Cost Analysis of Blockchains-based Peer to Peer Energy Trade

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***Abstract*—Blockchain is a promising platform for peer to peer energy trade as it lowers the cost of trade by eliminating 3rd parties to mediate among the prosumers. However, blockchain brings the cost in terms of computational resources used in mining blockchain transactions. The objective of this paper is to develop a method of a cost analysis of blockchain-based peer to peer energy trade systems as we analyze the tradeoff among the cost of the blockchain network, the appropriate throughput of the blockchain, and profit from the cheap energy price provided by a prosumer to another prosumer. We identify the factors which will lead to profitable blockchain-based peer to peer energy trade markets.**

***Index Terms*—Peer to peer energy trade, Blockchains, Cost Analysis**

I. Introduction

Blockchains is a promising platform for peer to peer energy trade as it lowers the cost of trade by eliminating 3rd parties to mediate among the prosumers. The cost, blockchain throughput problems of blockchain-based energy trade systems are as follows:

- **Cost:** The cost of a blockchain-based peer to peer energy trade system depends on the computational resources used in blockchain mining. We will assume that a proof of work-based blockchain is used in the P2P energy trade. Such a blockchain rewards the miners (who new creates blocks by aggregating undocumented transactions) for creating new blocks. Miners compete for such a reward as they complete to solve a mathematical puzzle and significant investments in computational resources are needed to complete in a blockchain mining market.
- **Price of Electricity:** The price of electricity to be traded in a P2P energy trade is usually lower than the price of buying energy from a utility company.
- **Transaction Throughput:** A blockchain with an appropriate transaction processing throughput is required to record events from the smart grid within a finite time delay.

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The objective of this paper is to develop a cost analysis method of blockchain-based peer to peer energy trade systems as we analyze the tradeoffs among the cost of the blockchain network, the appropriate throughput needed for the blockchain, and profit from the cheap energy price provided by a prosumer to another prosumer. We identify the factors which will lead to profitable blockchain-based peer to peer energy trade markets. Our main contributions are as follows:

1) We develop an agent-based complex systems model of blockchain-based P2P energy trade. In this energy trade model, we develop a network simulator of blockchains. Such a blockchain simulator highlights the tradeoffs between network size, network communication delay, blockchain transaction throughput, and the cost of mining.
2) The blockchain simulator is augmented with an agent-based model of P2P energy trade. We use a cooperative game formulation of P2P energy trade.
3) Next, we formulate relations between the cost of mining the blockchain network recording transactions from a peer to peer energy trade market and the reward of the miners in terms of transaction fees. We validate the cost formulation using the simulator of blockchains and peer to peer energy trade.

The paper is organized as follows: in section 2 we present an agent-based simulation of blockchain-based P2P energy trade, in section 3 we present the cost model of mining this blockchain network and we validate the cost formulation using the simulation of energy trade, in section 4 we present related literature and we conclude the paper in section 5.

II. Agent-based model of peer to peer energy trade

In this section, we will describe the blockchain and peer to peer energy trade simulator which will be used to validate the cost model of mining the blockchain network designed to record peer to peer energy trade information.

A. Blockchain Simulator

We simulate a blockchain network using agent-based modeling of the blockchain network. We use an asynchronous event simulator (using SIMPY library of Python). The workflow of each agent (who simulates a peer of the blockchain network) is as follows:

1) Each peer executes four processes in parallel.
2) $Process_3$ receives messages from its neighbors and if the message is not received before then it checks if the message contains a new transaction or a new block. If it receives a transaction then it informs $Process_2$ about the new transaction. If it receives a new block then it informs $Process_4$ about the new block.
3) $Process_2$ gathers new transactions from $Process_3$ and the new transaction is placed in a queue of undocumented transactions. We assume that the queue model is First In First Out. After adding the new transaction to its queue, a peer forwards the message containing the new transaction to its neighbors.
4) $Process_1$ empties the first k transactions from its queue of undocumented transactions and creates a new block. Then it solves the puzzle of Proof of work protocol and publishes the new block.
5) $Process_4$ examines the new block from $Process_3$, if all transactions of the new block are valid then: if the parent block of the new block is the last blockchain head known to the peer then it augments its blockchain by placing the new block as child block of its last known blockchain head and recognize the new block as the last know blockchain head. Otherwise, it finds the parent block of the new block in its blockchain and augments the blockchain by adding the new block as its child block.

We will assume that the miners are being paid in terms of transaction fees. Let θ be the transaction fee for any transaction and there are k transactions in every block. Hence a miner gets $\theta \times k$ as a reward for publishing a new block. We assume proof of work as the consensus model, hence miners compete to publish a new block. Let the blockchain processes a new block in every dt time interval. Let the cost of operational mining infrastructure for dt time is $f(x, dt)$ where x is a measure of computation infrastructure (in terms of CPU cycles and storage). The probability that a miner will win the race to publish a new block depends on its investment in the mining infrastructure. Let $P(x)$ be the probability that a peer will win the mining race if it has a computation infrastructure x. Thus the reward for a miner after every dt time interval is:

$$P(x) \times \theta \times k - f(x, dt) \quad (1)$$

Thus the revenue of each miner will depend on the probability that it will win mining races and throughput of the blockchain in terms of the number of blocks to be published per second.

B. Energy trade Model

We will use a cooperative trade model for P2P energy trade. We use the following notations to describe the trade scenario:

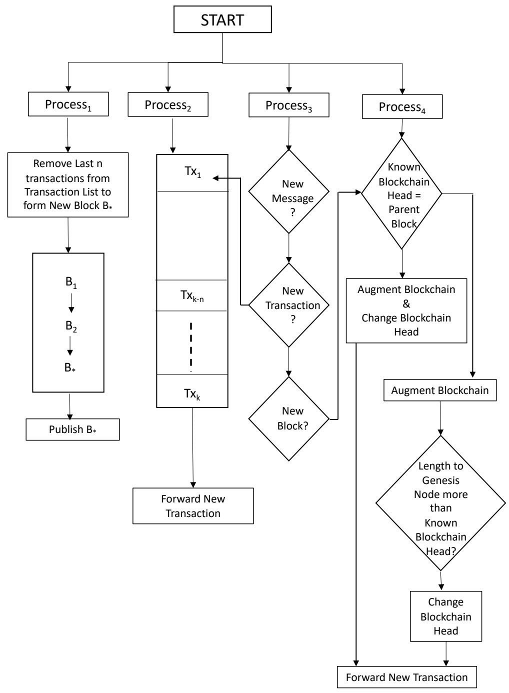

Fig. 1. Workflow of each miner of the blockchain network

$(1, 2, \ldots, n)$	A set of n prosumers
$G = (V, E)$	A network replicating the distribution networks with set of nodes V representing the prosumers and E denotes the distribution lines
$t = (1, 2, \ldots, T)$	T successive time instances with time duration dt between every pair of successive time instances
E^i_j	It is the estimated difference between electricity to be produced by i and energy demand of i at time j

The algorithm (shown in Algorithm 1) for finding coalitions is as follows:

1) Prosumers are the nodes with degree 1 and its neighboring prosumer is at most one hop away.
2) A bipartite graph is constructed with a set of nodes A with surplus energy and a set of nodes B with energy deficiency.
3) An edge from $i \in A$ to $j \in B$ is constructed if i, j are neighbouring prosumers and weight of the edge is $E^i_t + E^j_t$.
4) Next, a maximum weighted bipartite graph matching is found for this graph.
5) For each pair of matched pairs of nodes $(i \in A, j \in B)$, trade between i and j with the amount of electricity $Min(E^i_t, Abs(E^j_t))$ is added to set of trades π.
6) Next, we remove edges from i if all of its surplus energy

is matched with prosumers with energy deficiency. If there is surplus energy to i after serving j, then edges to j from any node A are removed.

7) Next, we update edge weights based on the remaining surplus energy of nodes in A.
8) This procedure is continued until either all surplus energy is traded or there is no energy deficiency.

Algorithm 1: P2P energy trade algorithm

Data: $\{E_t^i\}$ expected energy supply / demand at time t, $G = (V, E)$
Result: $\pi = \{i, j, x\}$ set of trades from i to j with amount of electricity x.

begin
  $Prosumer \leftarrow$ nodes with degree 1
  N_i neighbours of prosumer i within distance 2
  $H \leftarrow$ bipartite graph with set of set of nodes A(where $E_i > 0$) and another set of nodes B (where $E_i < 0$)
  for *Each* $i \in A$ **do**
    for *Each* $j \in B$ **do**
      Add edge $i \rightarrow j$ with weight $E_t^i + E_t^j$ to H
  $Continue \leftarrow True$
  while *Continue* == *True* **do**
    $Matching \leftarrow$ Maximum weighted bipartite graph matching
    $Continue \leftarrow False$
    for $i \in A$ **do**
      if $\exists j \in B : (A, B) \in Matching$ **then**
        Add $(i, j, MIN(E_t^i, Abs(E_t^j)))$ to π
        $Continue \leftarrow True$
        if $E_t^i \geq Abs(E_t^j)$ **then**
          $E_t^i = E_t^i - Abs(E_t^j)$
          Remove all edges to j from any node in A
          Update edge weight of all edges from $i \in A$ to any node in B using new value of E_t^i
        else
          Remove all edges from i to any node in B

C. Integrated Model

A method to execute trade algorithm 1 in the blockchain using smart contracts is as follows:

1) The trading algorithm can be implemented as a smart contract with prosumers are the participants.
2) Before the time instance t, all prosumers informs the smart contract about the difference between expected energy generation and its energy demand.

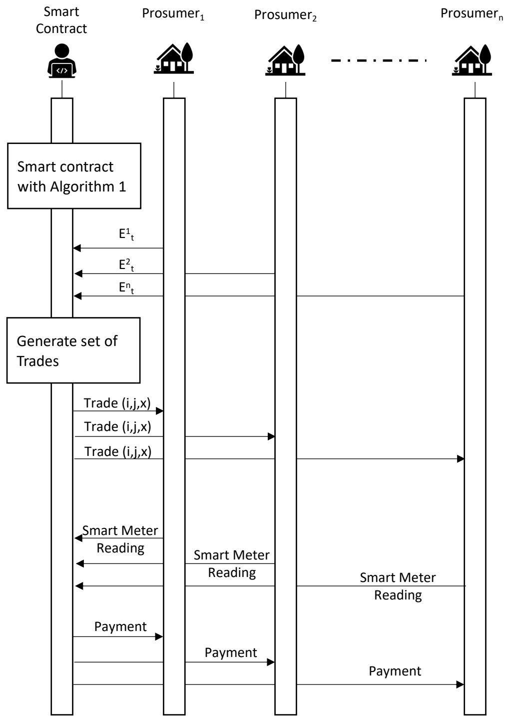

Fig. 2. Smart contract execution for Algorithm 1.

3) The smart contract will execute the algorithm 1 and inform the prosumers about the set of trades $\{i, j, x\}$ (from prosumer i, the prosumer j will buy energy of amount x)
4) After, time instance t, meter reading from smart meters will be transferred to the smart contract, and after verify promised energy supply/demand information, the smart contract settles payments between the prosumers.

The number of transactions required for each execution of the smart contract is:

1) At most n transactions are sent to the smart contract to collect energy supply-demand information.
2) At most n transactions from the smart meters are sent to the smart contract to collect actual energy generation/consumption information.
3) At most n transactions from the smart contract are sent to the prosumers as payments are settled.

III. Cost Model of Mining the Blockchain for Peer to Peer energy trade

First, we will estimate the throughput (number of blocks per second) needed in the blockchain to match with the throughput (number of energy transfer between any pair of prosumers) of the peer to peer energy trade.

A. Throughput of Peer to Peer Energy Trading

We will estimate the amount of energy to be traded for the trade window starting at time t and ending at time $t + 1$.

Also, we will estimate the number of transactions needed to record the energy trades among the prosumers during this time window. Let $G = (V, E)$ be the graph denoting the set of prosumers and with trade neighbors of the prosumers. Let each prosumer has at most d neighbors. Let $Max(E^i_j) = M_1$ and $Min(E^i_j) = M_2$. The total energy to be traded during time t is:

$$Min(Abs(\sum_{i:E^i_t<0} E^i_t), \sum_{i:E^i_t>0} E^i_t) \tag{2}$$

Let there are n_1 prosumers with $E^i_t > 0$ and n_2 prosumers with $E^i_t < 0$. In the worst case, P is empty, i.e., energy to be traded is 0. In the best case,

$$M_1 \times n_1 = M_2 \times n_2$$
$$M_1 \times n_1 = M_2 \times (n - n_1)$$
$$M_1 \times n_1 + M_2 \times n_1 = M_2 \times n$$
$$n_1(M_1 + M_2) = M_2 \times n$$
$$n_1 = \frac{M_2 \times n}{M_1 + M_2} \tag{3}$$
$$n_2 = n - \frac{M_2 \times n}{M_1 + M_2} = \frac{M_1 \times n}{M_1 + M_2} \tag{4}$$

Thus maximum energy to be traded is:

$$\frac{M_1 \times M_2 \times n}{M_1 + M_2} \tag{5}$$

Now the maximum number of transactions needed to record this energy trade can be calculated as follows: Let n_1 prosumers with $E^i_t > 0$. The maximum number of transactions per prosumer (with $E^i_t > 0$) is d where each neighbour of this prosumer has an energy deficiency ($E^j_t < 0$) and:

$$M_1 = d * M^*$$

where M^* is the average energy demand from its neighbours. There are at most n_1 such prosumers with $E^i_t > 0$. Hence maximum number of transactions needed to record the energy trade at time t is:

$$d * \frac{M_2 \times n}{M_1 + M_2} \tag{6}$$

We will validate these models of maximum energy to be traded and a maximum number of transactions using the blockchain and energy trade simulator. We simulate the blockchain-based energy simulator with a number of prosumers from 50 to 1000. We use a scale-free graph model of energy distribution networks developed in [1], [2] to identify the neighborhood of the prosumers, i.e., with whom they should trade. The nodes on the boundary of such a network with a low degree will be regarded as the prosumers while higher degree nodes represent energy generators and transmission network. We assume that two prosumers can trade energy if their distance is at most two edges.

Using the above-mentioned model of energy distribution network, we simulate the maximum energy to be traded in a peer to peer energy trade. As shown in figure 4, the estimated amount of trade using equation 5 is slightly higher than the trade estimated using simulations. It shows that the model of estimating maximum trade is valid. Note that we want to estimate the upper bound of the maximum trade in order to estimate the maximum number of transactions needed to be recorded in the blockchain. Hence a slightly higher value of trade amount estimation is valid. Next, as shown in figure 5, we use similar simulations to validate the calculation of the expected number of transactions. This estimation is also valid as it is more than the number of transactions seen in the simulation.

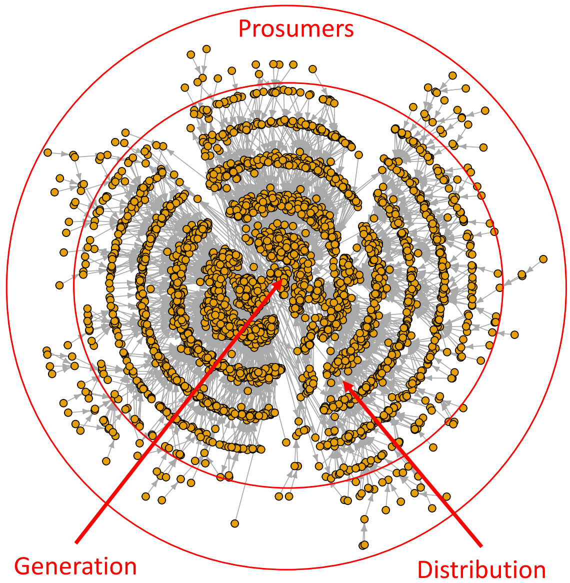

Fig. 3. Energy distribution network is modelled as scale free graph with prosumers on the boundary of the network

High throughput of a blockchain will require a high block generation rate. In a proof of work-based blockchain, the rate of block generation is controlled by the complexity of a puzzle that should be solved to publish a new block. The problem with the high block generation rate is the possibility of forks. If the complexity of the puzzle is low then it is more likely that more than one miner will solve it and publish a new block at the same time and hence it will lead to blockchain forks. Thus, communication infrastructure should also be improved

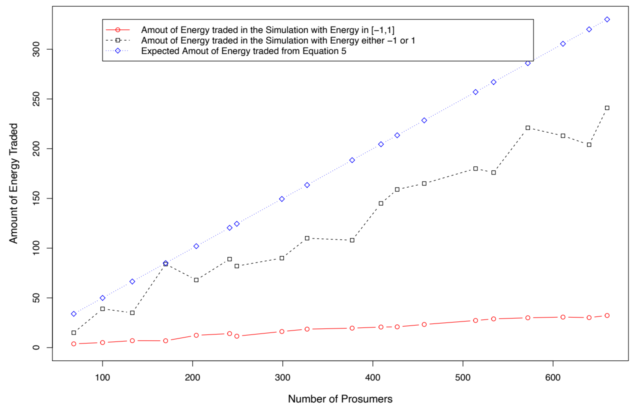

Fig. 4. Estimated amount of trade.

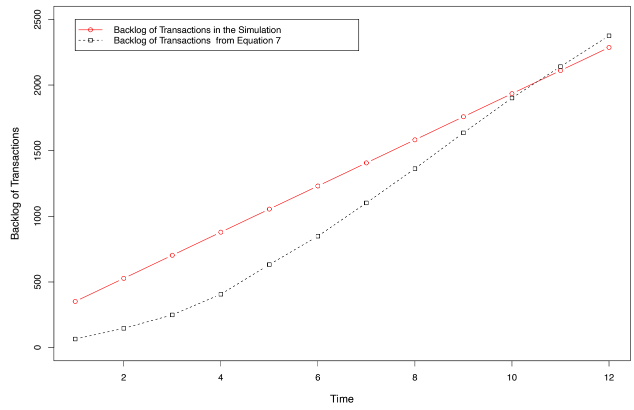

Fig. 6. Backlog of undocumented transactions

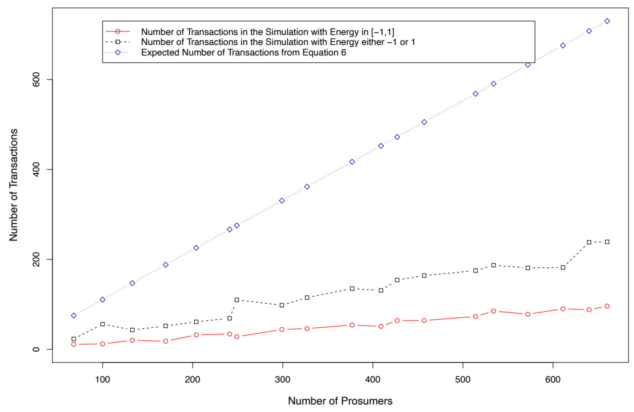

Fig. 5. Number of transactions needed to record peer to peer energy trade

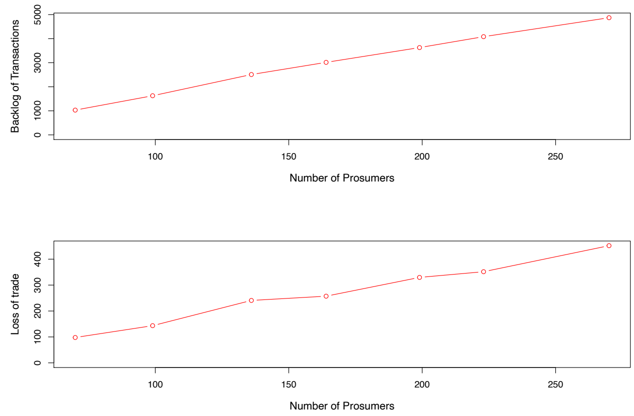

Fig. 7. Increase in transaction backlog and loss due to undocumented transactions.

to reduce the time it takes a block to reach all miners as we increase the block generation rate. Let the block generation rate is k_1 blocks per dt time interval. Let the block size is k_2, i.e., each block contains k_2 transactions in it. Thus, the queue of undocumented transactions at each miner has $d * \frac{M_2 \times n}{M_1 + M_2}$ new transactions and $k_1 \times k_2$ transactions are cleared from this queue. Hence at each dt time interval backlog at each miner's queue grows at the rate of:

$$d * \frac{M_2 \times n}{M_1 + M_2} - k_1 \times k_2. \quad (7)$$

We validate the above formulation of the backlog at the miners using simulations of peer to peer energy trade. As shown in figure 6, the average backlog at miners calculated using equation 7 matches with the observed backlog at the miners in the blockchain simulation. We also use similar simulations to illustrate the relationship between the increasing number of prosumers and the backlog of transactions. As shown in figure 7, the backlog grows with an increment of the number of prosumers. If we cancel an energy trade due to transactions not being in a block within a predefined time then we can estimate loss due to transaction backlog. Figure 7 shows that as we increase the number of prosumers while keeping the mining rate and the number of miners fixed, the loss due to trade cancellation for transactions not in the blockchain within a fixed time increases.

We need to increase the throughput of the blockchain by increasing its mining rate to reduce the loss of the prosumers due to trade cancellation for transactions not included in the blockchain within a fixed time. Next, we find the relation between the mining rate and such a fixed time within which a transaction should be included in a block in order to execute the energy trade.

If a transaction is created at time t, then it arrives at a miner with backlog $(t-1) \times [d * \frac{M_2 \times n}{M_1 + M_2} - k_1 \times k_2]$. Hence a new transaction created at time t will be recorded in a block after t^* time (measured as times of dt):

$$t^* = \frac{((t-1) \times [d * \frac{M_2 \times n}{M_1+M_2} - k_1 \times k_2])}{(k_1 \times k_2)}$$
$$(k_1 \times k_2)t^* = ((t-1) \times [d * \frac{M_2 \times n}{M_1+M_2} - k_1 \times k_2])$$
$$(k_1 \times k_2)t^* + (t-1)(k_1 \times k_2) = ((t-1) \times [d * \frac{M_2 \times n}{M_1+M_2}])$$
$$(k_1 \times k_2)(t^* + (t-1)) = ((t-1) \times [d * \frac{M_2 \times n}{M_1+M_2}])$$
$$k_1 = (t-1) \times [d * \frac{M_2 \times n}{M_1+M_2}] \times \frac{1}{k_2(t^* + (t-1))}$$
$$k_1 = \frac{n(t-1)}{k_2(t^* + t - 1)} \tag{8}$$

In the above equation we assume $M_1 = M_2$, $d = 2$ (as we found in the simulations). For small value of t^*, we conclude that:

$$k_1 = \frac{n}{k_2} \tag{9}$$

The above equation is justified as follows: it says that there will be a very low queue of undocumented transactions at the miners if the rate of mining is n/k_2. Note that n is the number of prosumers and k_2 is the size of a block. This means there will be a very low queue if the mining rate is n/k_2 per second where each prosumer creates one transaction per second.

B. Cost of Mining

We assume that all miners have approximately equal investment in their respective mining infrastructure and after each dt/k_1 time interval (k_1 is the block generation rate) a miner will publish one block chosen uniformly at random. Let f be the transaction fees. Hence expected revenue from mining for each miner after each dt time interval is:

$$\frac{1}{z} \times f \times k_2 \times k_1 - \theta(k_1) \tag{10}$$

where z is the number of miners and $\theta(k_1)$ is the cost of mining infrastructure for time duration dt. Blockchain-based peer to peer trade is feasible if a miner's revenue is positive. Hence following should hold:

$$\frac{1}{z} \times f \times k_2 \times k_1 > \theta(k_1)$$
$$\frac{1}{z} \times f \times k_2 \times \frac{n}{k_2} > \theta(k_1)$$
$$\frac{1}{z} \times f \times n > \theta(k_1) \tag{11}$$

The above equation can be interpreted as follows: the cost of operating mining infrastructure to remain competitive (this means the miner have invested in sufficient computation infrastructure so that probability of winning mining race is at least $1/z$ where z is the number of miners) in a mining rate of k_1 blocks per dt time is less than expected total transactions processing fees for dt time. In the future, we will extend this cost model with a better cost model of mining such as [3].

IV. Related Literature

Blockchain-based peer to peer energy trade has received a lot of attention recently. In [4] the authors presented a simulation of blockchain-based energy trade platform. In [5], [6] authors extended blockchain-based energy trade with electric vehicle charging. In [7] authors used double auction for peer to peer energy trade using blockchains. In [8] authors used coalition formation for peer to peer energy trade. In this paper, we use proof of work-based blockchains [9]. We refer to [10], [11] for a comprehensive review of blockchain-based peer to peer energy trade.

V. Conclusion

In this paper, we formulated the cost of mining the blockchain network in terms of the throughput of the blockchain needed to support the peer to peer energy trades. We have shown that the formulation is valid using a simulation of blockchain-based energy trade. In the future, we will extend this work with a game-theoretic formulation of the blockchain mining parameters. In this paper we investigate throughput of proof of work-based blockchains, in the future we will investigate other consensus protocols.

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