Review of Blockchain Enabled Decentralized Energy Trading Mechanisms

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***Abstract*—With special emphasis being put upon renewable sources of energy day-by-day, there is a growing demand for this new technology to be integrated into the existing framework. To be widely accepted and made sustainable, such a technology should be profitable for all participating entities; giving them incentive enough to continue using it. What remains to be answered is the question of how that will be done. We break down the traditional power grid into smaller clusters, called microgrid and discuss its properties as potential candidates for implementing Blockchain powered energy trading mechanisms. Blockchain enabled technology is chosen as it brings with it, a degree of security, transparency and automation; and cuts out the established monopoly with the decentralized network and peer-to-peer trading. Two such working algorithms are reviewed for their implementation into the microgrid. One algorithm works on an auction model while another is a calculative data-dependent model but both the models function using smart contracts. Pre-existing projects in this field and their implementation around the world are reviewed by us in the later section of the paper. We conclude this paper by encapsulating the deployment considerations and limitations of employing Blockchain technology in a microgrid.**

Keywords—Blockchain; renewable energy; decentralized; trading; smart grid; microgrid.

I. Introduction

The footprint of the generation of energy has been under extensive scrutiny to rely more on new upcoming technologies that shift focus more on renewable resources and rely less on conventional energy sources. Integrating the power produced from solar or wind generation plants into the centralized power network is a difficult challenge. The architecture used for power generation needs to be restructured as per the decentralized nature of these physical entities. Prosumers or consumers are defined as “Assets” in this restructured architecture. The transparent nature, traceability and security of the transactions will envision different approaches that will be proposed in this paper. In order to ensure a network where transactions will be secure and tracible, Blockchain Technology is used. However, Blockchain technology calls for big data management, flexible computing resources, and a suitable environment which foster the development of the applications under consideration [4].

In the wake of global warming, the energy industry has begun restructuring and reorganizing the changing energy trends, however, there are a couple of technical barriers meant to be overcome.

The development potential of microgrids is enormous with the effective use of power grids and renewable energy. But currently, the energy equipment for storage is expensive, while the efficiency of the storage equipment is low. The volume of power transaction is limited, while management has not been simplified, and the cost of control management in a microgrid is high. In addition to it, no subsidy schemes and tariffs for microgrid have been implemented. And there is no viable method to perfectly solve the huge grid fluctuation caused by integration in a microgrid [17].

In this paper, we propose a decentralized microgrid system that employs Blockchain for distributed energy exchanges between various nodes/entities including an energy storage system (ESS), consumers and prosumers [13].

II. Introduction to Microgrid

A. *Need for microgrid*

To counter the established monopoly in the energy sector, there is a need to address key issues of incentive sharing and distribution of power over the market. This deadlock can be broken by introducing decentralized agreements between participating parties through the medium of Blockchain.

A microgrid operator is required to minimize consumer costs, make reliable investments and generate a return for involved stakeholders. In order to prevent the operator to be fair and work towards the interest of the microgrid, regulatory audits are necessary.

This results in the regulatory measures costing the microgrid members more than a degree of inefficiency of the market, leading to a knot in the trust between the operator and the operating nodes of the microgrid; who cannot ascertain whether the bills they receive are in actual inflated for the profits of the operator or true costs.

This stress in trust between the two entities is evident in many distributed networks and is going on to become a greater problem in microgrids. Hence the need of introducing a fair, regulated and decentralized microgrid regulator: Blockchain enabled smart contracts [3].

B. *Properties that a microgrid should possess*

Privacy- Any external party that is not present in the network should not have access to personal data of the members within the network. The grid should also enforce and make sure that other members in the network should not have access to the total energy bill for one particular node or member based on the data exchanged when it is pertaining to that specific community.

Accuracy- The grid should be accurate in representing the transactions taking place in the network, which means that record should be updated whenever there is a fluctuation in the market.

Traceability- The grid should maintain a record of the origin of the generated energy and the correct flow of transactions between the prosumer (power generating node) and the consumer/ prosumer (power consuming node).

III. Introduction to Blockchain

A. *Blockchain and Smart Contracts*

A Blockchain is a distributed data structure whose multiple copies are shared among the members present in a network. Each node in the Blockchain carries a lot of transactions along with the hash value of the previous block which was appended in the network. It can be thought of as a ledger whose entries are logged as timestamped blocks. Each block is uniquely referred by its cryptographic hash. Each block links to the hash of the one that preceded it. This establishes a connection between two blocks, thus, lending the name, Blockchain. Each user in the network has a public and a private key, using which they interact with the network. Asymmetric cryptography technology offered by Blockchain ensures solidity and non-repudiation of the network it is based upon. Every node in the chain broadcasts its signed exchange to immediate adjacent nodes in the network. The receiving nodes ensure that this transacted data is valid before the broadcast the same further into the network. In such a manner, the data will be diffused through the entire Blockchain network. However, if the transaction is invalid, it is discarded. Once the transaction is validated, it is appended in the Blockchain network. Smart contracts are self-triggered programs stored permanently on the Blockchain; triggered whenever a request for a transaction is made in the network. The contract then executes independently and automatically on the lines of pre-defined behavior; upon every node existing in the network [1].

B. *How Blockchain satisfies the required properties of a microgrid*

Privacy- Blockchain provides privacy to the client in the form of complete anonymity, as only the public key of the node is referred to by a transaction (pseudonymity) [5]. In a local community, there lies a possibility to link the public key of the nodes with their real identity, which can be beneficial for the network as the nodes can verify the accuracy of the transactions made. However, a legal arrangement should be made to prevent the leakage of this private data to an external party.

Accuracy- Blockchain is a ledger which is dynamically updated by the network, whenever a transaction is made. This is analogous to the updating of the records with every fluctuation in the energy market

Traceability- The traceability of every transaction in this network is taken care of by three means- the proposed transactional model, the consensus mechanism and the Merkle tree. In the transactional model, the sum of outputs of the system (the energy supplied to deficit nodes) should be less than or equal to the sum of inputs (the energy generated in surplus). Thus, with Blockchain, all transactions are broadcasted across the network. To prevent any occurrence of a malicious transaction, a simple consensus mechanism is employed in the network wherein all mining nodes are involved in validating the transaction after it has been broadcasted in the network. Two popular consensus mechanisms are Proof of Work (PoW) and Proof of Stake (PoS) [5]. Merkle tree employs a Proof of Membership mechanism wherein two nodes form a branch and their collective hash value forms the hash of the upstream node.

IV. Proposed Network Components

A. *Defining a community*

A community is defined based on five rules; first, it should cover a limited geographical area like a street or a residential complex. Second, there should be at least one connection between the primary public grid and the community. Thirdly, every individual prosumer's generated electricity is recorded in its own virtual generation meter device. Fourth parameter being that the community should install a system to monitor every fluctuation in the local energy market. The final rule being that all the generation devices that a community has should be considered as the common property of the community itself.

B. *System for microgrids in the network*

A proposed plan of action is to create a private Blockchain network within the community so as to filter the entry of any malicious nodes. The installation of IoT devices, Energy Storage System (or ESS), a solar panel (for prosumers only) and a mining system in a smart home to generate, collect, process, and exchange vast amounts of data that can be used to manage, control and monitor everything that happens in a smart home, will serve as a single node in our system, i.e., a single smart home is a node in the network. The devices are connected to the internet so they constantly interact with the miner. The selected home miner of the node with the most stake collects the transactions not included in the block and works on validating the transaction to be appended into the Blockchain network. Once validated, the block consisting of several transactions is appended to the Blockchain and they are updated in the ledger of the system. After this, the transactions included in the block are never forged or falsified. Thus, as seen, the consensus algorithm used in this network is Proof of Stake. The smart contract for the trading in our network will be programmed in Solidity and the private Blockchain network will be constructed using 'geth' client distributed by Ethereum, as depicted in figure 1.a. and 1.b. respectively [6].

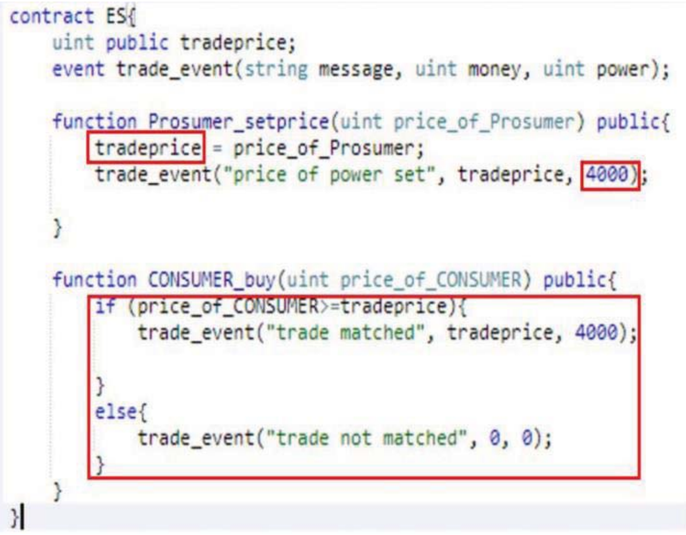

Fig. 1.a A Snippet of Smart Contract in Solidity [6]

Fig. 1.b. Private network with 2 nodes- prosumer and consumer [6]

C. *Consensus mechanism for the network*

Since the network that is being employed is a private network with whitelisted participants, a consensus mechanism which is not as computationally expensive as Proof of Work, is opted for [1]. Thus, the consensus algorithm that is being employed is Proof of Stake. In this algorithm, the miner is chosen on the basis of the wealth (in terms of cryptocurrency) that the miner possesses. The chance of getting selected as the miner is directly proportional to the wealth possessed by the node. Thus, not only is this algorithm faster than PoW but it also computationally less expensive as compared to PoW, adding to the fact that the miner is provided with no incentive; thereby increasing the throughput of the system. The algorithm works with the following steps:

Assume that there are ‘K’ nodes bolstering the network at a time.

1) Based on the wealth of a node’s relative wealth when compared to other nodes, we determine the wealth of each candidate miner. Although there are several ways of determining relative wealth, in our case, we choose the following wealth criteria to define the wealth of a node ‘k’, for a given K and for a time step Ti, as wealth,

$$W= (\alpha*E) +(\beta*A*k) + (\gamma*R) \qquad \ldots i$$

where;

‘E’ corresponds to the voting token which is pertaining to a subset of the volume of kilowatt-hours in the previous transactions. This metric is directly proportional to the probability of generating the next block.

‘A’ is a metric to measure the age of the previous block. The probability of generating the next block is directly proportional to the age of the last block created by the miner.

‘R’ is a metric to measure the reputation of a block. This metric prioritizes the miners that have already created blocks to the miners which have not yet created a block.

The constants ‘α’, ‘β’ and ‘γ’ are values which are contractually agreed on within the community.

2) A random number ‘Uk’ is created for every candidate ‘k’ lying in the interval [0, 1].

3) A miner is selected for the network on the basis of the maximum ratio of wealth and the randomly generated value, Uk [5].

V. SECURITY BY BLOCKCHAIN

It is the property of Blockchain technology to be immutable once blocks have joined the chain. This allows a distributed escrow to be designed on the basis of time-stamped blocks. The element of trust in the escrow is satisfied due to the Blockchain guarantee. Another indirect advantage of the immutability property of Blockchain is that it preserves the integrity of data.

One such Blockchain integrity mechanisms are the keyless signature infrastructure. Involving cryptographic signing mechanisms in this distributed microgrid increases data fidelity amongst nodes, which in turn is used to detect attacks on the grid. Data validation and filtering is possible as the Blockchain ledger consists of immutable data values.

The impact of any cyber-attack is judged by the number of nodes that are affected by it, directly or indirectly. By eliminating ‘middle-men’ or in other words, centralized operators, Blockchain reduces the number of nodes present in a network. Hence, fewer targets for attacks to impact and less impactful. Smart contracts, too help us detect ledger manipulations or changes in the system without any human interference [7].

VI. THEORETICAL WORKING OF THE NETWORK

The energy exchange process will proceed as follows- A smart contract for selling the produced energy is created as soon as the prosumers impart energy into the microgrid [13]; the selected miner will verify the validity and credibility of the smart contract transaction, and a part of their job is to verify whether the energy claimed to be produced by the prosumer has actually been generated or not. The consumers, meanwhile, generate a smart contract for purchasing energy from the prosumers. A smart contract is triggered to check whether the consumers can afford the listed energy in the ESS. Once verified, the consumers receive purchased energy through the ESS, with ESS serving as an entity which provides dynamic adjustments of energy flows and real-time communications between involved entities. The energy is stored locally within a node but exchanged using the ESS via the microgrid.

The steps of energy exchange are as follows-

1. The prosumer generates the energy EA, assigns their respective public key to it and sends its information to the ESS, where this information is stored.

2. The prosumer then makes a smart contract for selling the energy produced. This smart contract comprises of the smart contract code, the price of the produced energy, amount of energy and the respective prosumer's public key and the contract ID.

3. The selected miner (on the basis of PoS) will verify a set of prerequisites of the smart contract which includes verifying whether the contract has the key of the prosumer, whether a transaction fee is included for the transaction or not, the execution outcome of the smart contract code etc. The verification phase also includes the credibility check to confirm whether the prosumer actually has produced the claimed amount of energy. For this verification, we have two methods which can be implemented in the network. The first approach requires the miner to send an authentication request message to the ESS, which is then received with an authentication response message from the ESS to the miner. This module of sending an authentication request message is made part of the smart contract code, and it is programmed in such a way that these requests are automatically generated when the miners execute the code. An alternative to this slower mechanism, is to make the ESS send a broadcast transaction to the network as soon as it receives the energy information from the prosumer. Thus, the miner will immediately confirm the energy generated by just referring to the broadcasted message from the ESS.

4. The consumer generates a purchase request transaction with the intent of invoking the smart contract prepared by prosumer earlier. It includes the contract ID, payment to the prosumer and the public key. The selected miner verifies whether the consumer has enough balance to pay for the energy produced by the prosumer and if the transaction has the key of the concerned consumer in order to ensure non-repudiation.

5. The ESS releases energy from the smart grid as soon as the transaction is verified and appended to the Blockchain network.

VII. Algorithms

A. *Auction-based algorithm*

One proposed model is an auction-based model for the distribution of electricity generated locally by the prosumers (producers + consumers). The model deals with the idea of micro-grids that consist of the residential house in a local community. Each residential unit within the micro-grid is a prosumer and an independent node of the grid. Each node is fit with energy-generating solar panels and smart meters. The role of the smart meter is to monitor, keep logs and update the microgrid with the generation and consumption levels of the node as referred to in figure 2.a.

Like any other auction model, here as well, all buyers of the microgrid participate in the auction individually. The highest proposed price will win the auction round and get access to electricity. Since the Blockchain technology works on the basis of certification by all other parties of the network, the integrity and the security of the system is sustained as each Blockchain event needs to be verified by multiple parties before being accepted into the digital ledger. Since the prosumer lacks the experience, time and the incentive to form a market for the auction round, Blockchain enabled smart contracts facilitate this as referred in figure 2.b. They enforce the rules of the auction and automatically carry it out.

At every cycle of the auction, each prosumer who wishes to be a seller, of their respective local generation of energy, in the auction come together to form a coalition. This is done to cumulate the available energy units and hence maximize the sale, leading to better profits. The profit generated is then distributed back to each seller of the coalition in proportion to their contribution to the cumulative energy units. On the other side of the transaction, the consumer or the buyer will be unaware of other buyer's decision while they participate in the auction round.

The proposed model does not eliminate the connection of the microgrid from the main grid for possible reasons of the shortage of local generation of energy and there is a gap between the supply and demand in the microgrid. The market should be designed in such a way that the price per unit of electricity of the microgrid should be lower than that of the main grid. This will incentivize sale and production by the prosumers within the microgrid.

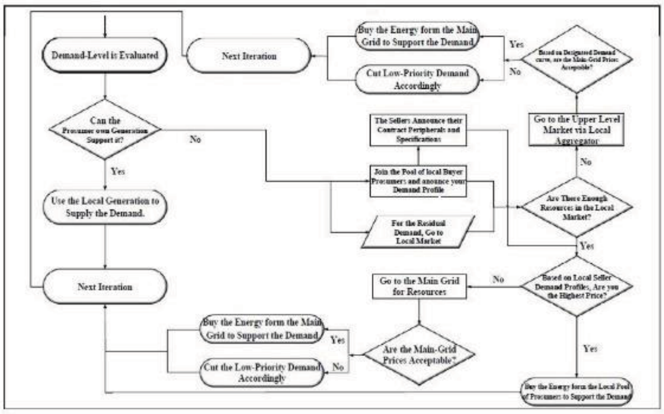

Fig. 2.a. Flowchart for the auction based algorithm [8]

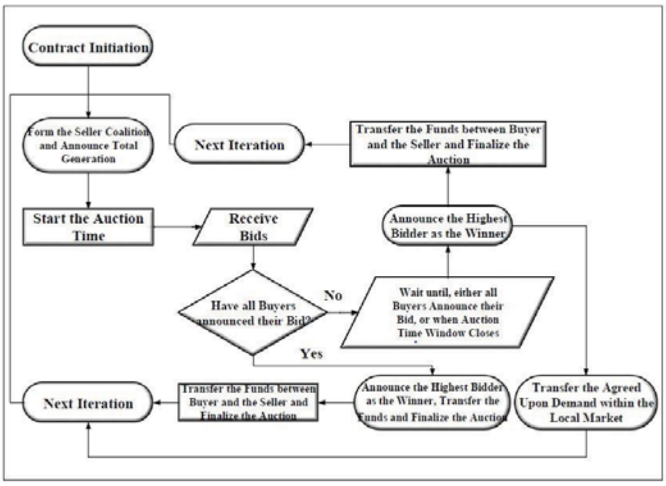

Fig. 2.b. Flowchart for implementation of Smart Contracts [8]

1) *Advantages of auction-based algorithm*

This kind of microgrid model proves to be an effective solution to power dissipation issues faced by the main grid; when it has to distribute energy from the centralized power source to the distant nodes of the network. The odds of cascade failure due to its islanding potential decreases along with reducing the load on the main grid.

Implementing smart contracts has its own benefits as well. It acts as the mediator between the buyer and the seller: by keeping track and announcing the available resources in the auction, conducting the auction by waiting for all bids and judging a winner and finally transferring the funds from the buyer to the seller once the auction is completed.

2) Disadvantages of auction-based algorithm

The proposed model does not specify the size of the microgrid and its physical limitations. We do not know what size of the microgrid would be effective enough; the size of a city or a neighborhood of the city. Further, competitive pricing by the centralized energy company might prosumers to generate energy and trade it, hence that risk still exists.

The integrity of the auction is the heart of this model. Any threats to it will compromise the system and put to risk the financial wealth and data of the participants of the microgrid [8].

B. *Scheduling based algorithm*

Optimal Dispatch Formulation considers scheduling of distribution of energy, a day in advance, bearing in mind the operational constraints which have to be followed while minimizing the cost of energy supply.

It proposes a model where each node in the microgrid will compute its constraints locally and pass them onto a smart contract. This smart contract gathers information from all such nodes and applies them into the Alternating Direction Method of Multipliers(ADMM) function as mentioned in [3] [12]. This is repeated until the ADMM finally converges to an optimum schedule and pricing, keeping in mind the constraints of the network.

Once the schedule and pricing is fixed, it is sent to a second smart contract. This smart contract then compares the energy consumption records transmitted to it by smart meters of each node and charges each node of the microgrid, the equivalent price directly via cryptocurrency mediums. Hence Blockchain enables us to use the algorithm to boost the benefit of all the nodes, all while being within the restraining constraints and eliminating the existence of a monopoly.

This model, referred to in figure 3, is limited by the overhead requirements for networking and communication, delays in which limit this algorithm to only a day-ahead scheduling. Nonetheless, its scope of improvement lies in the application of machine learning using previous schedules and data of each node, for better accuracy of scheduling in future, and increasing the network resilience by introducing fault detection algorithms to spot frauds in the system [3].

```
repeat:
   P(i): Private optimization, compute locally
         Gather private constraints
         compute requirements and send to smart contract S1
   S1: ADMM aggregator, on blockchain
         compute final schedule and clearing prices
until optimal schedule calculated by S1

M(i): Each Smart Meter
      record energy consumption
      send time stamped & signed consumption to S2
...time progresses
S2: Billing contract, on blockchain
      compare schedule from S1 -with meter readings
      compute payments and charges
      trasnfer payments between accounts
```

Fig. 3. Algorithm for scheduling based algorithm [3]

VIII. Existing Companies

A few of the existing projects which were studied are:

A. PWR company

The model for adopted by this company is to store the energy produced and then transfer it to the destination host. This is done in order to stabilize the grid and prevent lapses caused due to dynamic transfer. The company equates one PWRToken, which is the cryptocurrency powered by the company, to 1 Mwh. This can be traded on various exchange markets.

B. *PowerLedger*

This works on the basic theory of the nodes being able to trade the surplus energy they generate, to other nodes in the microgrid. The (DSO)distribution System Operators earn a commission on for the energy units distributed.

C. *Key2Energy*

The working principle the company has based its model on is that it aims to share the solar energy generated, amongst all the tenants in multi-apartment building societies and hence cut down on the cost each tenant will have to pay for those utilities. In situations of surplus generation, the energy can be sold on the market.

D. *LO3 Energy*

LO3 energy created the transActive grid that has been deployed in New York as the Brooklyn Microgrid project. TAG-e (TransActive Grid elements) consisting of computers and electric meters, which measure the amount of energy produced and sell the surplus energy within the grid itself after sharing information with other such TAG-e in the grid.

E. *Dajie*

It works on a similar trading platform except a user earns a coin for every 1KWh energy produced. These coins can be used as a currency to buy energy when needed or to redeem carbon credit.

F. *NRGcoin*

It implements a smart contract based skeleton of its model and has a validation check of whether the energy produced is consumed locally. If the validation is checked, only then the users are awarded with NRGcoins; one for each kilowatt. NRGcoin supports energy generation in all renewable energy forms.

G. GrunStromJeton

This setup does the opposite of other setups. It takes into consideration consumed energy instead of generated energy. It then predicts the relative amount of energy to be generated in the coming 36 hours and the amount the user will consume out this. The higher this prediction, the more Jetons are given to the consumer and more trading can be achieved on the platform.

H. Bankymoon

Contradictory to the other models proposed above, this is establishment provides Blockchain enabled meters that need to be preloaded with cryptocurrency in order to be used. Once loaded, the meter permits the equivalent amount of energy to be consumed [9].

IX. Role of Stakeholders

TABLE 1. ROLE OF DIFFERENT STAKEHOLDERS IN THE MICROGRID NETWORK [2].

Stakeholders	Role
Government Department	Establishing policies and standards to rationalise external mechanism, and coordinate each stakeholders liabilities and benefits.
Central Power Grid	The Central power grid serves as supplementary source of energy in case of power failures or shortages in any node.
Consumers	The node which is involved only in energy consumption and not generation
Prosumers	A necessary entity in the microgrid two-way interaction, actively participating in energy generation and as well as consumption
Equipment and service providers	Provide hardware and software foundation for microgrid construction

X. Inference and Observations

Table 2. compares the two implementation models that are discussed in the sections above. Throughput refers to the time consumed by each algorithm to compute the final trading between the nodes, which indirectly translates to the efficiency of the algorithm.

The auction-based algorithm is predicted to have a low throughput as the system lies idle while the auction phase is in process and each node bids for the energy. The scheduling algorithm has a predefined schedule, following which it allows the flow of energy almost immediately, optimizing system usage.

In event of a power failure or a system crash in between, the auction based algorithm loses all the data and transaction information which haven't been stored in the Blockchain ledger yet. This also affects the auction bids as these bids are raised in a dynamic fashion. For the scheduling based algorithm, a power failure is not equally impactful as the schedule is predefined and stored in the ledger.

An auction does not have a predetermined number of nodes participating in it nor does it have a limit on the number of the nodes auctioning. Therefore, adding a node is easy and can be accommodated in the system with much ease. In the scheduling problem, the number of nodes in the system makes a big difference as the algorithm has been pre-configured to schedule as per the number of nodes. Adding a new node requires the algorithm to be modified and is complicated.

The auction algorithm being dynamic has a high potential margin of error, whereas the predefined scheduling algorithm minimizes the margin of error as there is time to rectify the errors in the day in advance of which the schedule is computed.

TABLE 2. COMPARING THE TWO AUCTION AND SCHEDULING BASED ALGORITHMS

Parameters	Auction based algorithm	Scheduling based algorithm
Throughput	Low	High
Impact of power failure	High	Low
Addition of nodes	Easy	Complex
Interaction of nodes	Competition	Cooperation
Margin of error	Low	High

A. Limitations of microgrid

One primary observation that we made in the working mechanism of a microgrid is that the resources produced by the prosumers are not utilized on another local network, even though both these microgrids share the same centralized router. This means that if a surplus energy is available in a local grid and there is a separate network where there is a deficit of energy, then the deficit energy will be accommodated for, by the central power grid which is managing the local microgrids, rather than the surplus energy from the network with the surplus energy. Thus, due to this property of microgrids, there leaves a scope for further technological advancement to furthermore achieve decentralized peer-to-peer network in this system.

Another prominent observation that we made was that since Blockchain is a ledger which involves 3 primary designations in a network (the miner, prosumer and consumer) at a time, there is no room for achieving concurrency in this network, i.e., if the need for transaction arrives while another transaction is yet to be appended in the network, then that particular transaction will not be entertained unless and until the prior transaction is appended in to the Blockchain.

B. Deployment considerations

The smart contracts of the network serve as the crux of the system. Thus, we need to make sure that the smart contract being employed by the system is properly inspected and its logic is carefully examined. Fool-proof mechanisms should be ensured to ensure that there are no stalemates in the system during its execution.

The algorithm to select the miners in the system should ensure that the miner set should not be constant throughout the network. This means that though the miners are selected heavily on the basis of their wealth, there should be a scope for other miners to get into the miner set, thus maintaining an incentive for the stakeholders to gain credibility among the peers in the network.

XI. CONCLUSION

Blockchain is a promising technology for a secured and trusted network for trading and monitoring of energy entities and assets in a microgrid network, both in the private and public sector domain. It has been summarized how Blockchain and decentralized consensus techniques can be implemented both to synchronize the scheduling of energy resources which are distributed on a microgrid, and to accredit fair payments without the need for a centralized aggregator in a microgrid. By using ADMM, the problem is decomposed into a structure that naturally lends itself to a Blockchain implementation, and smart contracts and Blockchain can provide a reliable solution for the trust, security and immutability requirements of a microgrid network. The scope of existing projects will move in the direction to establish electricity markets with more flexible smart contracts in which the parameters vary as well as the contract structure. This change will accentuate better simulation of actual situations.

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