the end users; and the utilization of the resources can be optimized through the cooperative network between producers and consumers [11]. To make the P2P electricity trading viable, we should secure the profitability of the business first. In the examples we have seen above, all business models have a structure that benefits both prosumers who sell electricity from renewable energy and consumers that purchase electricity from the prosumers. To take an example of the German's sonnenCommunity, consumers pay 25 cents/kWh to power producers, which is lower than the electricity price paid to utilities for consumers and bigger than the profits earned from the Feed in Tariff (FIT) for prosumers. This business modle is possible when renewable energy or electricity supply costs are lower than the existing electricity rates. All of the cases examined in this study utilize structures that can benefit prosumers, brokers, and consumers in areas where the electricity market is deregulated. In the future, P2P electricity trading will continue to expand as the number of areas where electricity brokerage business is permitted increases and renewable energy and storage devices costs decrease. It is also expected that the technological development of energy storage devices will play a major role. The electricity produced by the prosumer through renewable energy has irregular output. When these distributed resources are concentrated in some areas, the voltage rise may occur locally for a certain time and the electric quality may be deteriorated. Small-scale renewable energy producers generate irregular output electricity, but consumers want to be supplied with electricity in a stable manner. To address these inconsistencies and maintain the balance between supply and demand, special means are required. The Germany's Sonnenbatteries promotes P2P electricity trading business by combining distributed power generation, energy storage technology, and digital networking technology. To provide better services for maintaining the balance between supply and demand at Piclo, the UK's Open Utility also plans to submit a proposal to the Office of Gas and Electricity Markets (Ofgem), a UK electric gas regulator, to utilize energy storage systems (ESS). A significant technical challenge of the P2P electricity trading is that every node in a P2P network must be responsive to grid conditions, energy prices, and local energy supply and demand. The development of ESS is expected to contribute to solving these technical problems. The recent P2P electricity trading is in its early stage, where it is still difficult for individuals to freely trade electricity, and the scale is also rather small. Thus, this study mainly examines what type of business is being promoted globally and the environment in which P2P electricity trading can be spurred. Some view the P2P electricity trading as shared services such as Airbnb and Uber, and others think from an energy democracy point of view that the power distribution can be used without discrimination. More and more individuals are increasingly producing electricity, sharing or trading surplus electricity, raising their voices in the energy economy. In the future, if the price of renewables is relatively competitive and the P2P electricity trading is more activated, the following should be taken into account: how the impact on the grid will be, how the increase of distribution network costs should be shared fairly, and how the existing centralized power supply system will be changed in the new electricity trading environment be harmonized with the new system. The environment in which P2P electricity trading is active will be different from the current electricity market, and the power load, the competition structure of the market participants, and the trading system will undergo major changes. Therefore, a number of issues that are not covered in this study should be additionally discussed in the future

Peer-to-peer energy trading in a microgrid leveraged by smart contracts

ABSTRACT: The current electricity networks were not initially designed for the high integration of variable generation technologies. They suffer significant losses due to the combustion of fossil fuels, the long-distance transmission, and distribution of the power to the network. Recently, prosumers, both consumers and producers, emerge with the increasing affordability to invest in domestic solar systems. Prosumers may trade within their communities to better manage their demand and supply as well as providing social and economic benefits. In this paper, we explore the use of Blockchain technologies and auction mechanisms to facilitate autonomous peer-to-peer energy trading within microgrids. We design two frameworks that utilize the smart contract functionality in Ethereum and employ the continuous double auction and uniform-price double-sided auction mechanisms, respectively. We validate our design by conducting A/B tests to compare the performance of different frameworks on a realworld dataset. The key characteristics of the two frameworks and several cost analyses are presented for comparison. Our results demonstrate that a P2P trading platform that integrates the blockchain technologies and agent-based systems is promising to complement the current centralized energy grid. We also identify a number of limitations, alternative solutions, and directions for future work.

Introduction : The current infrastructure of the national grid is aging and has been mainly built to support a one-way power flow. It is a centralized system that energy is generated in power plants, transmitted over long distances to consumptions sites, where consumers are majorly passive. See Fig. 1 (a) [1] for an illustration. The long-distance transmission not only creates power losses but also does not integrate demand and supply in real-time, which causes overproduction. For example, during winter 2017, Germany has experienced unexpected negative electricity prices, where they produce too much when there is not enough demand (over the weekends). As a consequence, they have to pay to be able to “sell” their product. Thus, people have been looking for alternatives to mitigate these problems. Meanwhile, we are moving to a more distributed network, arguably, also more complex, in which energy generation will no longer only come from power plants. This distributed network involves houses with solar photovoltaic panels (PV), electric vehicle (EV) charging stations (that can act as storage), locally produced wind power, and other renewable energy technologies. Individuals are no longer just consumers but are actively taking part in the productions of their energy and collectively feeding electricity into the grid. They are the so-called prosumers, both consumers and producers of energy. That is to say, the large companies will no longer be the only ones with a stake in the energy space, but the public as well. This new movement creates a range of opportunities to retrofit the centralized way of managing today’s grid, one of which is the possibility to introduce the ability to react in real-time to the intermittent generation and volatility of the national grid in the current wholesale market. A microgrid is formed by agglomerating small-scale prosumers; they constitute a local energy market and trade energy within their community. A microgrid can help with reflecting the real-time prices of energy and facilitate a sustainable and reliable way of locally balancing generation and consumption. The local energy markets can be viewed as a rising form of sharing economy, in addition to the well-developed house-sharing and transportation sharing. See Fig. 1(b) [1] for an illustration. Such an initiative can help reduce the latency for managing congestion and the distribution faults [2]. Its decentralized structure can help with cyber attack resilience. Overall, it helps communities become more self-sustainable, ecologically, and economically. Smart grid hardware, such as smart meters, has been a significant catalyst in moving to more autonomous networks. They can be used for handling more complex information, such as optimizing energy consumption patterns, adapting to them, and using these to optimize the price of energy as well as controlling the parameters of the appliances in their houses by using the customer-generated energy profile. In the meantime, these systems need a secure, reliable, and transparent mechanism to manage these markets, helping with their local energy balancing needs, and providing a user-friendly application for people to use. Therefore, we necessitate new control frameworks to fulfill these requests. The Blockchain technologies enable the possibility of building up an autonomous, secure, reliable, and transparent market. Blockchain is formed by a series of blocks which contain a record of transactions. Each block references the previous block via its hash value, thereby creating a chain of transactional records that can be traced back to the genesis block. The most trusted and reliable chain is the longest. The Blockchain is not provided from a single server but is a distributed transactional database with globally distributed nodes that are linked by gossip protocols. Blockchain protocols are designed to possess a number of important features including decentralization, immutability, and pseudoanonimity. Therefore, they provide a level of security, trustless, and privacy.