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Published in:
Proceedings of 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)

DOI (link to publication from Publisher):
10.1109/ISGT-Asia.2019.8881671

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Yue, J., Hu, Z., Li, C., Anvari-Moghaddam, A., Guerrero, J. M., & Dulout, J. (2019). Dynamic Pricing for Microgrids Energy Transaction in Blockchain-based Ecosystem. In *Proceedings of 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)* (pp. 1598-1602). [8881671] IEEE Press. Innovative Smart Grid Technologies - Asia (ISGT Asia), IEEE https://doi.org/10.1109/ISGT-Asia.2019.8881671

Dynamic Pricing for Microgrids Energy Transaction in Blockchain-based Ecosystem

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Abstract: **Microgrid (MG) is an efficient platform to integrate distributed energy resources in distribution networks. The operation of MG is also expected to take advantage of emerging smart grid technologies to improve operation and robustness. Among these emerging technologies, blockchain technology provide a big potential to rule the energy transaction in an innovative way. In this paper, a physical architecture of the ecosystem with MGs is firstly presented. Moreover, as the main parts of the blockchain technology, the operation of distributed ledger and smart contracts are introduced in the transaction process. Considering dynamic pricing scheme in the process of energy transaction in the ecosystem, we model the energy transaction between MGs and distribution system operator (DSO) to decide the trading amount and price of the energy. The welfare maximization mathematical model is established accordingly, and the formulated dual problem will be used to find the shadow price of selling renewable energy to grid and real-time retailer price from DSO. Finally, with the deployment of distribution ledger, the energy transaction process can be fully recorded, and transaction execution can be achieved with the help of smart contracts. In light of the mentioned perspective, beside demonstrated benefit brought to both MGs and DSO, the energy transaction and management based on the blockchain will result in higher reliability and improved auditability in the ecosystem.**

Keywords—microgrid, blockchain, ecosystem, dynamic real-time price, energy transaction.

I. INTRODUCTION

Microgrid (MG) with integrated distributed resources (e.g. wind turbine, Photovoltaic (PV), fuel cell, storage systems, etc.) is playing an increasingly important role in the distribution network by enabling bi-direction power flow throughout the network to trade energy with other entities [1][2]. Dynamic transaction pricing implementation can not only encourage customers to consume energy more wisely to alleviate peak-time loading, but also make the player to pursue maximum profit in the process of energy transaction [3][4].

Meanwhile, in the traditional ways of energy production and transaction, energy companies often execute lots of contracts and conduct extensive calculations, which demands high costs of transaction and risks management. The emerging blockchain technology with promising characteristics, such as decentralization, transparency, reliance and openness would contribute to alleviate aforementioned problem by distributed energy transaction [5].

Blockchain technology is an incorruptible digital ledger of transactions that can be programmed to virtual record of anything of value including digital currency can even be paid in decentralized cryptocurrency such as bitcoins [6]. In the recent research, some pilot paradigms in the energy field have moved from the theoretical study into practice exploration [7]–[9]. For instance, a transactive energy auction was built in a campus demonstration which enables the exchange of energy among distributed prosumers [7]. A localized peer-to-peer (P2P) electricity trading model for locally buying and selling electricity among electric vehicles was proposed in [9]. Energy company "LO3 Energy" established the world's first energy market based on blockchain technology in a microgrid in Brooklyn, United States [10]. "Power ledger" as an Australian blockchain startup, has run a blockchain-based cryptocurrency and energy trading platform that allows for decentralized selling and buying of renewable energy [11].

In this work, the main contributions and objectives are: 1) to propose an ecosystem including smart residential MGs and various entities for energy transaction and scheduling; 2) to model the energy transaction between MGs and DSO by calculating a dynamic transaction shadow price of selling and buying energy through the dual optimization problem based on the established mathematical model; 3) to incorporate blockchain technology to the energy transaction and benefit allocation among key players in the ecosystem.

The rest of paper is organized as follows: the ecosystem architecture is introduced in Section II, where the entities' mathematical models are built. The energy transaction problem is formulated and the optimization problem of shadow price for tariff and retail electricity price are described in Section III. Furthermore, an energy transaction instance is implemented to demonstrate the feasibility of the proposed method and process in the Section IV. Finally, the summary of the work is presented in the Section V.

II. BLOCKCHAIN BASED ECOSYSTEM ARCHITECTURE

To begin with, the composition of the entire ecosystem for microgrids and the blockchain deployment are firstly described to give a context of this study. The detailed model of each participant involved are in the following subsections.

A. *Models of participants in the ecosystem*

Blockchain-based ecosystem of MGs community is shown as Fig.1, where the participants are interconnected and interacted through information flow, energy flow and capital flow. Each participant maintains a private/public encryption key to allow pairing with an address and record signed trading with distributed ledger.

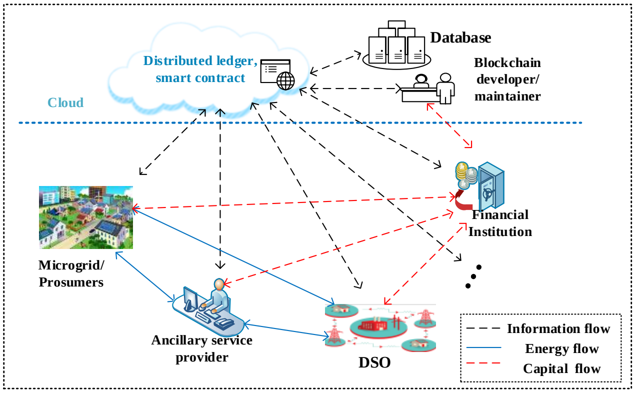

Fig. 1 Blockchain-based ecosystem diagram

In the ecosystem, energy transaction mainly occurs between MGs and DSO. Various entities perform their respective roles in the architecture to facilitate the energy transaction. Their functions and model are described as follows.

1) *Microgrid (MG) model*

The residential MG with renewable energy sources (RESs) and storage are the main participants since they have the capability for energy producing and energy consumption. We uses the functional concept of microeconomics to build a consumption utility model of residential MG. we refer [3] to define the consumption utility $U(x_i^t,\omega_i^t)$ as a quadratic function with marginal utility decreasing:

$$U(x_i^t,\omega_i^t)=\begin{cases}\omega_i^t x_i^t-\dfrac{\alpha_0}{2}(x_i^t)^2 & if \quad 0\le x_i^t\le\dfrac{\omega_i^t}{\alpha_0}\\[2ex] \dfrac{(\omega_i^t)^2}{2\alpha_0} & if \qquad x\ge\dfrac{\omega_i^t}{\alpha_0}\end{cases} \tag{1}$$

where x_i^t represents the energy consumption amount of MG-i at time slot t, and the parameter ω_i^t characterizes the MG's electricity consumption behavior, the parameter α_0 set in advance represents the uniform conditions. The x_i^t is constrained between a minimum and a maximum power level as:

$$x_i^{\min}\le x_i^t\le x_i^{\max} \tag{2}$$

Convex quadratic cost functions of RESs and storage are established as (3) [12]:

$$\begin{aligned}CR(y_i^t)&=\sum_t^T[\alpha_1(y_i^t)^2+\beta_1 y_i^t]\\ CS(r_i^t)&=\sum_t^T[\alpha_2(r_i^t)^2+\beta_2 r_i^t]\end{aligned} \tag{3}$$

where r_j^t is feed-in power of RES to grid, α_1 is a constant coefficient of RES cost function, β_1 represents average maintenance cost of RES. α_2 and β_2 are constant coefficients of storage cost, r_i^t is the charge/discharge power of the storage of the MG i at time slot t. The constraint of y_i^t is:

$$0\le y_i^t\le g_i^t+\sum_{t=0}^{t-1}b_i^t \tag{4}$$

where g_i^t is the RES output of MG i at time slot t. the b_i^t is the amount of energy in storage devices. Moreover, the model of amount of energy in storage b_i^t is

$$\begin{aligned}&b_i^t=\sum_{t=0}^{t}r_i^t\\ &-r_i^{\min}\le r_i^t\le r_i^{\max}\end{aligned} \tag{5}$$

where r_i^t is the charged energy amount ($r_i^t\ge 0$) or discharged energy amount ($r_i^t\le 0$) of prosumer i at time slot t. $r_i^{\max}$ and $r_i^{\min}$ denote the charge/discharge rate of storage of prosumer i. We denote the dynamic tariff as p_{tariff}^t , the total revenue of MG is summarized as:

$$F_{MG,i}^t=U(x_i^t,\omega_i^t)+p_{tariff}^t y_i^t-CR(y_i^t)-CS(r_i^t)-p_{retail}^t(x_i^t+r_i^t) \tag{6}$$

2) *Distribution system operator (DSO) model*

We define the revenue is the incomes minus the costs. In the transaction process, the revenue of DSO include carbon emission income F_1 cited from [13], energy purchasing cost from the wholesale market F_2 , retail electricity income F_3 , and purchasing RES cost F_4 . Therefore, the total revenue model of the DSO is

$$\begin{aligned}&F_{DSO}=F_1(Q^t)-F_2(E^t)+F_3(E^t,Q^t)-F_4(p_{tariff}^t,Q^k)\\ &F_1(Q^t)=a(Q^t)^2+bQ^t\\ &F_2(E^t)=p_{wholesale}E^t\\ &F_3(E^t,Q^t)=p_{\text{retail}}^t(E^t+Q^t)\\ &F_4(p_{tariff}^t,Q^k)=p_{tariff}^t Q^k\end{aligned} \tag{7}$$

where the Q^t is the purchasing RES amount at time slot t. a and b are the coefficients of carbon income. $p_{wholesale}$ and E^t represent the energy purchasing price and amount from wholesale market. p_{retail}^t and p_{tariff}^t are the dynamic retail price and tariff of RES to grid respectively.

3) *Other participants in the ecosystem*

- Financial institution: the financial institution (such as bank) settles the result of contracts according to the credible records and smart contacts. The financial institution can also make cryptocurrency exchange in the ecosystem.

- Ancillary service provider: for the efficient and economical energy usage and consumption, the ancillary services (such as load aggregation, demand response, transactive energy, etc.) could be carried out if necessary.

- Block chain developer & maintainer: the responsibility is for the cloud data storage and the blockchain development and maintenance. The data access of participants and smart contact enables efficient energy transaction and management in the ecosystem.

The revenue of above participants could be allocated as an appropriate share of the total transaction amount in the ecosystem, which is out of scope in this work.

B. Deployment of distributed ledger and smart contract

Blockchain technology mainly operates under two fundamental concepts namely Distributed Ledger and Smart Contracts, which can be deployed in the cloud to give access to the data to all participants as shown in Fig.1. In the ecosystem, the smart contract implementation requires several certain developer tools such as Ethereum, Hyperledger Fabric for smart contracts, Truebit for computation, ZeppelinOS for security, and Mattereum for legal contract execution [14]. The transaction interactions are stored on the distributed ledger, participant thus can be confident of the recorded data in which their history behaviors cannot be tampered. The smart contract contains two aspects, one is smart contract code and the other is smart legal contact. The smart code is like software written in a programming language. The smart legal contract can simulate contract logic in the real world and be self-executable.

III. ENERGY TRANSACTION FRAMEWORK IN ECOSYSTEM

A. Optimization Problem of Energy Transaction

The transaction operation between MGs and DSO can be modeled as an optimization problem which can be implanted by each participant in the energy transaction independently or in certain nodes selected as integrators. Each MG consumes x_i^t kWh power, charged or discharged amount r_i^t and feedback y_i^t kWh RES to grid at time slot t. In the transaction process, the real-time retail price and tariff price decision is formulated as a convex optimization problem which seeks the maximize social welfare including all the MGs' revenue (6) and DSO's revenue (7). Therefore, the optimal objective of the energy transaction is formulated as:

$$maximize \sum_{i=1}^{N}(U(x_i^t,\omega_i^t)-CR(y_i^t)-CS(r_i^t)+F_1(Q^t)-F_2(E^t) \quad (8)$$

Subject to

$$\begin{aligned}&\sum_i^N (x_i^t-y_i^t+r_i^t)\le E^t\\&\sum_i^N y_i^k = Q^t\end{aligned} \quad (9)$$

B. Lagrangian Dual Decomposition

To solve problem (8), we reconstructed the constrains (9) by applying Lagrangian multipliers as:

$$\begin{aligned}L(\varphi,\lambda^t,\mu^t)=&\sum_i^N\sum_t^T(U(x_i^t,\omega_i^t)-CR(y_i^t)-CS(r_i^t))\\&+\sum_t^T(F_1(Q^t)-F_2(E^t))\\&-\sum_t^T\lambda^t(\sum_i^N(x_i^t-y_i^t+r_i^t)-E^t)\\&+\sum_t^T\mu^t(\sum_i^N y_i^t-Q^t)\end{aligned} \quad (10)$$

where $\lambda=\left\{\lambda^t \mid t\in T\right\}$ and $\mu=\left\{\mu^t \mid t\in T\right\}$ are Lagrangian multipliers. The Lagrangian (10)with relaxed constrains can be rewritten as:

$$\begin{aligned}L'(\varphi,\lambda^t,\mu^t)=&\sum_i^N\sum_t^T(U(x_i^t,\omega_i^t)-CR(y_i^t)-CS(r_i^t))\\&-\lambda^t(x_i^t-y_i^t+r_i^t)+\mu^t y_i^t)\\&+\sum_t^T(F_1(Q^t)-F_2(E^t)+\lambda^t E^t-\mu^t y_i^t)\end{aligned} \quad (11)$$

Moreover, a Lagrangian dual function is introduced as:

$$\begin{aligned}k(\lambda^t,\mu^t)&=\max L'(\varphi,\lambda^t,\mu^t)\\&=\sum_i^N\max\sum_t^T(U(x_i^t,\omega_i^t)-CR(y_i^t)-CD(r_i^t))\\&\qquad-\lambda_t(x_i^t-y_i^t+r_i^t)+\mu_t y_i^t)\\&\quad+\max\sum_t^T(F_1(Q^t)-F_2(E^t)+\lambda^t E^t-\mu_t y_i^t)\end{aligned} \quad (12)$$

For simplicity, formula (12) can be rewritten as:

$$k(\lambda^t,\mu^t)=\sum_i^N\theta_i(\lambda^t,\mu^t)+\sigma(\lambda^t,\mu^t) \quad (13)$$

where

$$\begin{aligned}\theta_i(\lambda^t,\mu^t)=\max&\sum_t^T(U(x_i^t,\omega_i^t)-CR(y_i^t)-CS(r_i^t))\\&-\lambda_t(x_i^t-y_i^t+r_i^t)+\mu_t y_i^t)\end{aligned} \quad (14)$$

$$\sigma(\lambda^t,\mu^t)=\max\sum_t^T(F_1(Q^t)-F_2(E^t)+\lambda^t E^t-\mu_t y_i^t) \quad (15)$$

Here the Lagrange dual function (13) is separated into a MGs' subproblem (14) and a DSO subproblem (15). Furthermore, if the real-time retail electricity price p_{retail}^t is set as λ_t, subproblem (14) is identical to the MG revenue function (6). Meanwhile, if the real-time tariff of RES to grid p_{tariff}^t is set as $\lambda_t+\mu_t$, the subproblem (15) is identical to the DSO function (7).

C. Shadow Prices Solution and Transaction Execution

The convex dual problem can be regarded as a bilevel program, where the DSO formula (15) is upper-level problem, and the MG formula (14) is the lower-level problem. The interaction between MGs and DSO is used for solving shadow prices. The problem is finally formulated as bilevel program with Nash equilibrium, which can be solved with Mathematical Program with Equilibrium (EMP) solver of GAMS software. The full flow chart of the energy transaction execution process in the blockchain-based ecosystem is shown as Fig.2

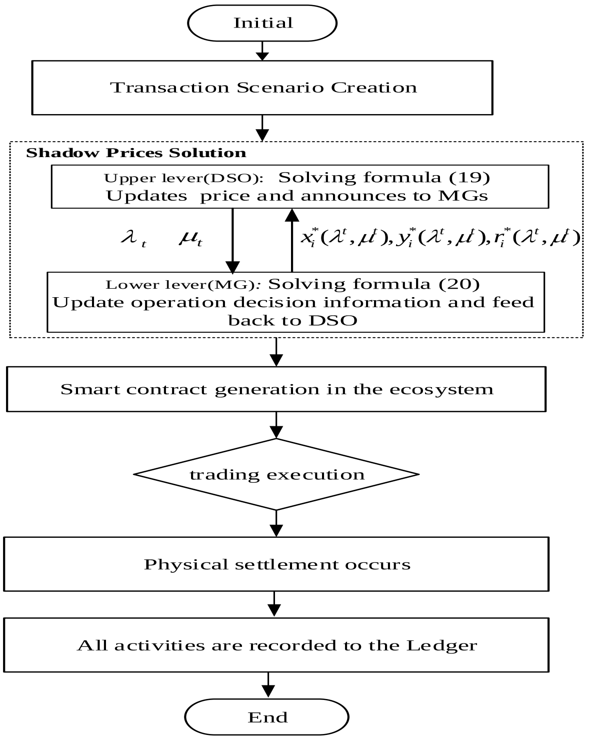

Fig. 2. Flow Chart of Transaction Execution with Interaction Loop

As described in Fig.2, in a specific transaction scenario, the transaction price and amount between MGs and DSO will be calculated in the smart contract after the interaction process. The participant connected to the ledger performs the task of validating and relaying transactions in a given time. If the deal term is determined, the transaction will be executed. Then, the physical settlement in terms of energy consumption and generation occurs with payment initiated immediately. Meanwhile, all activities are recorded to the distributed ledger.

IV. IMPLEMENTATION EVALUATION

In this section, we present the transaction execution results with the proposed dynamic real-time price algorithm in the blockchain-based ecosystem. In the ecosystem, we assume that there are 80 residential MGs, each MG equipped with a 20kW PV and a 13.5 kW Tesla Powerwall 2 storage [15]. The output of PV g_i^t is assumed as Fig.3 [16], the MGs' utility parameter α_0 is set to 0.3, and the normalized utility parameter ω_i^t ($0 < \omega_i^t \le 1$) representing the MGs' consumption behavior refers to the neural network regression results in [13], which is shown as Fig.4. The cost parameters of RES and storage are simply set as α_1=0.98, β_1=0, α_2=1, β_2=0 respectively. In this case study, the transmission losses are negligible. During the energy transaction process, the smart meter undertakes the communication task.

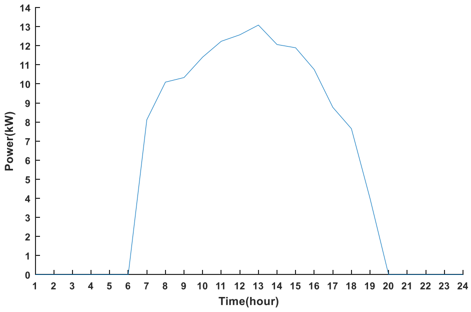

Fig. 3 PV's power output in one day

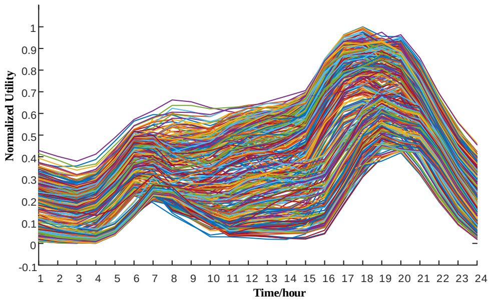

Fig. 4 MGs' Power Consumption behavior in one day

The proposed real-time transaction price can benefit both the MGs and DSO in term of revenue for MGs and load flattening for DSO. The simulation results for the average revenue of MGs for the proposed price as well as fixed price is shown in Fig.5. DSO does not only care the economic performance, but also theload profile which influence the usage of the network facility. As shown in Fig.6, the proposed transaction price algorithm can reduce the peak-to-average ratio of the grid compared to the fixed transaction price.

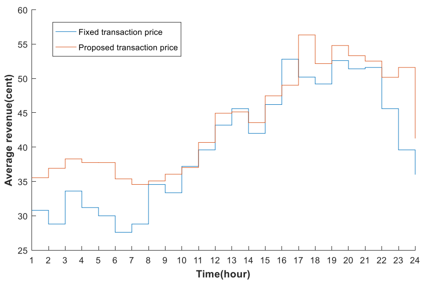

Fig. 5 Comparation of average revenue of MGs in one day

Fig. 6 Comparation of peak-to-average ratio of the grid

The results demonstrate that our dynamic price-based energy transaction make the benefit for both MGs and DSO.Moreover, the additional remarkable benefit of the emerging blockchain technology is that it can contribute to the reliable and auditability transaction in the proposed ecosystem.

V. CONCLUSION

This paper provided an insight into the formation of energy ecosystems based on emerging blockchain technology for microgrid application. Taking the vision of the energy transaction between MGs and DSO, the dynamic transaction prices were found through dual optimization problem. The distributed ledger and smart contract as the main component of the block chain technology deployment played important roles in this energy transaction process. It was also demonstrated that the revenue allocation and transaction process of entities in the ecosystem could be executed with the aid of blockchain technology, which ensures the secure inquiry of transaction records and the automatic performance of contracts.

In the future, more diverse participants will be connected to the ecosystem, and thus the according trading mechanism and market theory applied to the energy transaction is a future research direction. Moreover, as blockchain technology is still getting maturing, it takes more effort across the disciplinesto actually verify if this emerging technology could deliver on its promises to make all participants of the ecosystem more efficient and security.

REFERENCES

[1]B. A. Vaccaro, M. Popov, D. Villacci, and V. Terzija, "An Integrated Framework for Smart Microgrids Modeling , Communication , and Verification," *Proc. IEEE*, vol. 99, no. 1, pp. 119–132, 2011.

[2]C. Li, S. K. Chaudhary, M. Savaghebi, J. C. Vasquez, and J. M. Guerrero, "Power Flow Analysis for Low-voltage AC and DC Microgrids Considering Droop Control and Virtual Impedance," *IEEE Trans. Smart Grid*, 2016.

[3]P. Samadi, A.-H. Mohsenian-Rad, R. Schober, V. W. S. Wong, and J. Jatskevich, "Optimal Real-Time Pricing Algorithm Based on Utility Maximization for Smart Grid," *2010 First IEEE Int. Conf. Smart Grid Commun.*, pp. 415–420, 2010.

[4]J. Yue, Z. Hu, A. Anvari-Moghaddam, and J. Guerrero, “A Multi-Market-Driven Approach to Energy Scheduling of Smart Microgrids in Distribution Networks,” Sustainability, vol. 11, no. 2, p. 301, 2019.

[5]M. H. Yaghmaee, “Incentive Cloud-based Demand Response Program U sing Game Theory in Smart Grid,” 21 st Electr. Power Distrib. Conf. May 2016, Karaj- Alborz- Iran Incent., no. May, pp. 153–160, 2016.

[6]J. Jose, K. Kannoorpatti, B. Shanmugam, S. Azam, and K. C. Yeo, “A critical review of Bitcoins usage by cybercriminals,” 2017 Int. Conf. Comput. Commun. Informatics, ICCCI 2017, 2017.

[7]A. Hahn, R. Singh, C. C. Liu, and S. Chen, “Smart contract-based campus demonstration of decentralized transactive energy auctions,” 2017 IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. ISGT 2017, 2017.

[8]Y. Xu, M. Wu, Y. Lv, and S. Zhai, “Research on application of block chain in distributed energy transaction,” in Proceedings of 2017 IEEE 3rd Information Technology and Mechatronics Engineering Conference, ITOEC 2017, 2017.

[9]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 Trans. Ind. Informatics, vol. 13, no. 6, pp. 3154–3164, 2017.

[10]E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, “Designing microgrid energy markets: A case study: The Brooklyn Microgrid,” Appl. Energy, vol. 210, pp. 870–880, 2018.

[11]P. Ledger, “We believe empowering individuals and communities to co-create their energy future will underpin the development of a power system that is,” 2017.

[12]N. Li, L. Chen, and S. H. Low, “Optimal demand response based on utility maximization in power networks,” Power Energy Soc. Gen. Meet., pp. 1–8, 2011.

[13]J. Yue, Z. Hu, R. He, X. Zhang, J. Dulout, and C. Li, “Cloud-Fog Architecture Based Energy Management and Decision-Making for Next-Generation Distribution Network with Prosumers and Internet of Things Devices,” 2019.

[14]M. Yu, “Distributed Decision-making for Energy Trading between Agent-based Dual Microgrids.”

[15] “Powerwall | The Tesla Home Battery.” [Online]. Available: https://www.tesla.com/powerwall. [Accessed: 31-Dec-2018].

[16]J. Yue, Z. Hu, C. Li, J. C. Vasquez, and J. M. Guerrero, “Economic power schedule and transactive energy through an intelligent centralized energy management system for a DC residential distribution system,” Energies, vol. 10, no. 7, 2017.