Accepted for presentation at 2019 IEEE PES GTD Grand International Conference and Exposition Asia, Mar. 19-23, 2019, Bangkok, Thailand

Blockchain-based Negawatt Trading Platform: Conceptual Architecture and Case Studies

Zejia Jing, Manisa Pipattanasomporn and Saifur Rahman
Bradley Department of Electrical and Computer Engineering
Virginia Tech, Arlington, VA 22203, USA

Abstract - **Demand reduction, also known as Negawatts or negative watts, has emerged as another commodity that can be exchanged. This paper discusses conceptual architecture of a blockchain-based negawatt trading platform implemented on Hyperledger. Two trading scenarios are discussed. The first scenario involves negawatt trading between a demand response aggregator and buildings. The second scenario discusses negawatt trading among buildings to meet the contract shortfalls of buildings in the first scenario. Participants, assets, transactions and transaction flows of both scenarios are described, together with the smart contracts that describe how buyers and sellers are compensated for their negawatt exchange. Case studies are implemented and compared.**

Keywords - **Blockchain, Demand Response, Hyperledger, Negawatts, P2P trading.**

I. INTRODUCTION

Electrical energy (kWh) is typically bought and sold based on the amount of electricity generated. Demand reduction capability (kW) offered by building owners has emerged as another tradable commodity. Various demand reduction programs are being implemented to encourage peak demand reduction and reduce grid stress conditions in buildings. For instance, in Virginia, "Smart Cooling Rewards" allows homeowners to get an annual $40 credit in exchange of cycling their home's cooling system on some summer weekdays [1]. A contract between an electrical system operator and large commercial buildings has also been implemented. An example is the contract between PJM, Virginia's regional electric transmission grid operator, and Virginia Tech campus through the "Interruptible Load Reliability" program. Under this program, in June 2017, Virginia Tech reduced 7,000 kWh energy consumption and received a reward of $240,000 [2].

Although peak demand reduction can be achieved through load control, participants have to sacrifice their comfort [3]. Thus, a platform that enables negawatt trading among different participants based on their demand reduction capability is in need. This platform should also allow participants to select an acceptable temperature control bands based on their life style preference and value proposition.

Recently, the blockchain technology has emerged as a promising encryption ledger technology to record energy-related transactions at the distributed level. Several early-stage projects have already introduced the blockchain technology into energy trading market [4], such as Brooklyn Microgrid [5], Electron [6] and Solar Coin [7]. Most projects focus on energy trading of excess roof-top solar photovoltaic (PV).

The term "negawatts" is first invented by Amory Lovins in 1989 at the Green Energy Conference in Montreal [8]. Since then, people began to realize that energy savings are another kinds of energy resources [9]. Negawatts is defined in this paper as the electric power saved by reducing energy consumption in one hour or demand reduction (kW) in one hour. Negawatts can be estimated by comparing the baseline electrical load (which can be estimated based on historical data [10]) and the measured electrical consumption after implementing selected control measures (e.g., adjusting HVAC set points, turning OFF lighting or others). Several papers in the literature discuss peer-to-peer (P2P) energy and negawatt trading issues. In [11, 12], the authors propose the model of P2P energy trading in an energy market for homes with PV. Authors in [13] discuss federalism and the administrative law of negawatts trading in the U.S. and demonstrate the feasibility of P2P negawatts trading market. Authors in [14, 15] propose the pricing design of distributed negawatt trading in a real-time electricity market with energy storage systems.

Because the concept of negawatt trading is new and no existing solution is being proposed to accomplish this, this paper explores the use of blockchain technology—an emerging distributed ledger technology that allows secure record keeping based on consensus—for securely recording such negawatts transactions. Specifically, the conceptual architecture of the negawatt trading platform using blockchain technology is presented. Two trading scenarios being explored include: (a) DRA (Demand Response Aggregator) trading network where a DRA is an entity that provides demand response services in buildings. The demand reduction amount is then aggregated as a bid in wholesale energy markets; and (b) P2P negawatt trading network where buildings exchange their negawatt to meet the contract shortfalls of other buildings.

Participants, assets, transactions, transaction flows and smart contracts of these trading networks are defined. The open-source Hyperledger fabric blockchain framework [16] has been used as the development environment for case study demonstration.

II. TYPE I: DRA NEGAWATT TRADING NETWORK

The DRA negawatt trading network has been developed as a blockchain-based business network to support negawatt transactions between a DRA (i.e., a negawatt buyer) and buildings (i.e., negawatt sellers). The conceptual architecture of this negawatt trading network is depicted in Fig. 1.

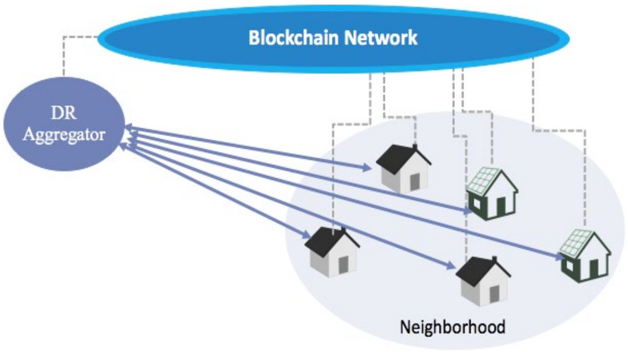

Fig. 1. Negawatt trading between DRA and buildings.

In this scenario, the DRA broadcasts a demand reduction signal to participating buildings. This signal comprises the required demand reduction amount and the time period, e.g., 50kW between 14:00 and 16:00. Once building owners receive the broadcasted message, they can respond with the negawatt amount (kW) and available negawatt period. One negawatt offer from a building may comprise available negawatt amount at different periods, e.g., 2kW between 14:00 and 15:00 and 3kW between 15:00 and 16:00. Finally, after the hourly market is cleared, the expected negawatts is traded by performing selected load controls, which can be accomplished using home/building energy management (HEM/BEM) software.

A. *Participants*

In this network, the negawatts trading is between the DRA and buildings. Hence, participants are of two types:

- Demand Response Aggregator (DRA)–who broadcasts the demand reduction request to buildings. In Hyperledger, DRA is defined using parameter 'Name', which is the ID of DRA.
- Building owners–who are willing to reduce their consumption when required. In Hyperledger, building owners are defined using the following parameters: 'balance (token)', 'buildingID', 'firstName' and 'lastName'. The 'balance' accounts for tokens in a building owner's wallet.

B. *Assets*

Assets are negawatt commodity called 'nWlisting' and digital currency called 'tokens'. Each 'nWlisting' is characterized by:

- 'listingID' represents the time period when demand reduction is requested.
- 'listingstate' comprises three kinds of the negawatts listing state: (i) FOR_SALE, indicating the bidding process is ongoing and offers from building owners are accepted; (ii) RESERVE_NOT_MET, indicating the bidding process is closed and the smart contract is taking effect; and (iii) CLOSE, indicating the bidding process is now closed. It means either the bidding process of this listing hour is not open yet or the bidding process has already ended.
- 'DRArequest' indicates the total demand reduction (kW) requested by a DRA during a specific hour.
- 'DRAOfferPrice' is used to represent the price that DRA is willing to pay to participants if the negawatts are successfully traded during that hour (tokens/kW).
- 'DRAunmet' indicates the demand reduction (kW) still in need after a transaction.
- 'DRApayment' indicates the total amount of tokens a DRA pays to negawatts providers during a specific hour.

'nWOffer', which is a transaction (defined below), is added as one of the parameters of 'nWlisting' after it is submitted by a building.

C. *Transaction & Transaction Flow*

The following three types of transactions are defined: RequestnWBroadcast, nWOffer, and ClosenWBidding.

- 'RequestnWBroadcast' - This broadcast message indicates that a DRA accepts negawatt offers from participating buildings during a certain hour. After this transaction is submitted, the corresponding hour listing's 'listingstate' will change from 'CLOSE' to 'FOR_SALE' making it available to accept bidding offers for that hour. This transaction is identified by: (i) 'listingID' as ID, e.g., {Nov11th14:00-15:00}, indicating this hour period is planned for demand reduction and negawatts can only be traded during the listed period; (ii) 'DRArequest' indicates the total demand reduction (kW) requested by a DRA during a specific hour; and (iii) 'DRAOfferPrice' is used to represent the price that DRA is willing to pay to participants (tokens/kW) if the negawatts are successfully traded during that hour.
- 'nWOffer' – In responding to the RequestnWBroadcast message, each participating building can submit a 'nWOffer'. A nWOffer comprises: (i) 'nWQuantity', which is the amount of negawatts to sell during a specific hour, identified by (ii) 'listingID'. Building owners can submit bids for more than one hour ahead by associating nWQuantity with corresponding 'listingID'; and (iii) 'buildingID' which identifies a building owner who submits the 'nWOffer'. Besides, the timestamp of every transaction is also recorded in distributed ledgers in the blockchain. After each successful trade, 'nWOffer' is appended with the remaining negawatts after the market is cleared, called 'nWUnsold'.

- 'ClosenWBidding' – This is a broadcast message identified by parameter 'listingID' as ID representing the auction ending signal. After the bidding is closed, the smart contract is initiated automatically to clear the market, and the token balance of each participant is updated.

D. *Smart Contract*

In this negawatt trading network, a smart contract defines how the market is cleared and how token balances are updated for participants.

In this particular DRA negawatt trading network, for each hour, the nWOffers by all negawatt sellers are sorted by their negawatts offer amount (from high to low). These sorted offers are aggregated until the negawatt requested by the DRA is fulfilled during a specific hour, which identifies successful negawatt sellers.

There are many ways to credit negawatt sellers. In this study, negawatt sellers are credited based on the DRAOfferPrice (note: this study uses the negawatts offer time and negawatts quantity to sort all offers. For further studies, double auction mechanisms can also be explored). Specifically, the token balance of each negawatt seller is updated by the amount of negawatt sold in one hour (kW) * DRAOfferPrice (tokens/kW). And the 'DRApayment' is also updated to reflect the total amount of tokens DRA pays to building owners.

E. *Case Study*

The case study of the DRA negawatt trading network has been carried out on the Hyperledger open-source blockchain platform. One DRA and five buildings are included in this case study. All five building owners are assumed to have the initial token balance of 500. These buildings are assumed to have a prior agreement with the DRA to sell their negawatt capability when requested.

Assuming that the DRA issues the 'RequestnWBroadcast' message with the 'listingID' of 'Nov11th14:00-15:00'. The total negawatt in need is 100kW between 14:00 and 15:00 with the DRAOfferPrice at 10 tokens/kW and this is broadcasted to all participating buildings in the blockchain network. Assuming that all five building owners submit their nWOffers in response to the broadcast message. Table I summarizes the request from DRA and all offers from five building owners.

TABLE I.
OFFER PARAMETERS FROM DRA AND PARTICIPANTS FOR THE "LISTINGID" NOV11TH14:00-15:00

Participant ID	Offer Parameters	
	DRAOfferPrice and DRArequest	Buildings-nWQuantity
Demand Response Aggregator	10 tokens/kW 100 kW	
buildingowner1@vt.edu		10 kW
buildingowner2@vt.edu		40 kW
buildingowner3@vt.edu		38 kW
buildingowner4@vt.edu		5 kW
buildingowner5@vt.edu		25 kW

After the 'ClosenWBidding' transaction is called, the smart contract is initiated, and the token balances of all building owners are updated accordingly.

The resulting token balances and negawatt quantity before and after the trading are summarized in Table II. Based on the designed smart contract, building owners who offer higher negawatt capability are the first to sell their negawatt to the DRA. Since the total DRA negawatt request is 100kW, building owners#2 and 3 can fully sell their negawatts at 40kW and 38kW, respectively. Building owner#5 can partially sell their negawatt at 100-40-38 = 22kW. Thus, at the DRA offer price of 10 tokens/kW, building owner#2 gets the total compensation of 40×10=400 tokens; building owner#3 gets the total compensation of 38×10=380 tokens. Lastly, building owner#5 gets a balance increase of 22×10=220 tokens. The total tokens paid by the DRA is 400+380+220=1,000 tokens in this case. Negawatts unsold from buildings#1, 4 and 5 are 10, 5 and 3kW, respectively.

TABLE II.
TOKEN BALANCES AND NEGAWATT QUANTITY OF ALL PARTICIPANTS IN THE DRA NEGAWATTS TRADING NETWORK BEFORE AND AFTER THE AUCTION

Participant ID	Balance (tokens)		Negawatt (kW)	
	Before	After	DRArequest/nWQuantity	DRAunmet/nWUnsold
DRA	1000 (Total DRA Payment)		100	0
buildingowner1@vt.edu	500	500	10	10
buildingowner2@vt.edu	500	900	40	0
buildingowner3@vt.edu	500	880	38	0
buildingowner4@vt.edu	500	500	5	5
buildingowner5@vt.edu	500	720	25	3

III. TYPE II: P2P NEGAWATT TRADING NETWORK

The P2P negawatt trading network has been developed as a blockchain-based business network to allow negawatt exchange among buildings. The conceptual architecture of this negawatts trading network is depicted in Fig. 2, assuming that building owners#1 and 2 request to buy negawatts from their neighbors.

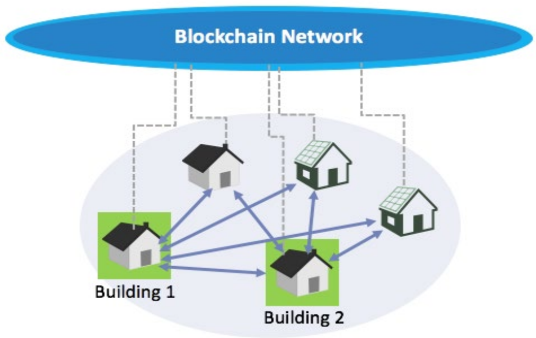

Fig. 2. Peer-to-peer negawatt trading.

In this scenario, building owners, who cannot meet the demand reduction requested by the DRA (in the first scenario), let other buildings know of their negawatts contract shortfalls by broadcasting a message to the blockchain network. This signal comprises the demand reduction needed from its neighbors (kW), the maximum price (token/kW) the building owner is willing to pay, and the one-hour demand reduction period, e.g., 70kW, 20 tokens/kW, between 14:00 and 16:00. Building owners, who are interested to sell their negawatts, can respond to the broadcast message with the negawatt amount (kW), the bid price (token/kW), and the available negawatt period. One negawatt selling offer may comprise available negawatt amount at different periods, e.g., 2kW, 10 tokens/kW, between 14:00 and 15:00 and 3kW, 8 tokens/kW, between 15:00 and 16:00.

A. Participants

In this network, the negawatts are traded among the buildings. Hence, participants are of only one type：

- Building owners- who are involved in buying/selling negawatts. The attributes of building owners are the same as those in the DRA negawatt trading network.

B. Assets

Assets are negawatt commodity called 'P2PnWlisting', and digital currency called 'tokens'. Each 'P2PnWlisting' is characterized by:

- 'listingID' and 'listingstate' are the same as the Type I negawatt trading network.
- 'P2PnWrequest' indicates the total demand reduction (kW) requested by all building owners during a specific hour.
- 'P2PnWforsale' indicates the total demand reduction (kW) available for sale during a specific hour.
- 'P2PnWunmet' indicates the total demand reduction still in need after a transaction.
- 'P2PnWsaleleft' indicates the total demand reduction still available for sale after a transaction.
- 'MCP' represents the hourly market clearing price.

'nWBuyOffer' and 'nWSellOffer', which are transactions (defined below), are added as the parameters of 'P2PnWlisting' after they are submitted by building(s).

C. Transaction & Transaction Flow

The following four types of transactions are defined: RequestP2PnWBroadcast, nWBuyOffer, nWSellOffer and CloseP2PnWBidding.

- 'RequestP2PnWBroadcast' – This broadcast message indicates that the P2P negawatt trading network accepts buy/sell offers from participating buildings during a certain hour. After this transaction is submitted, the corresponding hour listing's 'listingstate' will be updated to 'FOR_SALE' making it available to accept bidding offers for that hour. This transaction is identified by 'listingID' as ID, e.g., {Nov11th15:00-16:00}, indicating this hour is planned for P2P demand reduction. Negawatts can only be traded during the listed period;
- 'nWBuyOffer' – In responding to the above broadcast message, any participating building that would like to buy negawatts from other buildings can submit a 'nWBuyOffer'. It comprises: (i) 'nWQuantity', which is the amount of negawatts (kW) to buy during a specific hour, identified by (ii) 'listingID'. Building owners can submit bids for more than one hour ahead by associating nWQuantity with corresponding 'listingID'; (iii) 'OfferPrice', which is the maximum price (token/kW) that the building owner is willing to pay for its negawatt purchases during that hour, and (iv) 'buildingID' which identifies a building submitting the 'nWBuyOffer'. After each successful trade, 'nWBuyOffer' is appended with the remaining negawatts still in need after the market is cleared, called 'nWUnmet';
- 'nWSellOffer' – In responding to the broadcast message, any participating building that would like to sell negawatts to other buildings can submit a 'nWSellOffer'. It comprises: (i) 'nWQuantity', which is the amount of negawatts (kW) to sell during a specific hour, identified by (ii) 'listingID'. Similar to the 'nWBuyOffer', building owners can submit negawatts selling capability for more than one hour ahead; (iii) 'BidPrice', which represents the minimum price (token/ kW) that the building owner is willing to sell its negawatts during that hour, and (iv) 'buildingID' which identifies a building submitting the 'nWSellOffer'. After each successful trade, 'nWSellOffer' is appended with the remaining negawatts still available to sell after the market is cleared, called 'nWUnsold';
- 'CloseP2PnWBidding' – This transaction represents the auction ending signal identified by 'listingID'. After the bidding is closed, the smart contract is initiated automatically to clear the market, and the token balance of each participant is updated.

D. Smart Contract

In this study, a simplified smart contract is specified to identify how the negawatts are traded among building owners. That is, for each hour, the market clearing price is calculated as the average negawatt price offered by all sellers. See (1). This is the price at which all negawatts are compensated.

$$MCP_t = \frac{\sum_{i=0}^{n} \beta_i \times \mathrm{kW}_i}{\sum_{i=0}^{n} \mathrm{kW}_i} \quad (1)$$

Where:

MCP_t: Market Clearing Price at time t (tokens/kW)
n : Number of negawatts sellers

i : Index of negawatts seller
β : Negawatt seller's bid price (tokens/kW)
kW : Negawatt amount to sell (kW)

Secondly, the 'OfferPrice' in each 'nWBuyOffer' is compared with MCP. Only those with 'OfferPrice' higher than or equal to MCP can participate in the transaction.

Thirdly, 'nWSellOffers' are sorted by the products of their negawatts quantity and bid price (from high to low). These sorted offers are aggregated until the negawatts requested by all negawatts buyers are fulfilled during a specific hour. This identifies successful negawatt sellers.

In this study, negawatt sellers are credited based on the MCP (note: for further studies, double auction mechanisms can also be explored). Specifically, the token balance of each negawatt buyer and seller is updated by the amount of negawatt bought and sold in one hour (kW) * MCP (tokens/kW).

E. Case Study

The case study of the P2P negawatt trading network has been carried out on the Hyperledger open-source blockchain platform. Five negawatts sellers and two negawatts buyers are included in this case study. All seven building owners are assumed to have the beginning token balance of 600.

Assuming that the 'RequestP2PnWBroadcast' message with the 'listingID' of 'Nov11th15:00-16:00' is broadcasted to participating buildings in the P2P negawatts trading network. Assuming that five building owners respond with 'nWSellOffers' and two building owners respond with 'nWBuyOffer'.

Table III summarizes their 'nWSellOffer' and 'nWBuyOffer'.

TABLE III.
OFFER PARAMETERS FROM PARTICIPANTS FOR THE "LISTINGID" NOV11TH15:00-16:00

Participant ID	Offer Parameters	
	BidPrice (tokens/kW)	nWQuantity (kW)
buildingowner1@vt.edu (seller)	20	10
buildingowner2@vt.edu (seller)	8	40
buildingowner3@vt.edu (seller)	7	5
buildingowner4@vt.edu (seller)	15	10
buildingowner5@vt.edu (seller)	5	50
buildingowner6@vt.edu (buyer)	5	50
buildingowner7@vt.edu (buyer)	16	70

After the 'CloseP2PnWBidding' transaction is called, the smart contract is initiated, and the token balances of all building owners are updated accordingly.

The resulting token balances after negawatt trading are summarized in Table IV.

TABLE IV.
TOKEN BALANCES AND NEGAWATT QUANTITY OF ALL PARTICIPANTS IN P2P NEGAWATTS TRADING NETWORK BEFORE AND AFTER THE AUCTION

	Balance (tokens)		Negawatt (kW)	
Participant ID	Before	After	nWUnmet	nWUnsold
buildingowner1 @vt.edu	600	600		10
buildingowner2 @vt.edu	600	932.17		0
buildingowner3 @vt.edu	600	600		5
buildingowner4 @vt.edu	600	600		10
buildingowner5 @vt.edu	600	849.13		20
buildingowner6 @vt.edu	600	600	50	
buildingowner7 @vt.edu	600	18.70	0	

In this case, there are seven building owners, including five negawatts sellers and two negawatts buyers, submitting offers to the P2P blockchain network in response to the 'RequestP2PnWBroadcast' message with the 'listingID' of 'Nov11th15:00-16:00'.

Based on the designed smart contract, firstly, the MCP price is calculated as shown below:

$$\text{MCP} = \frac{20 \times 10 + 8 \times 40 + 7 \times 5 + 15 \times 10 + 5 \times 50}{10 + 40 + 5 + 10 + 50} = 8.30\ tokens/kW$$

Secondly, the buy offers are compared against MCP. According to the designed smart contract, only building owner#7 whose offer price is higher than MCP of 8.30 tokens/kW is able to buy negawatts from negawatt sellers.

Thirdly, negawatt sellers are sorted according to their negawatt quantity (kW) * bid price (tokens/kW). Thus, the priority order of the negawatt sellers are as follows: building owners #2, 5, 1, 4 and 3.

In this case, building owner#7 can buy 70kW, which is fulfilled according to the selling order above. That is, building owner#2 sells its negawatt capability of 40 kW at the price of MCP 8.30 tokens/kW and gets the credit of 8.30×40=332.17 tokens. Building owner#5 sells the remaining 30kW at MCP and gets a credit of 8.30×30=249.13 tokens. Accordingly, building owner#7 buys 70 kWh negawatt at MCP and pays 581.30 tokens. The remaining 'nWSellOffers' from building owners#1, 3 and 4 remain untraded in the P2P negawatt trading network. After the bidding process is closed, the transaction listing state during this hour changes to 'CLOSE'.

IV. CONCLUSION

Negawatts are being recognized as a new kind of commodity that can be exchanged. This paper presents a conceptual architecture and examples of two kinds of negawatts trading business networks, implemented using the blockchain technology, namely the DRA negawatt trading network (Type I) and the P2P negawatt trading network (Type II). Participants, assets, transactions and transaction flows of both business networks, together with the smart contracts, are discussed in details. Examples demonstrating these negawatt trading case studies are discussed. This work can serve as a basis for future blockchain-based negawatts trading applications. With a building energy management unit, the ability to allow buildings to perform load control while maintaining occupant comfort requirements can be achieved. Possible future work may include addressing potential mismatches between the predicted demand reduction capability and the actual negawatt traded. Additionally, instead of considering only offered prices by sellers to calculate MCP, double auction and game theory can also be used that takes into account offers from both buyers and sellers.

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