Applying blockchain technology to decentralized operation in future energy internet

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Applying Blockchain Technology to Decentralized Operation in Future Energy Internet

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Abstract—This paper presents the potential application of the blockchain technology in future Energy Internet operation, which would be more decentralized and self-executing. A blockchain system could solve several problems in the newly emerged scenarios with the support of the consensus mechanism, encryption methods and validation mechanism. Applying blockchains in decetralized operational framework of energy internet will bring the system with a more secure, flexible and low-cost operational solution.

Keywords*—*blockchain; smart grid; Energy Internet; decentralized system

I. Introduction

THE increasing demand for reliable, sustainable, renewable and economical energy has been calling for an new paradigm of cyber-physical energy system, namely the Energy Internet [1]. Energy Internet is a complex concept which could be interpreted as a multiple energy (*e.g.* heating, cooling, electricity, gas, transportation, etc.) coupling system, which is deeply equipped with Information Communications Technology (ICT) and associated with the idea of sharing economy. The rapid development and evolution has been attracting a series of newly emerged technologies into the future energy blueprints, among which the blockchain technology is one of the most promising fields.

Blockchains are attracting increasing attention with a series of applications in various fields since Satoshi [2] proposed the Bitcoin framework based on blockchains system in 2009. With the decentralized nature of blockchains, it enables applications without trusted intermediary to be running with the support of cryptography (or digital signatures), honest nodes and its consensus mechanism. Practically, blockchains have a series of applications in various fields including: financial and banking system [3], Internet of Things (IoT) [4], and in public services of government [5]. The most well-known and commonly-accepted application is the Bitcoin, the economy and transaction network of the decentralized digital currency [6]. Beyond these application, there might have been other related fields in which the potential of blockchains could be utilized as an trustworthy, decentralized and unforgeable ledger system.

In addition to the mainstream utilization in the financial, banking and transaction sectors, the technology could also solve the pain points in decentralized operation of future Energy Internet. The purpose of this paper is to provide a tentative outlook with the potential of blockchain technologies when applied to decentralized operations in an Energy Internet environment. This work aims to be a reference and initial exploration to consider interactions between the two areas of blockchains and future energy systems.

The remainder of this paper is organized as follows. Section II presents the future blueprints and main features of decentralized operation in Energy Internet. Section III describe the potential application of blockchain technology in decentralized operations of Energy Internet. Then, case studies are carried out in Section IV by applying blockchains to decentralized energy prosumer network. Shortcomings of the technology in Energy Internet applications are described in Section V and concluding remarks are given in Section VI.

II. Future Blueprints of Decentralized Operation in Energy Internet

In future blueprints of smart energy system, increasing penetration of prosumers with distributed energy resources (DER) such as gas turbines (GT), wind power (WP), photovoltaic (PV), electric vehicles (EV) and other devices should be a undeniable tendency. S. Grijalva *et al.* [7] defined a prosumer as an economically motivated entity with the ability to consume, produce, and store power, which will also be a mainstream form of participants in future energy system. The energy prosumer network of energy internet would have the following developing trends:

Decentralized - An energy system with a large quantity of prosumers could no longer be working under a conventional

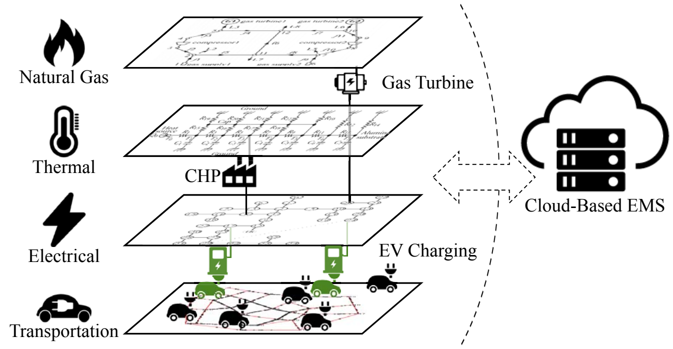

Fig. 1. Sample of an Energy Internet system with cloud-based EMS

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centralized energy management system (EMS) [8]. Thus, a decentralized method is essential considering the large amount of controllable devices and elements.

Multi-energy integrated - Energy prosumers in an energy internet will consist of various types of energy carriers, including but not limited to electricity, natural gas, heat and multiple energy storage systems [9], which could belongs to different operational entities.

Cloud-based EMS - In this multi-energy system scenario, future cloud-based EMS could be introduced for different levels of diversified participants [10]. The mutual cloud-based dispatch problem in a plug & play operational mode could bring up authority-related problems such as modification on optimization model and access to the dispatch plan.

An probable example of an integrated Energy Internet system is shown in Fig. 1. The multi-energy system is integrated through EV charging, gas turbine (GT), combined heat and power (CHP) facilities or other devices. It should be noted that these interdependent networks usually belong to different entities or independent system operator (ISO). Energy management applications such as scheduling and control could be hard to be implemented by a single operator in practice. Thus, a cloud-based EMS could be undertaking all the related complex data processing works and be solving the complicated optimization problems. Moreover, the large amount of energy prosumer nodes could hardly agree on one operational model or optimization strategy without a single coordinate center that takes control of nodes from different networks. This consensus problem is originated from the fact that these coupled networks should be working according to one schedule while they are owned by different entities. Consequently, a decentralized operational framework is needed considering the multiple ownership of the integrated energy system.

III. Applying Blockchains in Decentralized Operational Framework of Energy Internet

A. Basic features of blockchain technology

A blockchain is a distributed, collectively maintained and reliable database (ledger system) with a continuously extending chain of data records (blocks), where newly added blocks are authenticated across the distributed network before attaching to the chain. The idea that distributed peer-to-peer network could be working without relying on a trusted third party were paid close attention and were discussed heatedly. With the decentralized nature of blockchains, it enables applications without trusted intermediary to be running with the support of cryptography (or digital signatures), honest nodes and its consensus mechanism. Generally, the advantages of the blockchain technology could meet the essential needs and challenges of future energy consumption environment in **consensus**, **flexibility** and **secruity** by establishing a decentralized and secure information network.

Consensus - The blockchain technology allow for an open group of peers to reach consensus in a decentralized way. Every single node is involved in the mutually maintenance of the data. This is extremely important for scheduling and optimization problem in multi-energy system, where prosumer nodes should be provided with proper access to modify the mutual system model. What's more, prosumers can form electricity transactions between each other without the need of involving a third party due to the consensus algorithm of blockchain, which reduces the transaction fee. Besides, private blockchains (permissioned blockchains), which can reduce the consensus time and allow more modifications to be made in a certain period, could be used in the decentralized operational framework.

Flexibility - No control center is needed in the decentralized system to face the challenges of flexibility in network topology, energy flow and prosumers' ability to plug-in/off. Every equal single node in the decentralized system could create a block or determine with absolute certainty whether a block is valid, which could allow the sharing of local information securely among all nodes in the network. Consequently, the system could have the advantages of high flexibility in a plug & play mode.

In addition, the flexibility of controlling mode is also concerned. This framework could be working in different modes according to dominant nodes selected in the system. For example, a system with only one central node (working as the control center) is working with the monocentric mode, a system with several selected central controlling nodes is working with the partial decentralized polycentric mode, a system completely without selected central nodes is working with the fully decentralized mode.

Security - The method could potentially work with private blockchains that may have limited access available only to properly authenticated prosumers. The key to a blockchain's security is called a hash, which is a bit of cryptographic mathematics that makes the links between blocks virtually unbreakable. The system is protected by cryptography and thus could ensure system security in that other intruders could not inject malicious data directly into the blockchain. Moreover, altering or rewrite a history block would require controlling more than 51% of the network, which could be a prohibitively high cost in the decentralized system.

In conclusion, the blockchain technology could achieve a decentralized, transparent and opening environment energy system with high security and reliability.

B. Applications of blockchain technology from energy perspective

Regarding energy transactions, in the TransActive Grid [11] and the Grid Singularity [12] concept, tokens were introduced as measuring units for electricity transferring and blockchain transactions. This combination of blockchains with Internet of Things (IoT) (*e.g.* smart meters) could probably transform a conventional "top-down energy system" into a decentralized and self-executing energy system. Slock.it [13] partnered with energy giant RWE by introducing digital wallets and smart contracts for electric vehicles (EVs) charging. Filament [14] applied wireless sensor network for smart grid monitoring through a blockchain network from the prospect of Internet of Things (IoT). NRGcoin [15] allowed prosumers to produced renewable energy and trade locally by using this decentralized digital currency. A application case of blockchain-based green certificates was introduced in [16]. A localized peer-to-peer transaction model aimed at EV energy trading is demonstrated in [17].Besides, transaction security in decentralized energy trading system was focused in [18] with security and performance analysis and evaluation.

Apart from most common utilization in trading, financing and IoT, some reseachers also found cooperative combinations of blockchain technologies with smart energy system. Yang *et. al.* [19] summarized the state-of-art on blockchains in energy internet with considerations of energy transactions and other typical utilizations. Moreover, a hybrid blockchain data storage architecture and its applications in Energy Internet were discussed in [20]. Zeng *et. al.* [21] proposed a blockchain framework for distributed decision making and cooperative autonomous operation of energy internet.

C. Applying blockchains to decentralized energy prosumer network

Beyond all the previous studies, this paper emphasizes the role of blockchain technologies in operations and control of future Energy Internet framework. In such a system, every prosumer node from different networks was average and equal with no single node could overpower the others. These nodes are operating in highly-interdependent networks when supporting the multi-energy system. Besides, the fully decentralized controlling framework should be working in a public cyber environment with a cloud-based EMS. Consequently, it is of great importance for the cloud-based EMS to have the same description of the power flow model and operational constraints of the power resources.

In the decentralized framework, there should be an effective and trusted way for global information (*e.g.* model modifications) to be broadcasted and verified. The aforementioned information could only be observed or noticed by a single unit in the decentralized system but may be essential to a larger set of concerning units, which may include:

- plug-in or plug-off energy elements (*e.g.* DERs) in a plug & play mode
- changes in network topology (line outage or reconfiguration) or component parameters
- contingency or fault detection in physical or cyber systems
- changes in the working conditions/constraints of the DGs or operational planning of the devices
- other global information to be broadcast

Blockchain technology could serve as a secure and flexible way to establish a trusted information connection with the system, where the system model and optimization problem should be accessed with trusted prosumer nodes in a flexible plug & play way. Take Fig. 2 as an example, a decentralized energy network contains multi-directional energy flow and information exchange in an open network environment. When a prosumer node containing DERs and ESSs was connected to or disconnected from the system, information including the exterior characteristics, topology changes, operational model and constraints should be shared among all participants for operational optimization and smart contracts in energy transactions. The detailed operational procedures will be discussed in the next section.

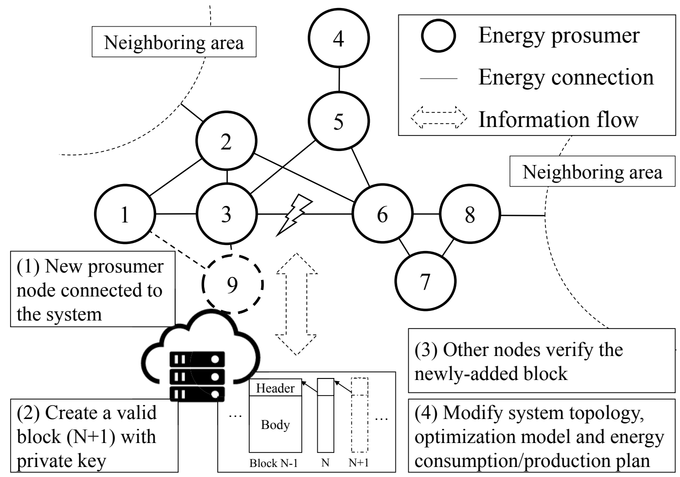

Fig. 2. Structure of energy network and information exchange in decentralized framework

IV. Case Studies

This section will explain the details of applying blockchain technology to decentralized operation in an Energy Internet system.

A simplified case is given by Fig. 2. As node 9 becomes connected, a block containing the aforementioned sharing information will be created and attached to the chain by this newly-added distributed node in the blockchain network. A time-stamp and a link to the previous block are contained in this newly created block. Other nodes would read the data from this block after the verification process and then update the local optimization model. Next, the optimization problem will be recalculated on the cloud server and local energy consumption/production plan will be modified. This process could ensure the consensus of the global information in each of the system participants through the decentralized framework. Basically, it is the blockchain technology that ensure the security and flexibility of the trusted information interaction and model maintenance of the system in an open access network environment.

A more detailed case is shown in Fig. 3. The integrated energy system with a decentralized operational framework is modelled. The electric power network contains 7 nodes with 2 GTs, 2 PVs, 1 ESS, 2 EVs and 3 common loads. The natural gas system is connected to the electric power system through gas turbines.

To list a few possible model modification on the blockchain of cloud-based EMS, several occasions in system operations are taken as examples.

1) Line outage or reconfiguration

In the system, the topology of the electric power system could change in cases where line outage or reconfiguration happens. A block containing actions of network switches will be added to the blockchain to record the changes in network topology.

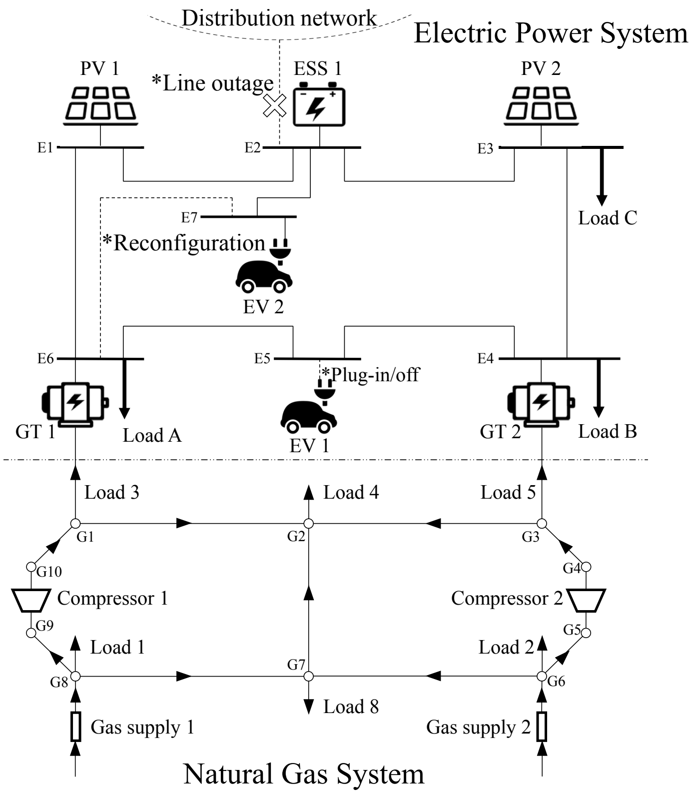

Fig. 3. Structure of a Simplified Sample Decentralized Energy Internet

2) Device connected or disconnected

This happens when domestic DER devices are connected to or disconnected from the electric power system. Take a solar panel for example, the node should be updating the detailed model of its device for the cloud-based EMS, which are listed below:

$\overline{P}/\underline{P}$	upper/lower limit of active power
$\overline{Q}/\underline{Q}$	upper/lower limit of reactive power
$\overline{\phi}/\underline{\phi}$	upper/lower limit of power factor
$\Pi(\mu, \Sigma, S)$	probability distribution uncertainty set

The detail of probability distribution set is discussed in [22] with a distributionally robust optimization method.

3) EV plug-in or plug-off

EVs are considered as energy storage devices with temporal and spatial flexibility. Apart from the physical limits of the batteries (*e.g.* capacity, state of charge SoC, etc.), parameters related to users' traveling behaviors should also be considered, which are listed below:

$SoC_u^{a/d}$	SoC on arrival / expected on departure of EV u
B_u	battery capacity (kWh)
$\overline{P}_u^{c/d}$	upper limit of charging/discharging power (kW)
$\eta_u^{c/d}$	charging/discharging efficiency
D_u	estimated energy demand (kWh)
ET_u	estimated charging time before departure

4) Compressor

Parameters of compressors in a natural gas system may include the following aspects: maximum/minimum inlet flow, maximum outlet pressure, maximum inlet pressure, range of compression ratio, etc. The coupling analysis of the natural gas and electricity coupled networks and the detailed model settings are discussed in [23]. The different operational mode of a compressor (fixed flow, fixed inlet/outlet pressure, fixed compression ratio) should be considered when establishing the optimization model.

Whenever the system model is changed, the optimization model on the cloud server should be modified. Authorized access to the mutually maintained data for each prosumer nodes in the energy internet is the basis of a secure and reliable operational framework. Here, blockchains could be combining openness of the Internet with the security of cryptography, where decentralized verification is made by the consensus of multiple users. In conclusion, the blockchain technology is an effective solution to ensuring flexibility and security of decentralized operations in Energy Internet.

V. Shortcomings of Blockchains in Smart Grid Applications

Despite the potential applications discussed previously, there would still be several shortcomings for the blockchain technology to be applied to extremely large scale energy internet in the future. Namely:

- limited maximum number of occurrences and communication efficiency due to verification mechanism
- participants lack of direct economical benefits from the decentralization process
- potential cyber-physical contingency or even catastrophic cascade of failures due to the close decoupled network structure
- the leak of private key could be used by attackers and thus the security of the system might be threatened
- large amount of data requires high level of storage capacity of nodes in the system, which may be expensive

While there is still room for improvements, it should be noted that the blockchain technology is in its early phases and will experience upgrades or even revolutionary advancement in the future.

VI. Conclusions

In this article, the applications of blockchain technology in future vision energy internet operation is introduced.

Blockchains could promote a consensus among the decentralized institutions of various energy entities. A business ecosystem with multiple centers could also be formed during this alliances process, which is in perfect accord with the features of Energy Internet. This technology could serve as an effective method for information sharing and model updating in a decentralized operational framework with a cloud-based EMS platform. In general, despite the currently existing drawbacks, there is a bright future with significant potential in combinations of blockchain technologies and Energy Internet.

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REFERENCES

[1] X. Yu and Y. Xue, "Smart Grids: A Cyber-Physical Systems Perspective," *Proceedings of the IEEE*, vol. 104, no. 5, pp. 1058–1070, 2016.

[2] S. Nakamoto, "Bitcoin: A peer-to-peer electronic cash system," *Consulted*, 2009.

[3] W. T. Tsai, R. Blower, Y. Zhu, and L. Yu, "A system view of financial blockchains," in *2016 IEEE Symposium on Service-Oriented System Engineering (SOSE)*, Mar. 2016, pp. 450–457.

[4] K. Christidis and M. Devetsikiotis, "Blockchains and smart contracts for the internet of things," *IEEE Access*, vol. 4, pp. 2292–2303, 2016.

[5] M. Walport, "Distributed ledger technology: beyond block chain," UK Government Office for Science, Jan. 2016, [Online]. Available: https://www.gov.uk/government/publications/distributed-ledger-technology-blackett-review.

[6] M. Lischke and B. Fabian, "Analyzing the bitcoin network: The first four years," *Future Internet*, vol. 8, no. 1, 2016.

[7] S. Grijalva and M. U. Tariq, "Prosumer-based smart grid architecture enables a flat, sustainable electricity industry," in *Innovative Smart Grid Technologies (ISGT), IEEE PES*, Jan. 2011, pp. 1–6.

[8] W. Zheng, W. Wu, B. Zhang, H. Sun, and Y. Liu, "A fully distributed reactive power optimization and control method for active distribution networks," *IEEE Transactions on Smart Grid*, vol. 7, no. 2, pp. 1021–1033, Mar. 2016.

[9] M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klockl, G. Andersson, and K. Frohlich, "Energy hubs for the future," *IEEE Power and Energy Magazine*, vol. 5, no. 1, pp. 24–30, Jan 2007.

[10] S. Xin, Q. Guo, J. Wang, C. Chen, H. Sun, and B. Zhang, "Information masking theory for data protection in future cloud-based energy management," *IEEE Transactions on Smart Grid*, vol. PP, no. 99, pp. 1–1, 2017.

[11] "Transactive grid," [Online]. Available: http://transactivegrid.net/.

[12] "Grid singularity," [Online]. Available: http://gridsingularity.com/.

[13] "Slock.it," [Online]. Available: https://slock.it/.

[14] "Filament," [Online]. Available: https://filament.com/.

[15] M. Mihaylov, S. Jurado, N. Avellana, K. V. Moffaert, I. M. de Abril, and A. Now, "NRGcoin: Virtual currency for trading of renewable energy in smart grids," in *11th International Conference on the European Energy Market (EEM14)*, May 2014, pp. 1–6.

[16] F. Imbault, M. Swiatek, R. de Beaufort, and R. Plana, "The green blockchain: Managing decentralized energy production and consumption," in *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I CPS Europe)*, June 2017, pp. 1–5.

[17] 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. PP, no. 99, pp. 1–1, 2017.

[18] N. Z. Aitzhan and D. Svetinovic, "Security and privacy in decentralized energy trading through multi-signatures, blockchain and anonymous messaging streams," *IEEE Transactions on Dependable and Secure Computing*, vol. PP, no. 99, pp. 1–1, 2016.

[19] D. Yang, X. Zhao, Z. Xu, Y. Li, and Q. Li, "Developing status and prospect analysis of blockchain in energy internet," *Proceedings of the CSEE*, vol. 37, no. 13, pp. 3664–3671, 2017.

[20] L. Wu, K. Meng, S. Xu, S. Li, M. Ding, and Y. Suo, "Democratic centralism: A hybrid blockchain architecture and its applications in energy internet," in *2017 IEEE International Conference on Energy Internet (ICEI)*, April 2017, pp. 176–181.

[21] M. Zeng, J. Cheng, Y. Wang, Y. Li, Y. Yang, and J. Dou, "Primarily research for multi module cooperative autonomous mode of energy internet under blockchain framework," *Proceedings of the CSEE*, vol. 37, no. 13, pp. 3672–3681, 2017.

[22] X. Chen, W. Wu, B. Zhang, and C. Lin, "Data-driven dg capacity assessment method for active distribution networks," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3946–3957, Sept 2017.

[23] Z. Qiao, Q. Guo, H. Sun, Z. Pan, Y. Liu, and W. Xiong, "An interval gas flow analysis in natural gas and electricity coupled networks considering the uncertainty of wind power," *Applied Energy*, vol. 201, pp. 343 – 353, 2017.