Peer-to-Peer (P2P) Electricity Trading in Distribution Systems of the Future

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1. Introduction

In recent years, the total installed capacity and the amount of electric energy generation of distributed energy resources (DER) have been increased significantly. For instance, in U.S., electric energy generation from DERs reached 185,334GWh in 2015 and is projected to be 317,323GWh at 2040, corresponding to 4.7% and 6.7% of the total utility-scale generation [1]. Indeed, among different types of DER technologies, the growth of rooftop solar generation is particularly prominent, which is expected to increase from 13,453GWh in 2015 to 64,485GWh in 2040, representing a growth from 0.3% to 1.4% in total utility-scale generation and occupying about half of the DER growth [1].

The significant growth of rooftop solar energy generation is mainly driven by two major forces: One is the pressure on carbon emission reduction in electricity production, which has been mainly relying on fossil fuel and contributes about one third carbon emission each year. According to the Clean Power Plan 2015, the U.S. power sector targets to reduce 32% of its CO_2 emission level by 2030 [2]. In order to achieve this goal, both federal and state governments have issued policies to promote the development and deployment of distributed renewable resources, such as Renewable Energy Credits and Renewable Electricity Production Tax Credit [3]. Solar energy generation is one of the beneficiaries. The other force is the reduction in installation costs of solar energy generation due to larger scale productions and lower raw material prices. Although installation costs vary based on a number of factors such as locations, providers, and scales, solar energy generation at small commercial scales, i.e., typically around 200 kilowatts (kW), has a cost around $1.85/watt in 2017 as compared to $2.78/watt in 2014, and a residential-scale solar energy generation typically sized as 6 kW has an average installation cost of $2.80/watt in 2017 compared to $3.92/watt in 2013 [4]. These reference costs include solar panel modules as well as associated software and hardware, such as structural components, electrical components, and inverters. Indeed, cost of a single solar panel module has reduced dramatically during 2011-2017 due to the aforementioned second force, contributing to a significant reduction in the total cost of rooftop solar energy generation [4].

Another noteworthy technology that flourishes at the resident level of distribution systems in recent years is electric

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vehicles (EV). In U.S., the cumulative sales of EVs reached 500,000 units in August 2016, which was doubled and exceeded 1 million milestone in September 2018. Prices of EVs range from $25,000 to over $100,000, covering auto markets of luxury and economy models [5]. The three largest manufacturers are Tesla, General motors (Chevrolet), and Ford, in which Tesla focuses on high-end market and the other two target on economic vehicles [6]. The prosperity of the EV market is mainly dependent on several driving forces. One force is the pressure on energy conservation so that incentives from both federal and state governments, such as income tax credit and purchase rebate, are offered. The second one is the price drop due to peer competitions. Indeed, besides the three mentioned top market share manufacturers, other traditional vehicle manufacturers, such as BMW, Nissan, Kia, etc. also introduce EV models and some have even established sub-brands especially for EVs. There are dozens of alternative EV models available in the market. The third force is performance improvement of EVs brought by technological advancements. The continuous R&D investments from manufacturers have made EV technologies improved rapidly, which positively feedback to EV performance including speed control, endurance, and driving experience. Besides economic and environmental considerations, EVs themselves are a reason people buy EVs.

Solar energy generation that provides electricity locally in distribution systems brings magnitudes of benefits to power systems. Specifically, in distribution power grid, they can help reduce real power losses, mitigate upstream overload of distribution lines, and enhance power supply reliability; in transmission grids, they can ease congestions on transmission lines and defer generation and transmission upgrades. EVs have the ability to shift electricity spatiotemporally. Under economical arrangements, they can be utilized to shift peak loads and even act as power sources. Furthermore, EVs can coordinate with solar energy generation to increase solar utilization and reduce curtailment. However, although power grids can benefit from the deeper deployment of solar power generation and EVs at the distribution level, incentives from electricity markets and utilities that are supposed to further promote their development are lacking. Indeed, it is believed that among aforementioned driven forces, incentives provided by government policies should be gradually transferred to be provided by the beneficiary groups.

It is a common practice of current utilities that residentials and small commercial electricity consumers equipped with renewable resources purchase electricity from utilities through fixed tariff or time-of-use (TOU) prices [7], which can sell back excessive electricity via power purchase agreements (PPA) [8] back to utilities as shown in Figure 1. PPAs generally provide long-term fixed feed-in tariffs to renewable resource owners for their excessive electric energy. Different utilities may provide offers of heterogenous forms. For instance, in the Power Purchase Agreement for Small Renewable Generation of PG&E [9], feed-in tariffs are settled as products of two parameters, Market Price References (MRP) and Time-of-Day Factors (TDP), where the former is a reference price related to length of the PPA contract and the later reflects electricity value during different periods of a day. For example, the MRP of a 10-year PPA contract is $0.098/kWh, and TDPs for peak, shoulder, and night load periods of a day during winter months are respectively 1.1, 0.9 and 0.65, which settles feed-in tariffs from $0.064/kWh to $0.108/kWh. It is not surprising that TOU prices would be much higher than feed-in tariffs. In comparison, TOU prices from PG&E typically range from $0.20/kWh to $0.30/kWh during same months. Because of the relatively low feed-in tariffs, residentials and small commercial electricity consumers usually take their own electricity consumption levels as a reference when

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determining installation capacities of their renewable resources, hoping to cover installation costs by cutting their electricity bills. However, they are reluctant to expand installation scales to sell surplus electricity back to utilities, because low feed-in tariffs make it unprofitable. This could potentially limit the further deployment of DERs in distribution systems. In addition, EV owners prefer to charge when TOUs are low but may be unwilling to discharge which could potentially help shift peak loads, because feed-in tariffs are unable to compensate battery life losses caused by frequent charging and discharging. This limits the potential contribution of EVs.

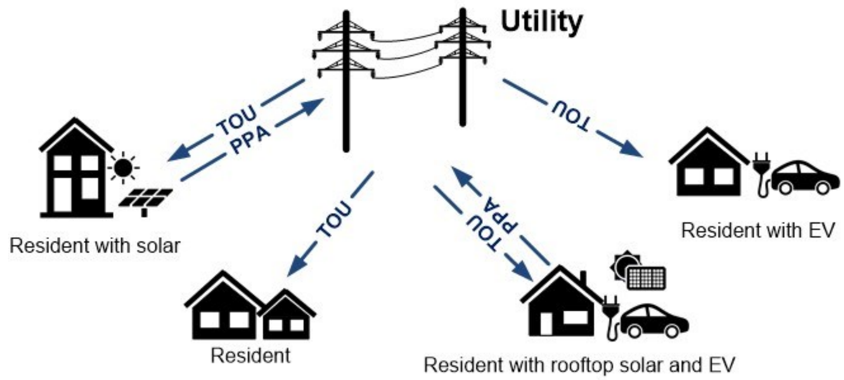

Figure 1: Current trading structure of residential customers owing solar and/or EV with utilities.

In general, under the current situation of a large amount of existing DERs and EVs connected into distribution systems and with the desire to provide more incentives from power systems to promote further DER and EV deployments, the Peer-to-peer energy (P2P) electricity trading as shown in Figure 2 was born. In P2P electricity trading, participants are considered as prosumers, which are allowed to switch their roles between buyers and sellers to either purchase or sell electricity, and are able to directly trade electricity with each other to achieve a win-win outcome via seeking a proper price between relatively high TOU prices and low feed in tariffs so that buyers can save costs while sellers can receive more profit. P2P electricity trading has already been widely discussed in the academic field, and a lot of work has been done to verify its effectiveness and explore its potentials. Different trading mechanisms and models have been proposed and analyzed [10]-[16]. Furthermore, several realistic pilot P2P electricity trading projects have been implemented, including Piclo, Vandebron, SonnenCommunity, etc. [17].

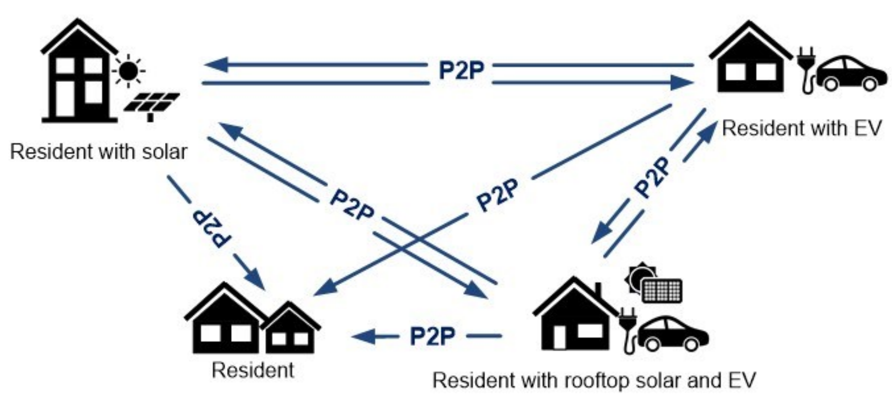

Figure 2: Structure of P2P electricity trading.

In the remaining of this paper, two types of P2P electricity trading mechanisms in distribution systems of the future are introduced and discussed in Sections 2 and 3, respectively. Furthermore, Section 4 introduces two important enchantments of introducing P2P electricity trading mechanisms. Conclusions are addressed in Section 5.

2. Auction-Based P2P Electricity Trading Mechanism

Under auction-based P2P electricity trading mechanism in a distribution system, a distribution system operator (DSO) is designed with responsibilities to securely and reliably operate the system and administrate a competitive P2P electricity trading market. Prosumers are considered as self-interested entities with private economic objectives. They schedule their own available generation and load resources to pursue the objectives in a decentralized manner, while their objectives may be against with each other and not be consistent with DSO.

In the bidding time window for a certain operation period, individual prosumers are allowed submit their bids, including electricity prices and/or quantities, to the DSO either to purchase or sell electricity. Bids of a prosumer are only accessible to the DSO but confidential to other prosumers. It is worthwhile to mention that, if the DSO is independent from the utility which has jurisdiction to this distribution system, in principle, the utility should not be excluded from participating in the market, which means it can also submit bids to the DSO as any other prosumer does. After collecting all bids from prosumers or reaching certain points in time during the bidding time window, the DSO will clear the distribution market. The objective of the distribution market clearing is to maximize the social welfare by matching bids of purchasing and selling electricity, while satisfying system secure operation constraints such as distribution line power flow constraints and bus voltage constraints. Then, the DSO determines and issues the market clearing price at which prosumers pay or get paid for the amount of electricity being traded. The market clearing price is not limited to be based on marginal pricing, but could be on other mechanisms, such as mid-rate and bill sharing [18]. Generally, the market clearing price can be represented as an abstract pricing function that is changeable marker by market. Many existing literatures delicately design the pricing function [18]-[19]. After receiving the issued market clearing price from the DSO, prosumers would have a chance to refine their bids based on it and any other available information and resubmit new bids to the DSO. With new bids from prosumers, the DSO will clear the market again and reissue a new market clearing price to them. This process will be implemented iteratively until no prosumers are willing to modify their bids or a certain number of iterations is reached. The iterative process actually represents a negotiation procedure between prosumers. It is called converged when it terminates with no new bids being resubmitted. However, regardless of convergence or not, the market clearing result in the last iteration will be awarded and the corresponding market clearing price will be set as the final price to settle awarded electricity transactions. The flowchart of the mechanism is shown in Figure 3.

From the perspective of game theory, the auction-based P2P electricity trading mechanism forms a non-cooperative game in prosumers (i.e., players). Convergence in the iterative negotiation process is highly desired, which may occur after multiple iterations, because it could indicate the existence of a Nash equilibrium that achieves a consensus with more effective trading and equitable benefit distribution. Under the framework of this mechanism, some literatures have proved the existence of a Nash equilibrium, with respect to specified models of the DSO and the prosumers and pricing functions as well as certain assumptions on prosumers' behaviors [10]-[11], [20]-[21]. However, in practice, prosumers are unlikely to strictly obey those pre-specified models and assumptions. Thus, although a theoretical equilibrium may exist, in practical implementation, convergence could be difficult to achieve. Reference [10] proposed two practically applicable techniques, step length control and learning process involvement, for the purpose of enhancing convergence. Finally, it is emphasized that the iterative negotiation process is to enable more transactions and to maximize the overall social welfare. However, in the practical implementation, considering the difficulties in interacting with prosumers in real time, a one-time auction process may be adopted instead.

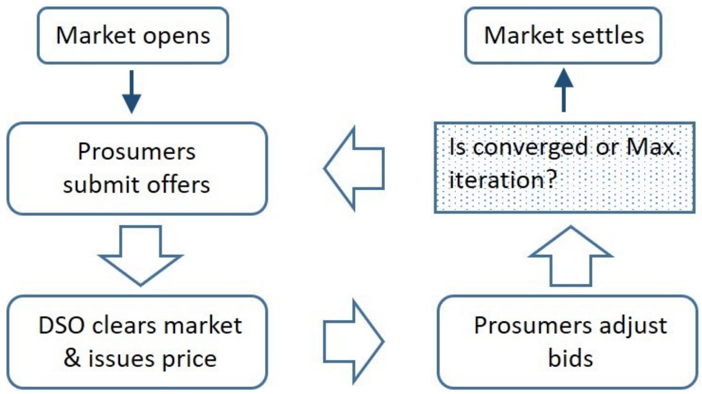

Figure 3: Flowchart of auction-based P2P electricity trading mechanism.

3. Bilateral Contract-Based P2P Electricity Trading Mechanism

Under bilateral contract-based P2P energy trading mechanism, a DSO in a distribution system with similar responsibilities as in previous mechanism is designed. However, the difference is that instead of administrating a market, the DSO operates a platform where trading offers are posted and handshakes are made. In addition, in order to prevent arbitrage, prosumers are required to register as either a buyer or a seller in the platform for a certain operation period. Prosumers are still considered as self-interested and aim at pursuing more profits in the trading.

Similarly, in the offering time window for a certain operation period, buyers and sellers respectively submit their purchasing and selling offers, which are consisted of electricity prices and/or quantities, to the DSO. Buyers and sellers are allowed to simultaneously submit multiple offers. Then, purchasing offers are broadcasted to all sellers, and selling offers are broadcasted to all buyers. In the meanwhile, the platform displays all available offers, where buyers and sellers can browse respectively accessible offers besides submitting their own offers. When a buyer browses to a selling offer and has willingness to make a deal, it can send a contract to owner of the offer and request its confirmation. Similarly, sellers can browse and select purchasing offers to seek for the deal. After a contract is confirmed, it will be automatically sent to the DSO for final approval and the corresponding offer showing in the platform will be removed to prevent multiple purchases. At certain points in time during the offering time window, the DSO conducts the approving process, which checks all currently received contracts against system secure operation constraints, rejects contracts that cause violations, and approves the remaining. Buyers and sellers involved in approved contracts will be notified, and they are unable to retract the approved contracts any more. Prosumers that have contracts being rejected may resubmit their offers after adjustment. The DSO will conduct preset times of approving processes at certain points in time during the offering time window. Subsequent approving processes always admit the previously approved contracts, namely approved contracts will not be rejected in subsequent approving processes.

There are a couple of important features that need to be further clarified. First, utility that has jurisdiction to the distribution system is not necessarily to be excluded from accessing the platform. However, it can only act as either a buyer or a seller like any other prosumer does. Second, during the offering time window, buyers and sellers can submit, retract, and modify their offers at any time. However, approving process occurs at certain points in time, and only approved contracts are valid in the final settlement. Third, a contract sent to the DSO contains information of both buyer and seller, electricity prices and qualities, and rejection mode. Indeed, prices will not impact the final approving process, but are used in the final settlement. Rejection mode defines whether the DSO can partially reject a contract, namely approving part of the transaction quantity. If not, a contract will be rejected as a whole if causing network security violations. At last, when violation occurs, it could be related to multiple contracts because of the fact that voltage and current quantities on the grid are jointly impacted by contracts. The violation may be eliminated by rejecting one or multiple the related contracts. Thus, the rules for rejecting contracts are critical and could be platform dependent. An example is the last-on-first-off principle, describing that contracts created at a later time will have higher possibilities to be rejected.

This mechanism can easily enable Multi-class Electricity Trading (MET) [22]-[23]. MET is based on admitting the heterogeneity of electricity, which does not differentiate electricity in the physical sense but recognizes differences in economic and social values of a same amount of electricity associated with different producers and/or consumers. Under bilateral contract-based mechanism, buyers/sellers can be further allowed to submit offers with different prices to multiple potential sellers/buyers. For example, a seller may be willing to give a discount to buyers in low-income communities and charge more for merchant buyers. Accordingly, rules of rejecting contracts may need to be properly adjusted when considering MET.

4. Enchantments on P2P Energy Trading Mechanisms

P2P electricity trading agents and decentralized P2P electricity trading are two possible enchantments for the introduction of P2P electricity trading mechanisms.

4.1. P2P Electricity Trading Agents

For a prosumer composed of a single resident, the hidden cost of participating into P2P electricity trading could be high. From Sections 2 and 3, it can be learned that P2P electricity trading mechanisms generally require the participants to actively and properly interact with the DSO and potentially other participants, for the purpose of achieving higher profits. However, this is non-trivial and could be associated with a high opportunity cost. Although interactions could be done automatically by decentralized software agent, user intervention is still hard to be fully avoided. In addition, risks of a single prosumer for not being able to fulfill contracts and instructions from DSO are high, because a single resident's electricity consumption, production, and even EV charging and discharging schedules may not be flexible enough. In order to avoid potential economic losses and punishments due to failure to fulfill contracts and instructions, a prosumer has to adopt a very conservative strategy.

On the other hand, this obviously presents opportunities for communities, microgrids, and third-party trading companies to organize and manage scattered prosumers and participate in electricity trading as a group. Inside a group, a centralized agent is built with three responsibilities: (i) optimally bid or offer in the electricity trading, (ii) properly coordinate sources of involved prosumers to fulfill contracts and instructions, and (iii) fairly distribute profits to involved prosumers. Essentially, from the perspective of game theory, it can be seen that a cooperative game is established within the group while the group itself is in an external non-cooperative game. Therefore, two factors are important to such a group: one is how to maximize the profit on behalf of a group in the non-cooperative game, and the other is how to distribute the profit to prosumers internally so that prosumers have no incentives to leave the group. The structure of electricity trading is shown in Figure 4. Detailed discussion of this trading structure can be found in references [24].

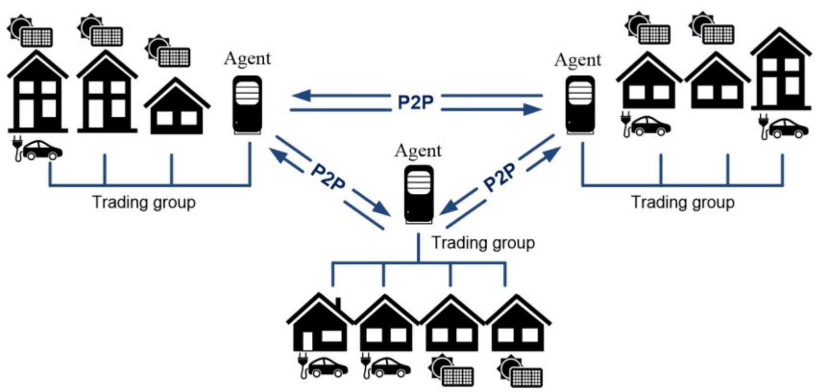

Figure 4: Structure of electricity trading with trading aggregators.

4.2. Decentralized P2P Electricity Trading

From the two mechanisms introduced in Sections 2 and 3, it can be seen that a designed DSO is in charge of the electricity trading market/platform, i.e., the two mechanisms are both centralized. Blockchain technology, as the underlying technology of the rapidly swelling virtual currency, has been introduced to decentralize P2P electricity trading [25]. It is admitted to present advantages in decentralization, security, and anonymity that could enable electricity trading in a decentralized and secure manner. Reference [26] introduced the Brooklyn microgrid project that applied blockchain technology, and concluded that blockchain is an eligible technology to operate decentralized electricity trading in microgrids. However, debates on the decentralization still exist. Specifically, in the two introduced mechanisms, the DSO not only administrates the trading market/platform, but is also responsible for securely operating the grid and promptly responding to deviations, disturbances, and failures. Indeed, different from other systems of similar complexity, quantities and objects of electricity trading are tightly related to the secure operation of physical distribution systems that cannot be separated from each other. Thus, when a centralized DSO is absent, how to ensure secure operation of physical distribution systems remains a major concern [27].

5. Final Words

A considerable amount of research and pilot projects has been conducted, which illustrate effectiveness of P2P electricity trading as a potential solution for promoting and managing proliferated prosumers in distribution systems of the future. However, mechanisms of P2P electricity trading are diverse, and are most likely need to be customized according to target distribution systems to achieve desirable benefits. Thus, on the one hand, further exploration on the P2P electricity trading mechanisms of future distribution systems is worth pursuing; On the other hand, design guidelines and comprehensive evaluation platforms on P2P electricity trading mechanisms are desired. Several attempts have been undergoing [10], while more work is expected.

References

[1] Department of Energy, “Quadrennial energy review transforming the nation’s electricity system: the second installment of the QER”, Jan. 2017. https://www.energy.gov/sites/prod/files/2017/02/f34/ Quadrennial%20 Energy%20Review--Second%20Installment%20%28Full%20Report%29.pdf. (Accessed 01/23/2019).

[2] W. Hogan, “Electricity markets and the clean power plan,” The Electricity Journal, vol. 28, no. 9, pp. 9-32, Nov. 2015.

[3] Renewable Electricity Production Tax Credit. https://www.energy.gov/savings/renewable-electricity-production-tax-credit-ptc. (Accessed 01/23/2019).

[4] R. Fu, D. Feldman, and R. Margolis, “U.S. solar photovoltaic system cost benchmark”, 2017. https://www.nrel.gov/docs/fy17osti/68925.pdf. (Accessed 01/23/2019).

[5] “Plug-in electric vehicles in the United States”, https://en.wikipedia.org/wiki/Plug-in_electric_vehicles_ in_the_United_States. (Accessed 01/23/2019).

[6] P. Slowik, and N. Lutsey, “Expanding the electric vehicle market in U.S. Cities”, Jul. 2017. https://www.theicct.org/publications/expanding-electric-vehicle-market-us-cities. (Accessed 01/23/2019).

[7] A. Thumann and E. A. Woodroof, Energy Project Financing: Resources and Strategies for Success. Lilburn, GA, USA: Fairmont Press, 2009.

[8] New York State Energy Research and Development Authority, “Microgrids for critical facility resiliency in New York state”, DEC. 2014, https://www.nyserda.ny.gov/-/media/Files/Publications/Research/Electric-Power-Delivery/Microgrids-for-Critical-Facility-NYS.pdf. (Accessed 01/23/2019).

[9] PG&E’s Power Purchase Agreement for Small Renewable Generation. https://www.pge.com/includes/docs/ pdfs/b2b/wholesaleelectricsuppliersolicitation/Feedin_Tariffs_FAQs.pdf. (accessed 01.23.19).

[10] Y. Zhou, J. Wu, and C. Long, “Evaluation of peer-to-peer energy sharing mechanisms based on a multi-agent simulation framework”, Applied Energy, 222, 933-1022, 2018.

[11] C. Zhang, J. Wu, Y. Zhou, M. Cheng, and C. Long, “Peer-to-Peer energy trading in a microgrid”, Applied Energy, 220, pp. 1-12, 2018.

[12] J. Abdella, and K. Shuaib, “Peer to peer distributed energy trading in smart grids: A survey”, Energies, 11, 1560, 2018.

[13] T. Sousaa, T. Soaresb, P. Pinsona, F. Moreta, T. Barochec, and E. Sorina, “Peer-to-peer and community-based markets: A comprehensive review”, Jan. 2019. https://arxiv.org/abs/1810.09859. (Accessed 01/23/2019).

[14] C. Parka, and T. Yongb, “Comparative review and discussion on P2P electricity trading”, Energy Procedia, vol. 128, pp. 3-9, Sep. 2017.

[15] J. Li, Y. Liu, and L. Wu, “Optimal operation for community-based multi-party microgrid in grid-connected and islanded modes”, IEEE Transactions on Smart Grid, vol. 9, no. 2, pp. 756-764, Mar. 2018.

[16] Y. Parag, and B. K. Sovacool, “Electricity market design for the prosumer era”, Nature Energy, vol.1, article number: 16032, 2016.

[17] C. Zhang, J. Wu, C. Long, and M. Cheng, “Review of existing peer-to-peer energy trading projects”, Energy Procedia, vol. 105, pp. 2563-2568, May 2017.

[18] C. Long, J. Wu, C. Zhang, L. Thomas, M. Cheng, and N. Jenkins, “Peer to peer energy trading in a community microgrid”, IEEE Power & Energy Society General Meeting, Chicago, IL, USA, Jul. 2017.

[19] N. Liu, X. Yu, C. Wang, C. Li, L. Ma, and J. Lei, “Energy-sharing model with price-based demand response for microgrids of peer-to-peer prosumers”, IEEE Transactions on Power Systems, vol. 32, no. 5, pp.356-3583, Sep. 2017.

[20] A. Paudel, K. Chaudhari, C. Long, and H. B. Gooi, “Peer-to-peer energy trading in a prosumer based community microgrid: A game-theoretic model”, IEEE Transactions on Industrial Electronics, DOI: 10.1109/TIE.2018.2874578, Oct. 2018.

[21] W. Tushar, T. K. Saha, C. Yuen, P. Liddell, R. Bean, and H. V. Poor, “Peer-to-peer energy trading with sustainable user participation: A game theoretic approach”, IEEE Access, digital object identifier: 10.1109/ACCESS.2018.2875405, Nov. 2018.

[22] E. Sorin, L. Bobo, and P. Pinson, “Consensus-based approach to peer-to-peer electricity markets with product differentiation”, IEEE Transactions on Power Systems, DOI: 10.1109/TPWRS.2018.2872880, Oct. 2018.

[23] T. Morstyn, and M. D. McCulloch, “Multi-class energy management for peer-to-peer energy trading driven by prosumer preferences”, IEEE Transactions on Power Systems, DOI: 10.1109/TPWRS.2018.2834472, May. 2018.

[24] Y. Wu, X. Sun, X. Tan, L. Meng, L. Yu, W. Song, and D. H. Tsang, “Cooperative distributed energy generation and energy trading for future smart grid” Proceedings of the 33rd Chinese Control Conference, Nanjing, China, Jul, 2014.

[25] J. Kang, R. Yu, X. Huang, S. Maharjan, Y. Zhang, and E. Hossain, “Enabling localized peer-to-peer electricity trading among plug-in hybrid electric vehicles using consortium blockchains”, IEEE Transactions on Industrial Informatics, vol. 13, no. 6, pp. 3154-3164, Dec. 2017.

[26] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C Weinhardt, “Designing microgrid energy markets a case study: The Brooklyn Microgrid”, Applied Energy, 210, pp. 870-880, 2018.

[27] J. Guerrero, A. Chapman, and G. Verbic, “Decentralized P2P energy trading under network constraints in a low-voltage network”, Sep. 2018. https://arxiv.org/abs/1809.06976. (Accessed 01/23/2019).