# Decentralized bottom-up energy trading using Ethereum as a platform

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# Decentralized Bottom-up Energy Trading using Ethereum as a Platform

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**ABSTRACT**

In the past decade, there has been a significant increase of distributed energy resources. This transformation has rendered the grid more bidirectional and transformed many small consumers to prosumers. However, these small power producers are not able to optimize their revenue since currently they can only sell to local energy suppliers or opt to sell at a fixed feed-in tariff. If intermediaries are eliminated from energy trading, both individual buyers and prosumers can increase their profitability. Blockchain technology could facilitate this scenario. In this research study, a simulated environment of a hierarchical energy trading market using Ethereum's smart-contract technology is created as a proof-of-concept of using blockhain technology in energy trading. A dynamic grid fee based on electrical network loading is calculated to demonstrate an economic incentive for agents to have flexible load demand, as well to promote local resource utilisation. The price volatility of cryptocurrency is addressed by designing a specific energy token for the model.

**KEYWORDS:** Blockchain; Ethereum; Smart Grid; Energy Trading; Energy Management; Renewable Energy

# Contents

## List of Figures

# List of Tables

# 1 Introduction

Historically electricity has been generated mainly by a few far-off high-capacity generators that is transmitted and distributed to end consumers. However, after getting renewable energy (especially Photovoltaic Panels) more and more economical, there has been a huge increase of traditional consumers converting to prosumers making electricity grid bidirectional. This bidirectional electricity grid is in need for major reforms to enable efficient utilization of these distributed energy resources (Roberts, 2018).

The objective of this paper is to develop and test a blockchain platform for a local energy trading market, enabling individual prosumers and consumers to trade energy locally but also have the option of trading energy with a neighboring microgrid with the payment of an additional grid fee. This approach, on one hand could potentially reduce the huge investment in electric grid infrastructure in terms of electric grid reinforcement and on the other hand in case of unforeseeable circumstances like disconnection from main grid could enable the local community to self-sustain the local grid without the involvement of third party (Merz, 2016).

## 1.1 Liberalized Electricity Networks and Markets

Electricity Market used to be vertically integrated, making one company responsible for power generation, transmission and distribution. When the energy market gets liberalized there is a separation between commodity trades and network operations. Distribution Network Operators (DNO) although enjoy a Natural Monopoly but are highly regulated.

The electricity systems is mainly divided into:

1. Physical subsystem - Centred around the production, transmission and distribution of electricity.
2. Commodity Subsystem - Centred around energy product trading.

### 1.1.1 The Physical Subsystem

As shown in lower part of Figure 1, The Physical Subsystem consists of all the equipment that produces and transport electricity to customers as well as hardware that uses the electricity. The structure of the physical subsystem consists of Generators (Large Power Producer and Distributed Generators), Transmission Networks, Distribution Networks and Loads. Relation 1 shows the agreement between the Large Power Producer and Transmission System Operator (TSO), TSO then distribute it to several DSOs (2), DSO then distribute it to the Final Consumer (5), DGs normally feeds electricity directly to DSO (3) or in some cases power produced by DG is directly consumed by Consumers (6). Due to increasing amount of DGs, the situation may arise when DSOs have feed-back electricity to TSOs (4) (Kok, 2013).

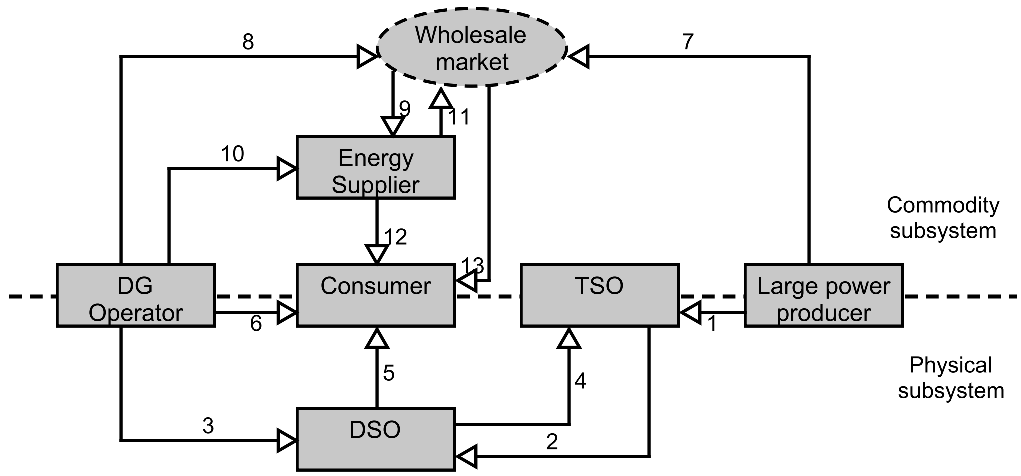


Figure 1: Overview of transactions within liberalized electricity market (Kok, 2013)

### 1.1.2 The Commodity Subsystem

The economic transactions related to the commodity flow is depicted in upper part of Figure 1. The commodity subsystem includes the actors involved in the production, trade or consumption of electricity. Large power producers (7) and some large DG operators (8) offers the commodity on the wholesale market. Large electricity consumers (13) can directly buy the electricity on wholesale, whereas energy suppliers buy electricity from the wholesale market (9) and some also buy directly from DG operators (10) and sell it to the small-scale consumer (12). Usually, the energy suppliers buy more energy than the consumers actually consume, in many cases they also sell back the previously purchased electricity back to the wholesale market (11) (Kok, 2013).

Energy suppliers is a third party who purchases electricity on behalf of actual consumers and in many cases, there is a deviation in forecasted and actual consumption of electricity or deviation of production output normally seen by renewable power producer due to weather uncertainty. In both cases, in order to exactly match demand and supply there is a need to create additional short-term balancing market (Kok, 2013).

## 1.2 The Smart Energy Management Matrix

Traditionally, unpredictability in the energy balance is done by adding controllability at the supply side. However, with the increase in solar and wind energy share in electricity grid which are weather dependant and cannot be controlled; Demand response will be crucial in order to make electricity grid smart (Kok, 2013).

There are a number of automatic response programs predominantly based on one-way signaling from the utility to consuming devices at the end-customer. However, other approaches do exist. Existing smart energy management approaches are filled in Figure 2. The matrix distinguishes if an approach takes decision locally or centrally and whether the approach uses one-way or two-way communications. The energy management approaches are filled with: Top-down switching, Price Reaction, Centralized Optimization and Market Integration (Kok, 2013).

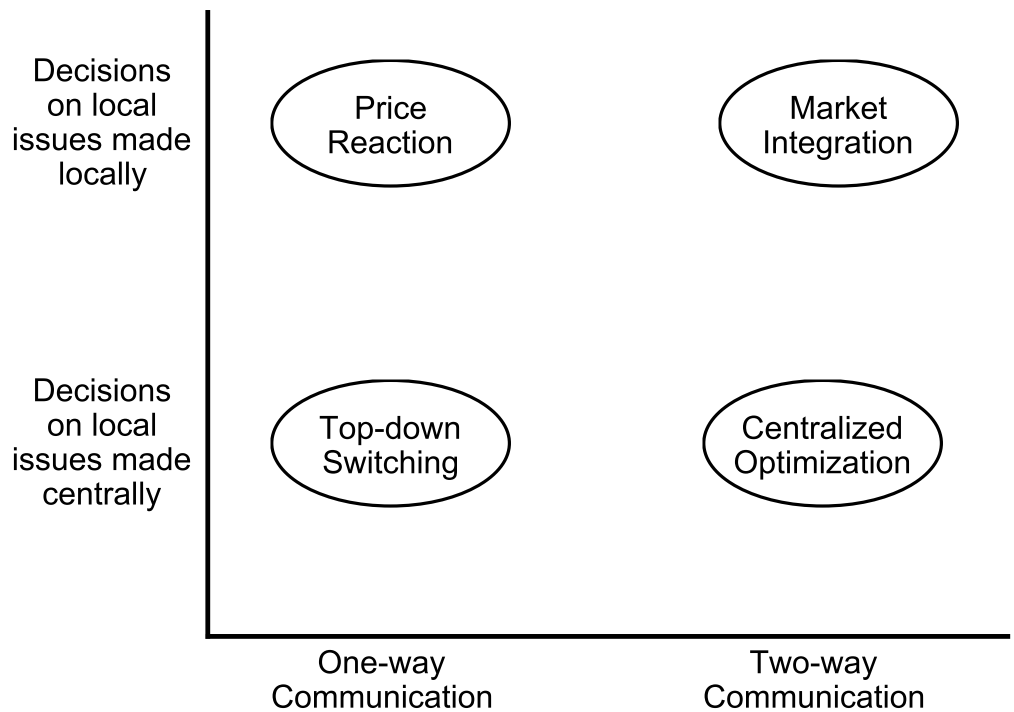


Figure 2: The four main categories of smart energy management (Kok, 2013)

### 1.2.1 Top-down Switching

This approach is either switching devices 'on' or switching them 'off'. With this approach, utility have the control to schedule loads during off-peak hours. However, with this approach, there is an issue of consumer autonomy. It can directly influence the living environment of consumers such as hot shower might not be available exactly when the consumer needs it or the room temperature is not set as per individual consumer's self-preferences (Kok, 2013). In case of electric vehicles, owners use to have their own driving preferences and can't accept this top-down switching method.

#### 1.2.2 Centralized Optimization

Moving towards the left side of the quadrant as shown in Figure 2 i.e. from top-down switching to centralized optimization local decisions are still made centrally, however, there is a two-way communication. A heavy optimization engine would be overseeing all flexible demand and supply in the smart grid cluster under consideration, also the global and local control goals, the optimizer searches for the best solution for the cluster (Marco Zugno, 2015).

Although there is a two-way communication but still there is an omniscient central authority taking a decision that could lead to sub-optimal operating conditions for some consumers.

#### 1.2.3 Price Reaction

This approach is based on one way signaling of a dynamic price to end-customers and based on real-time electricity price, decisions are made locally.

The Advantage of this approach is that it enables end-customer's DER to react independently based on external prices rather than being switched externally.

However, device's ability to react to a particular price depends on its state. Since this information is not known centrally in this approach the reaction of the cluster as a whole is uncertain(Kok, 2013).

#### 1.2.4 Market Integration

Integrating flexible DER devices as well as small consumers into electricity market could enable exact demand response of the market. In this type of market design approach, agent's devices communicate their available flexibility to the market through a bidding mechanism. Through this approach, demand response is known beforehand at a certain price (Kok, 2013).

### 1.3 Microgrid

U.S. Department of Energy Microgrid Exchange Group defines Microgrid as (*About Microgrids*, 2018):

> '*A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.*'

The restructuring of the energy system into several interconnected microgrids can improve the efficient integration of RES, reliability and environmental sustainability of the energy system and simultaneously provide economic benefits in energy self-sufficiency as well as the possibility of energy cost reduction and increase network flexbility (Mengelkamp et al., 2018).

### Microgrid Energy Markets

Microgrids can ensure reliability by operating in both grid-connected as well as islanded-mode. Microgrid energy market can give small prosumers and consumers a platform to trade energy locally rather than relying on getting a fixed tariff from their energy suppliers. Local utilization of energy could also reduce the expensive and inefficient energy transportation with substantial losses. Microgrid energy market can enable local community in energy self-sufficiency and provide the possibility of energy cost reduction (Bahrami & Amini, 2017).

## 1.4 Blockchain Technology

'*Blockchain is a technology that enables so-called "peer-to-peer" transactions. With this type of transaction, every participant in a network can transact directly with every other network participant without involving a third-party intermediary* '(Felix Hasse et al., 2016).

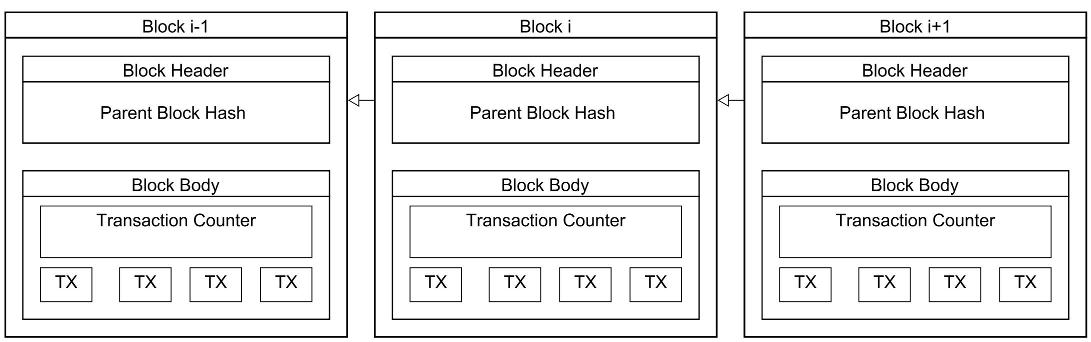


Figure 3: Sequence of blocks in a blockchain (Zheng et al., 2017)

### 1.4.1 Blockchain Architecture

Figure 3, illustrates the architecture of blockchain. It consists of a sequence of blocks, which holds a complete list of the transaction record. The first block of a blockchain is called genesis block, having no parent, represented with "Block i-1", whereas all the rest of block contains a parent block hash. The block body is composed of a transaction counter and transactions (TX). The size of each transaction and the block size determines the maximum number of transactions that a block can carry. Asymmetric cryptography mechanism is used to validate the authentication of transactions. Digital signatures based on asymmetric cryptography is used in an untrustworthy environment (Zheng et al., 2017).

### 1.4.2 Key characteristics of blockchain

Following are the key characteristics of the blockchain.

1. Decentralization: In centralized transaction systems, validation is done by the central trusted agency, that results in the cost and the performance bottlenecks at the central servers. However, in case of the blockchain, no third party is needed. Blockchain uses consensus algorithms to maintain data consistency in distributed networks.

2. Everyone can write - everyone can read: Fundamentally everyone is allowed to do the transaction on blockchain as well as watch historical data (Merz, 2016).

3. Failsafe: Blockchain is an always-on network. It's almost impossible for hackers to put all nodes down at the same time (Merz, 2016).

4. Immutability: As blockchain data copies are maintained by every participant, it's almost impossible for any participants to change the history in blockchain unless it gets 51% of hash power which is highly unlikely to happen (Zheng et al., 2017).

### 1.4.3 Consensus Algorithms

Consensus algorithm in a blockchain is a transformation of the Byzantine Generals (BG) Problem, which was raised in (Lamport, Shostak, & Pease, 1982). In BG problem, a group of generals who command a portion of Byzantine army circle the city and those generals have to reach consensus on either to attack or retreat; Otherwise the attack would fail, if only part of the generals attacks the city. It is also a problem for a distributed network like blockchain as there is no central node to ensure ledgers on the distributed nodes are all the same. Some protocols are needed to ensure ledgers in different nodes are consistent (Zheng et al., 2017).

Following three are most popularly used consensus mechanisms:

#### Proof of work

Bitcoin network uses consensus mechanism called PoW (proof of work). In PoW, someone must be selected to record the transaction in a decentralized network. It could be done randomly but it makes the system vulnerable to attacks. So a node has to do a lot of computer calculation to prove that it is not likely to attack the network if it wants to publish a block of the transaction (Nakamoto, 2008).

### Proof of stake

PoS (proof of stake) is an energy-saving alternative to PoW. In PoS, a large group of distributed users are continuously verifying the hashes of transactions through the mining process. In order to update the current status of the blockchain assets, PoS requires users to repeatedly prove ownership of their own share in the underlying currency. The selection based on account balance is quite unfair because the one with more stake could dominate the network. Ethereum is planning to move from Ethhash (close to PoW) (Wood, 2014) to Casper(close to PoS)(Zamfir, 2015).

### Proof of authority

Proof of authority (PoA) is close to Proof of Stake (PoS) where instead of stake with the monetary value, a validator's identity performs the role of stake. In PoS, if miners starts the selfish mining they would be losing their stake (having a monetary value); Whereas in case PoA, selfish miners would be losing their social standing (*Proof of Authority: consensus model with Identity at Stake*, 2018). This kind of consensus mechanism is used by Energy Web Foundation (Hartnett, 2018).

### 1.4.4 Tokens comparision and its application in Energy Industry

Bitcoin is the most widely known cryptocurrency and the first blockchain based application. It enables its own digital currency named 'Bitcoin' between peers without the involvement of third-party. Just like bitcoin, Ethereum is also a blockchain. The thing that distinguishes Ethereum from Bitcoin is its 'Smart Contract' functionality (making it Turing-complete), an application that runs exactly as programmed without any possibility of downtime, as its code runs on a blockchain network that is not controlled by any individual or central entity (*Ethereum Project*, 2018), (Rosaic, 2018).

Smart contract is a computer code that runs on blockchain. Once smart contract is deployed, its code cannot be tampered or changed. The smart contract execution is also a transaction and the gas price is calculated by the number of bytes a smart contract holds. Hence, a large number of gas is needed to execute a big smart contract. The execution means whether data is added to the blockchain or deleted from the blockchain. The 'write' operation cost some gas but the read operation does not cost any gas. The 'write' operation of the smart contracts is quite slow because it is needed to be mined whereas read operation is relatively fast because it is directly called from the global state or database in a local node which receives the read call. It can help you exchange money, property, shares without the involvement of third-party (Rosaic, 2018).

The most significant difference between Bitcoin and Ethereum is their purpose and capability. Bitcoin blockchain is only dedicated to a peer to peer electronic cash system, whereas

| Blockchain Platform | Smart Contract | Consensus Algorithm | Block Time |
|---|---|---|---|
| Bitcoin | NO | PoW | 10 mins |
| Ethereum | YES | PoW | 10-20 secs |
| EWF | YES | PoA | 3-4 secs |

Table 1: Comparision of Blockchains

the Ethereum blockchain in addition to its own digital currency focuses on running the programming code of any decentralized application (Rosaic, 2018).

Considering the complexity of current energy market, as discussed in Section 1.1.2, the small-scale consumers and prosumers do not have an opportunity to optimize their profit as they always get a flat electricity rate from their energy suppliers. Blockchain, due to its decentralized and failsafe nature, discussed earlier in section 1.4.2 can enable prosumers and consumers to find its own buyers and sellers independently, and also with potentially lower transaction cost. Another advantage would be to have a local energy market, where individual prosumers and consumers can trade energy locally but also have the option of trading energy with neighboring microgrid with the payment of additional grid fee. This approach, on one hand, could reduce the huge investment in electric grid infrastructure as well as in case of unforeseeable circumstance like disconnection from main grid could enable the local community to self-sustain the local grid (Eric Münsing, 2017).

Table 1 shows the comparision of three major blockchains. Energy Web Foundation's blockchain in addition to smart contract functionality is based on PoA that is tailored to make blockhain feasible for energy industry by improving the blocktime[1] as well as savings in energy in terms of redundant competition between miners (Hartnett, 2018).

## 2 Methodology

The scope of our work is to implement a microgrid energy market on blockchain using a cellular approach (*C-sells Das Schaufenster für die nachhaltige Energiewende*, 2018), so that small prosumers/consumers would have the freedom to trade energy locally. As shown in Figure 4, a small microgrid is created with individual consumers and prosumers connected to common distribution transformer (T 1 & T 2 in Figure 4) enabling them to trade energy locally first allowing local grid to be self-sustainable and in case of residual demand and supply, it could be bought or sold at higher hierarchy (at substation/local district/state level etc).

Local aggregate market (*Merit order curve*, 2018) is created with a 15-minute trading cycle (Merz, 2016) and bilateral trading market (Peck & Wagman, 2017) is created to enable

[1] Block time defines the time it takes to mine a block.

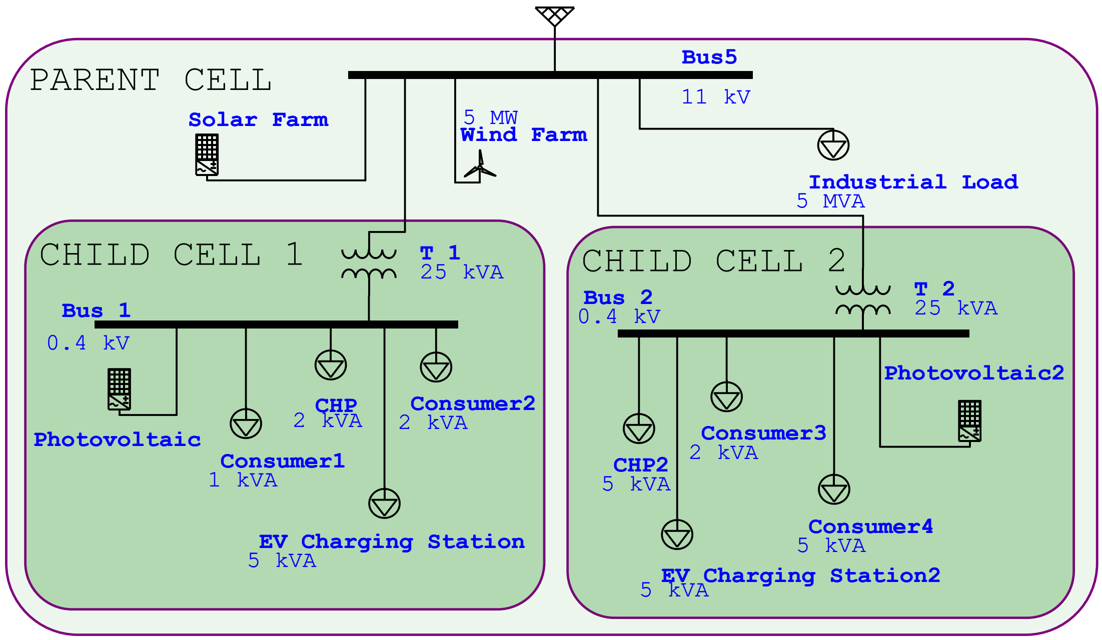


Figure 4: Cellular structure of microgrid

individual producers and consumers to have an energy trading contract mutually. Bilateral trading also enables consumers to select the type of energy they want to buy, especially ones who as a social responsibility will prefer to use clean energy. All consumers and prosumers have the freedom of trading in both, bilateral and aggregate energy trading market based on their personal preferences that leads to market integration of all local prosumers and consumers, as discussed earlier in section 1.2.4.

In this piece of research, an Ethereum based private blockchain using PoW as consensus algorithm is created and several smart contracts were developed to form a blockchain based energy trading market (Chakravarty, 2018). Figure 5 shows the interaction of several Solidity based smart contracts. OLIDetails.sol maintains the information associated with all agents and is used as a certificate to participate in energy trading. ChildAuction.sol smart contract collects bids from agents of their respective cluster (Child Cell), arrange bids in merit order and communicate market clearing price back to agents. ParentAuction.sol also works like ChildAuction.sol but running on a higher hierarchy/Parent Cell (Figure 4), collects bids from agents directly connected to it or from Child Cells). OLIBilateral.sol facilitates bilateral energy trading between two consumer and producer. DynamicGridFee.sol is calculating grid fee based on percentage loading of distribution circuit and transformer. OLICoin.sol contract is maintaining the billing record of all agents. All smart contracts are explained further in detail in the next sub-section.

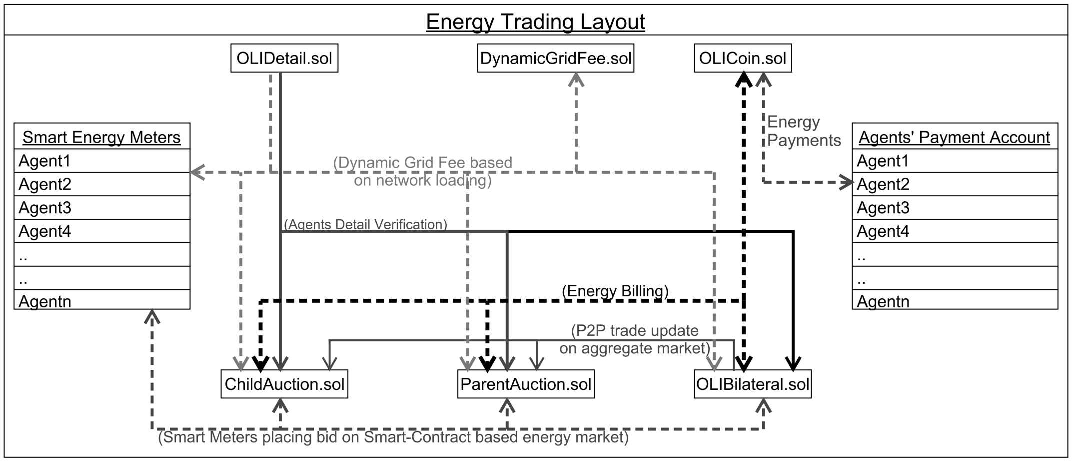


Figure 5: Interaction of several smart contracts to create a blockchain based microgrid energy market

## 2.1 Blockchain based Registry System

To set up a microgrid, the structure of microgrid has to be defined first. To do that, information of all prosumers, consumers, as well as DSOs, are mapped. Following are some important prosumers' & consumers' associated details:

1. GPS coordinates - Indicating the origin of agent where electricity is produced.
2. Local Transformer ID - Indicating to which distribution transformer that agent is connected.
3. Agent Type - Indicating the type of power it is selling or buying.
4. Peak Power - Indicating the maximum demand/supply of agent.
5. Ethereum's Payment Address - Indicating the agents' EOA, where its financial accounting would be maintained.

These details are static and entered into OLIDetails.sol shown in Figure 5, to form a blockchain based agents' Registry System. Using this registry, details associated with agents are verified before enabling them to purchase energy from energy trading market, also shown with a thinner black arrow in Figure 5.

| Producer | Power (Watts) | Rate (€ cents/kW) | Consumer | Rate (€ cents/kW) |
|---|---|---|---|---|
| A | 300 | 6 | B | 7 |
| | | | C | 8 |
| | | | D | 9 |

Table 2: Bilateral Energy Trading Contract

## 2.2 Microgrid Energy Market

Two types of energy trading markets are created in this manuscript:

1. Bilateral Energy Trading
2. Merit Order based Energy Trading

These two markets would be operating in parallel and all agents would be having the freedom to choose based on their personal preferences. In case of bilateral trading, agents would be having a long-term bilateral energy trading contract and in case of energy trading in the aggregate market, agents have to buy and sell energy with a 15min time interval (however for running a simulation to get results faster, this time cycle is reduced to 90 seconds). As all agents are committing their supply/demand in advance, complete market integration is achieved using approach discussed in Section 1.2.4.

### 2.2.1 Bilateral Energy Trading

In a microgrid based energy market, it is highly likely that a consumer would prefer to buy electricity from a neighbor having a roof-top PV with excess energy to sell. As shown in Figure 5, OliBilateral.sol script will facilitate long-term P2P energy trading contract between power producers and consumers.

Consider the example shown in Table 2, where, producer A wants to sell 300 Watts of power at a rate of €6 cents/kW. Local interested consumers bid with their willingness to purchase it. Once the bidding time is over, the highest bidder is having a bilateral energy trading contract with producer A, i.e, producer A and consumer D now have a bilateral energy trading contract in this case.

### 2.2.2 Merit Order based Energy Trading

In this piece of research, ChildAuction.sol & ParentAuction.sol (Figure 5) scripts are facilitating energy trading based on Merit Order Effect (Figure 6) and calculate Local Market Clearing Price. ChildAuction.sol gathers bids from agents clustered together in the same Child Cell (Figure 4), arrange them in merit order effect and calculate market clearing price (Figure 6). Bid winners are then allowed to trade their committed energy whereas


Figure 6: Producers' and consumers' bid based on merit order

bid losers have the option to go to ParentAuction.sol running on Parent Cell (Figure 5). ParentAuction.sol scripts will collect bids from several Child Cell as well as agents connected directly to Parent Cell, arrange them in merit order and calculate market clearing price (Figure 6). Agents of Child Cell can trade energy on Parent Cell by paying additional grid fee based on percentage loading of the distribution transformer. The benefit of this kind of hierarchical energy trading market would be that agents would be promoted towards local resource utilization and in case of any disconnection from the main grid, it will enable local agents to self-sustain their own grid.

### 2.3 Energy Billing

All agents' energy bills are calculated using the following formula:

$$energy_{bill} = rate * \frac{power}{1000} * time \tag{1}$$

where ,

energybill = €1 = 100OLICoin;
rate= (€ cents/kW);
power = (Watts);
time =(hours)

The biggest problem with digital currency is their price volatility, making it hard to use it directly to bill energy trading agents (*Cryptocurrency Market Capitalizations*, 2018). However, Ethereum enables to create a digital currency on top of it after its ERC20 Token

Standard (*ERC20 Token Standard*, 2018). In this piece of research, stable token called OLICoin is developed for energy billing without the involvement of any central agency (Rusitschka, 2018). As shown in Figure 5, OLICoin.sol script will maintain stable token supply based on which energy trading is done. All consumers, prosumers and energy generators are rewarded and billed using this token. Later, agents can redeem EUR by exchanging OLICoin such that €1=100OLICoin either mutually or through registered cryptocurrency exchanges . In case, of redeeming through cryptocurrency exchanges, they would also have to pay some extra service charges.

Figure 7 shows the layout of token exchange. There is no central agency that is issuing tokens to buy and sell energy. Tokens are minted automatically after every successful energy trading. The Token balance of energy producer rises positively whereas the token balance of energy consumers rises negatively. Since for every energy production, there would also be a consumer. Therefore, the net token volume would always be zero leading to constant supply/demand of tokens, enabling tokens to always have a fixed value.

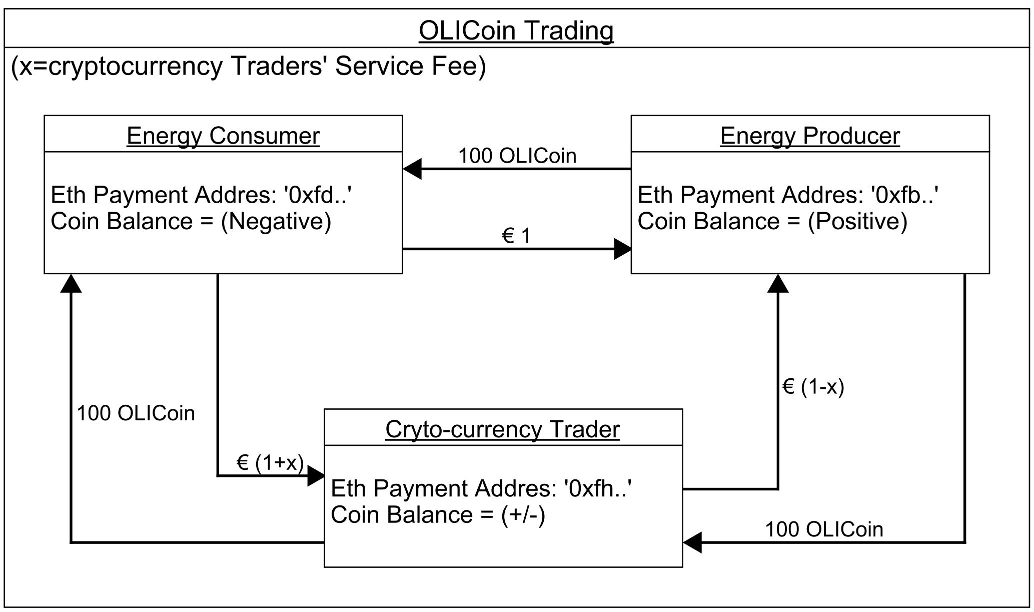


Figure 7: Layout of Token Exchange

## 2.4 Dynamic Grid Fee

The GridFee.sol (Figure 5) is created for calculating the dynamic fee based on grid loading to promote utilization of local energy sources. Network loading and hierarchy based grid fee is calculated to promote local utilization of energy. In the lowest level, all distribution circuits have separate grid fee. As shown in Figure 8, Circuit-1 and Circuit-2 would have a separate grid fee based on their percentage loading. In case if agents trade energy within the same cell, then they only pay a fee based on circuit loading to which they are connected. In case if agents trade energy on a higher hierarchy, i.e, in parent cell (Figure 4) then agents pay grid fee based on percentage loading of distribution transformer (T 1 & T 2 in Figure 4) to which it is connected. Through this dynamic grid fee approach based on network loading, agents will be having economic incentive to first self-utilize their own resources then towards energy trading locally and then to higher hierarchy energy market.

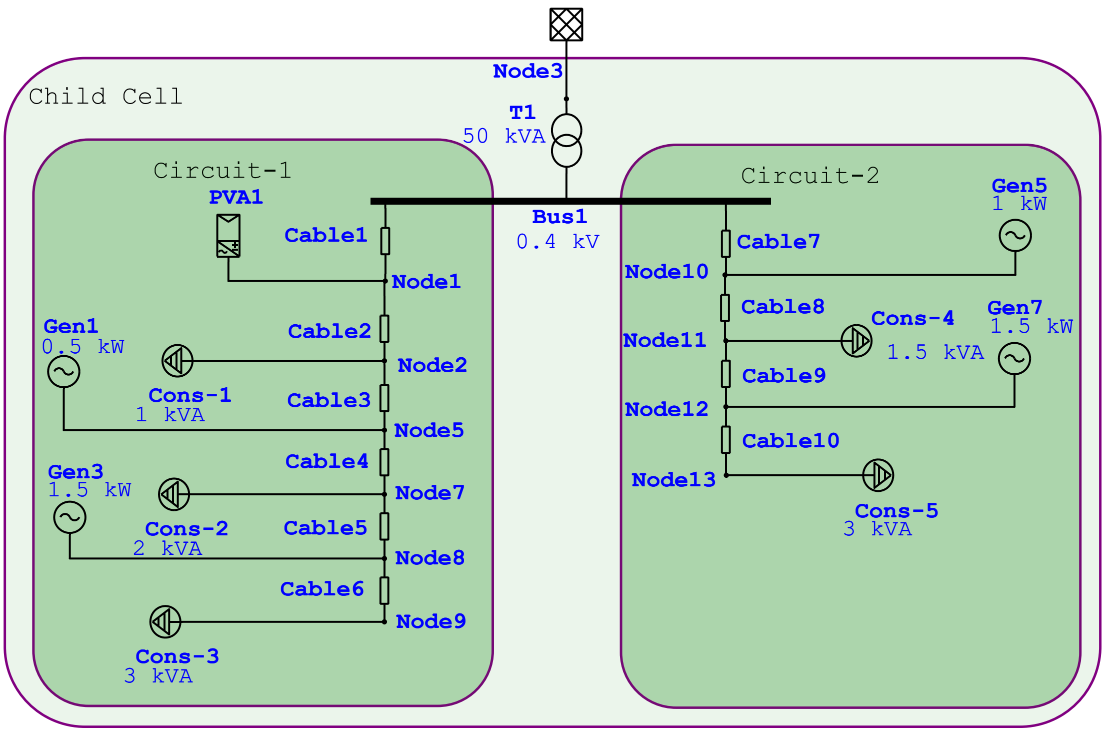


Figure 8: Low voltage distribution grid

## 3 Results

To set up a testing environment, Ethereum based private blockchain is created; Geth client is used to connect to the private blockchain. Smart contracts are written in Solidity. The simulation environment is created using python scripts. Results are monitored on a browser connected to local geth node.

| Ethereum Address | Latitude | Longitude | TRAFO ID | CIRCUIT | TYPE | PEAK LOAD (Watts) |
|---|---|---|---|---|---|---|
| 0x8d4cc2430a69d2ff5531cb5b543fa8a801b9a052 | 49.30 | 8.35 | 67376 | FIRST | PV | 2000 |
| 0x70c2df548200573304e68103e09332b267527d3d | 48.39 | 9.97 | 67376 | SECOND | CHP | 7000 |
| 0x157e9fac2f0fce439f2a74112a20ade62f4aae4a | 48.77 | 9.16 | 67376 | FIRST | BATTERY | 1500 |
| 0x831ca5e9fd7f657057c1f26a8a1b31d7c6afe4ac | 49.40 | 8.67 | 67376 | SECOND | PV | 2500 |
| 0xe2ce89c7e81428018067ee5491e075ed7563222a | 48.89 | 9.20 | 67376 | FIRST | BATTERY | 2000 |
| 0x85794a34ff485c3ff78fdbebae94eb8b80840f00 | 48.62 | 9.83 | 67376 | SECOND | BATTERY | 1500 |
| 0x3cba5c8df0c87912dedcd1e4e74a3b956b99dd43 | 48.00 | 7.84 | 67376 | FIRST | BATTERY | 2000 |
| 0x6ce80ebfd0b5d3ac0e1dcd1b058a1ceaf82b2e2f | 48.49 | 8.47 | 67376 | SECOND | CONSUMER | 3000 |
| 0xa3da6c30a3ed293dc05040d084f5d06486ddd349 | 49.32 | 8.44 | 67376 | FIRST | CONSUMER | 1500 |
| 0xda9f248c4df6047df32c1c2254613db838080c3b | 48.41 | 10.00 | 67376 | SECOND | CONSUMER | 3500 |
| 0x72e777ed91bf13a1d23c49f86854b270cc7364c1 | 48.69 | 9.21 | 67377 | FIRST | PV | 4500 |
| 0x9633783b5acd7792f984ef6e6e28e4099e9e995d | 49.47 | 8.47 | 67377 | SECOND | CHP | 2500 |
| 0xa388592f2994b98f59119e5c67f67840616b98b0 | 48.42 | 10.07 | 67377 | FIRST | BATTERY | 2500 |
| 0xecf5cd0e0d46a119a18c49ec742060eea0abd154 | 48.80 | 9.22 | 67377 | SECOND | PV | 2500 |
| 0xb7c92d1a3464752eefba79c003ae1dfe983136ca | 48.87 | 9.22 | 67377 | FIRST | BATTERY | 2000 |
| 0xb8b90cc6c1aa8aaa69e3049cf0ff3d7bf018e14d | 48.87 | 9.19 | 67377 | SECOND | BATTERY | 2500 |
| 0x57343b07e5024d06b1eaf8e4b589dca9030e41fc | 48.81 | 9.18 | 67377 | FIRST | BATTERY | 2000 |
| 0xfa0ec7bf98a55358dd936d1c80d91357e20dd7e0 | 48.40 | 9.96 | 67377 | SECOND | CONSUMER | 2500 |
| 0xff64f98ff75e05ac97802747904a38137a05fca0 | 48.50 | 10.06 | 67377 | FIRST | CONSUMER | 2000 |
| 0xa9322a0fc5d21b0ecf6cf3b3a8a9c5027f8e3838 | 48.6 | 10.16 | 67377 | SECOND | CONSUMER | 3500 |

Table 3: Agents' Mapping

| Ethereum Address | Trafo ID | Ckt ID | Trafo Load (Watts) | Ckt Load (Watts) |
|---|---|---|---|---|
| 0xbfd6614d47b71c8f731a6e029f7e9637afd038cf | 67376 | 0 | 50000 | 10000 |
| | | 1 | | 10000 |
| 0x0794825bc62933ec7851dad84235ba5b5bdd8a90 | 67377 | 0 | 50000 | 10000 |
| | | 1 | | 10000 |

Table 4: Distribution grid mapping

## 3.1 Testing of Blockchain based Registry System

Blockchain based agents' registry system is tested with information given in Table 3. In Table 3, all agents have a unique Ethereum address also called Externally Owned Account - EOA. With this unique Ethereum address, their GPS coordinate, transformer ID and radial circuit ID to which that agent is connected, type of energy that particular agent has, as well as its peak contract power are mapped. All the registries done in blockchain were also monitored through a browser connected to blockchain.

All distribution transformers are also given a unique transformer ID for clustering agents connected to the same transformer to form a microgrid and defining the connection points. Transformer as well as circuits maximum load bearing capacity is also mapped for the calculation of percentage loading based grid fee (Section 2.4). As shown in Table 4, two different distribution grids (called Child Cell in this manuscript) are mapped with their transformer ID, transformer load, number of distribution circuit and their respective load-bearing capacity. These associated details were also monitored on a browser connected to blockchain.

## 3.2 Testing of Bilateral Energy Trading

This bilateral contract is simulated using python script and monitored on a browser connected to blockchain (Figure 9) using JavaScript. First Producer registered his/her stock with the amount of power to sell and minimum rate willing to accept with contract duration and period till he/she is accepting the bid. Once the stock has been registered, there are several bidders, who are willing to purchase, bid with their willingness to pay for this stock. Once the bidding time is over, there is a bilateral contract between the power producer and highest bidder.

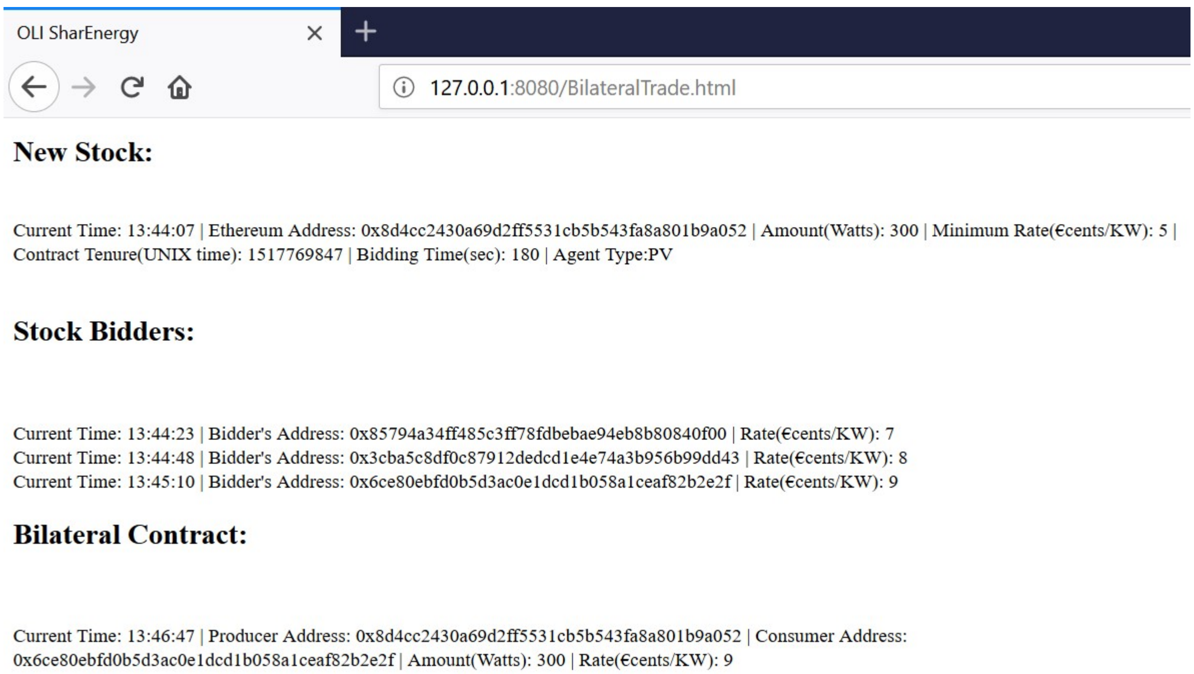


Figure 9: Blockchain based bilateral energy trade contract monitoring on browser

## 3.3 Testing of Energy Trading via Bids Aggregation

In this manuscript, two hierarchies of Aggregate Energy Markets are created and tested:

1. Child Cell (Lower hierarchy)
2. Parent Cell (Higher hierarchy)

At lower hierarchy, two parallel aggregate energy markets are created and tested called Child Cell # 1 and Child Cell # 2 (in reference to Figure 4). Agents are clustered in their respective Child Cells based on the transformer to which they are connected. Agents connected to a transformer ID ‘67376’ are clustered in Child Cell # 1 whereas agents connected

| Producers' Bid | | |
|---|---|---|
| Ethereum Address | Energy Rate (€ cents/kWh) | Amount(Watts) |
| 0x8d4cc2430a69d2ff5531cb5b543fa8a801b9a052 | 3 | 6500 |
| 0x70c2df548200573304e68103e09332b267527d3d | 10 | 1015 |
| 0x157e9fac2f0fce439f2a74112a20ade62f4aae4a | 13 | 542 |
| 0x831ca5e9fd7f657057c1f26a8a1b31d7c6afe4ac | 14 | 2027 |
| 0xe2ce89c7e81428018067ee5491e075ed7563222a | 15 | 1567 |
| Consumers' Bid | | |
| Ethereum Address | Energy Rate (€ cents/kWh) | Amount(Watts) |
| 0x85794a34ff485c3ff78fdbebae94eb8b80840f00 | 9 | 1007 |
| 0x3cba5c8df0c87912dedcd1e4e74a3b956b99dd43 | 10 | 1511 |
| 0x6ce80ebfd0b5d3ac0e1dcd1b058a1ceaf82b2e2f | 12 | 2510 |
| 0xa3da6c30a3ed293dc05040d084f5d06486ddd349 | 13 | 1010 |
| 0xda9f248c4df6047df32c1c2254613db838080c3b | 14 | 3025 |

Table 5: Agents' bidding in child cell # 1

to a transformer ID '67377' are clustered in Child Cell # 2. ChildAuction.sol is clustering agents on their respective cells by getting agents' transformer ID from OLIDetail.sol. At the time of deployment ChildAuction.sol, transformer ID is hard-wired by using function constructor .

Agents clustered in Child Cell # 1 will bid with the amount of power with their price preference as shown in Table 5. ChildAuction.sol that is hardwired with transformer ID '67376', verifies the agents' transformer ID from OLIDetail.sol and then aggregates all the bids based on merit order and calculate the market clearing price, shown in Figure 10. On the basis of this market clearing price communicated back to agents, they had to fulfill their commitment. The scenario showed in Figure 10, MCP calculated is €10 cents/kW, so producers who bid lower than this MCP are allowed to produce energy in this cycle and the rest have to shut down their production. Consumers who bid higher than MCP can consume, the one who bid lower than MCP have to completely shut down their load. Agents who bid equal to MCP may have to vary their supply/demand to maintain power balancing.

Agents clustered in Child Cell # 2 (Figure 4) will bid the amount power and their price preference as shown in Table 6 on separate ChildAuction.sol, that is hardwired with transformer ID '67377' aggregates all the bids on the basis of merit order and calculate the market clearing price, shown in Figure 11. On the basis of this market clearing price communicated back to agents, they had to fulfill their commitment.

The same kind of aggregate energy market is also conducted at a higher hierarchy (called Parent Cell in this manuscript). Transformers IDs of Child Cells that are connected to Parent Cell are hard wired (in reference to Figure 4) so that only agents of Child Cell that are connected to Parent Cell via transformer or agents that are directly connected to

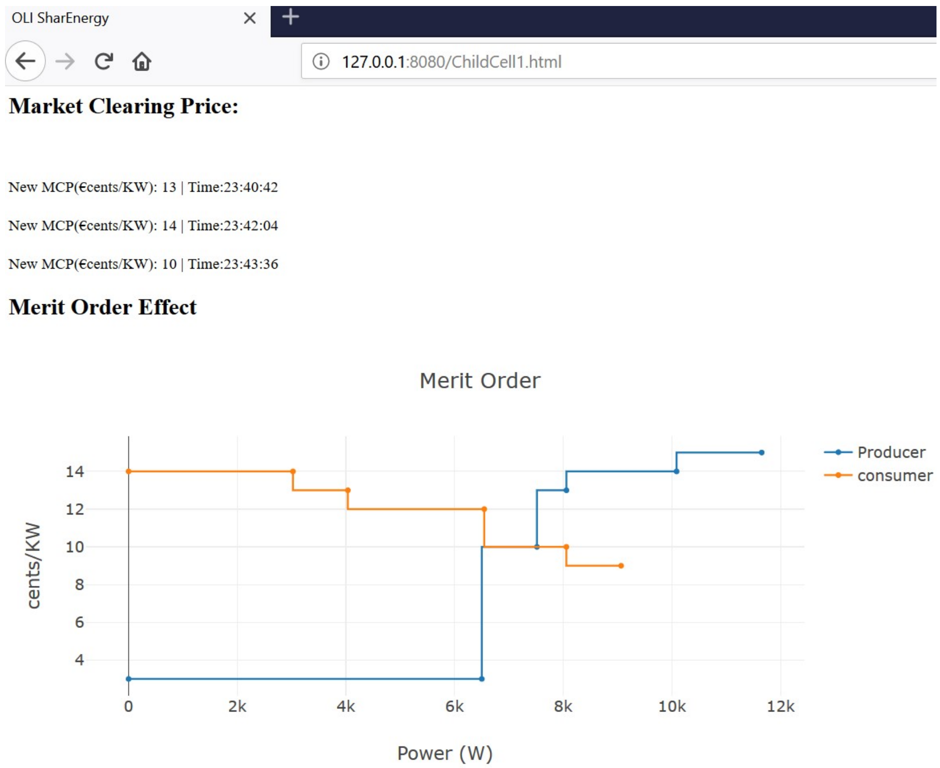


Figure 10: Real-time blockchain based aggregate market visualization of child cell # 1

Parent Cell are allowed to bid in Parent Cell's aggregate energy market. ParentAuction.sol collects agents' bid as shown in Table 7, aggregates the bids on merit order and calculate MCP as shown in Figure 12, however, the only difference between energy trading in Child Cell or Parent Cell is the higher amount of grid fee charged, will be discussed in detail in Section 3.5.

## 3.4 Grid Fee Setting

Setting grid fee is a jurisdiction and economic dependant debate (Jahn, 2014). In this manuscript, its floor and ceiling values are manually set by smart contract owner at the time of smart contract deployment to keep it simple; However, in future a more robust mechanism could be designed based on DAO[2] smart contract (*Ethereum Project*, 2018). Using this grid fee range, dynamic grid fee would be dictated based on existing network loading. As shown in Table 8, distribution grid fee's (ie energy traded in child cell) mini-

[2]A DAO (Decentralized Autonomous Organization) can be seen as the most complex form of a smart contract, where the bylaws of the decentralized organization are embedded into the code of the smart contract

| Producers' Bid | | |
|---|---|---|
| Ethereum Address | Energy Rate (€ cents/kWh) | Amount(Watts) |
| 0x72e777ed91bf13a1d23c49f86854b270cc7364c1 | 5 | 4500 |
| 0x9633783b5acd7792f984ef6e6e28e4099e9e995d | 10 | 2037 |
| 0xa388592f2994b98f59119e5c67f67840616b98b0 | 12 | 843 |
| 0xecf5cd0e0d46a119a18c49ec742060eea0abd154 | 13 | 2027 |
| 0xb7c92d1a3464752eefba79c003ae1dfe983136ca | 14 | 1553 |
| Consumers' Bid | | |
| Ethereum Address | Energy Rate (€ cents/kWh) | Amount(Watts) |
| 0xb8b90cc6c1aa8aaa69e3049cf0ff3d7bf018e14d | 7 | 2205 |
| 0x57343b07e5024d06b1eaf8e4b589dca9030e41fc | 9 | 1540 |
| 0xfa0ec7bf98a55358dd936d1c80d91357e20dd7e0 | 11 | 2348 |
| 0xff64f98ff75e05ac97802747904a38137a05fca0 | 12 | 1044 |
| 0xa9322a0fc5d21b0ecf6cf3b3a8a9c5027f8e3838 | 13 | 3045 |

Table 6: Agents' bidding in child cell # 2

| Producers' Bid | | |
|---|---|---|
| Ethereum Address | Energy Rate (€ cents/kWh) | Amount(Watts) |
| 0x72e777ed91bf13a1d23c49f86854b270cc7364c1 | 13 | 502 |
| 0x9633783b5acd7792f984ef6e6e28e4099e9e995d | 14 | 2000 |
| 0xa388592f2994b98f59119e5c67f67840616b98b0 | 15 | 1504 |
| 0xe2ce89c7e81428018067ee5491e075ed7563222a | 10 | 1000 |
| Consumers' Bid | | |
| Ethereum Address | Energy Rate (€ cents/kWh) | Amount(Watts) |
| 0xb8b90cc6c1aa8aaa69e3049cf0ff3d7bf018e14d | 10 | 1500 |
| 0x57343b07e5024d06b1eaf8e4b589dca9030e41fc | 12 | 2001 |
| 0xfa0ec7bf98a55358dd936d1c80d91357e20dd7e0 | 13 | 1001 |
| 0xff64f98ff75e05ac97802747904a38137a05fca0 | 14 | 1600 |

Table 7: Agents' bidding in parent cell

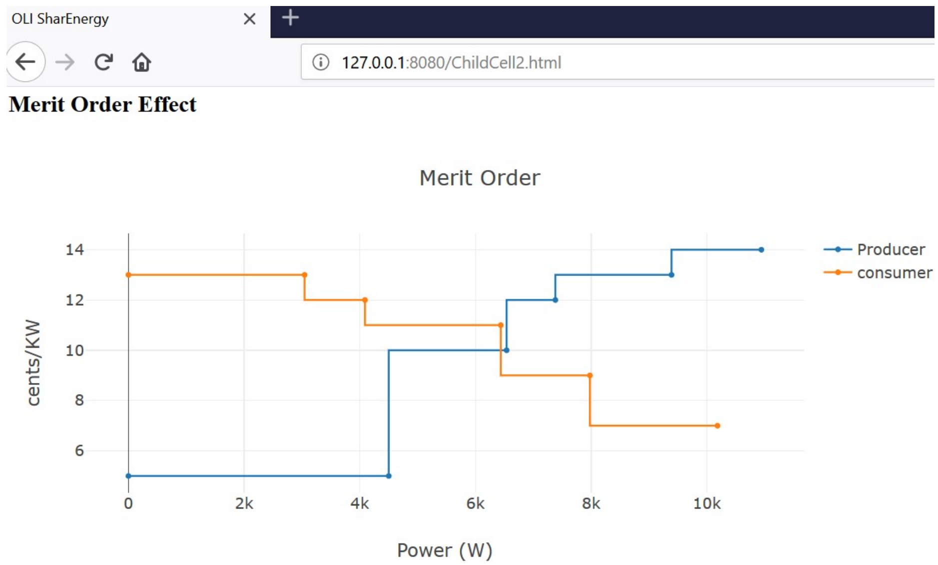


Figure 11: Real-time blockchain based aggregate market visualization of child cell # 2

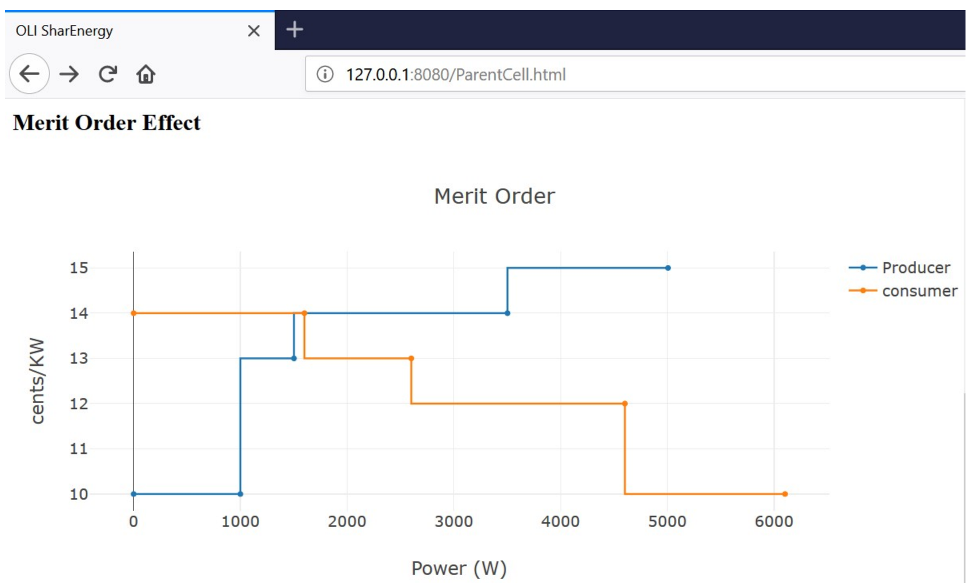


Figure 12: Real-time blockchain based aggregate market visualization of parent cell

mum value is set as €1 cent/kW, maximum value is set as €3 cents/kW. Agents trading energy locally (within child cell) only pay distribution grid fee. Transmission grid fee's (i.e. energy traded in parent cell) minimum value is set as €4 cents/kW, maximum value

| | Fee - Min/Max (€cents/kW) |
|---|---|
| Child Cell | 1/3 |
| Parent Cell | 4/6 |

Table 8: Grid Fee Setting

| Distribution Grid Fee | | Transmission Grid Fee | |
|---|---|---|---|
| Circuit Loading (%) | Fee - Min/Max (€cents/kW) | Transformer Loading (%) | Fee - Min/Max (€cents/kW) |
| <35 | 1 | <35 | 4 |
| 35-90 | 2 | 35-90 | 5 |
| >90 | 3 | >90 | 6 |

Table 9: Criteria for grid fee calculation

is set as €6 cents/kW. Agents trading energy on a higher hierarchy (parent cell) have to pay transmission grid fee. Python script is used to set grid fee limit on smart contract named DynamicGridFee.sol which is responsible for dictating the real-time grid fee based on percentage loading.

### 3.5 Dynamic Grid Fee Monitoring

In this manuscript, grid fee is a dynamic value and calculated for every cycle of energy trading through DynamicGridFee.sol which is basically calculating grid fee based on percentage loading of grid. Table 9 shows the way DynamicGridFee.sol (Figure 5) is calculating the grid fee. It basically splits the grid fee into three steps, that is if network loading is below 35 %, floor value of grid fee would be charged, if it is between 35% to 90% then the mid value of grid fee would be charged and if loading goes above 90% then the ceiling value of grid fee would be charged.

Figure 13 shows the historical grid fee for energy trading in Child Cell and percentage loading of that distribution circuit. Grid fee in Child Cell is directly related to percentage loading of distribution circuit ('Circuit-1' & 'Circuit-2' are distribution circuits shown in Figure 8).

Figure 14 shows the historical grid fee for energy trading in Parent Cell as well as percentage loading of distribution transformer. Grid fee in Parent Cell is directly related to percentage loading of distribution transformer (T1 & T6 are distribution transformers shown in Figure 4). It can be observed from Figure 13 and Figure 14, that grid fee for energy trading in Child Cell is lower than the grid fee for energy trading in Parent Cell, which will promote agents to trade energy locally (within Child Cell).

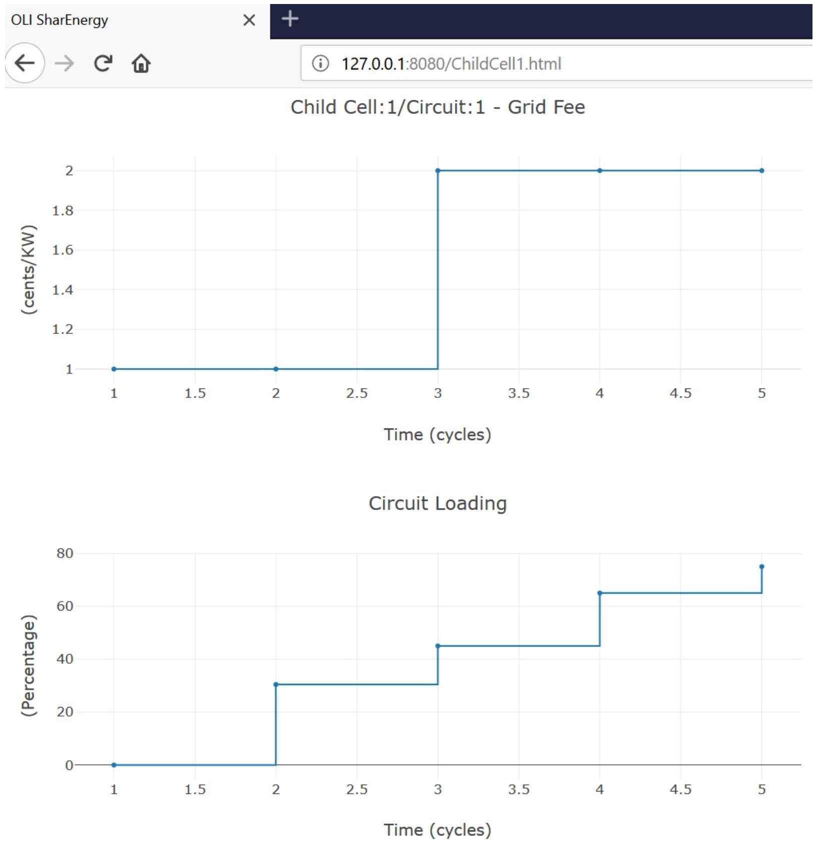


Figure 13: Real-time grid fee in Child Cell

### 3.6 Mutual Energy Bill Settlement

Agents can settle their energy bills mutually without the involvement of any utility or any cryptocurrency exchanges Figure 15 shows an example of mutual energy bill settlement between two agents. Positive coin balance shows that agent must be paid of the equivalent amount of energy he/she had sold, whereas negative coin balance shows that he/she has to pay the equivalent amount of energy he/she had consumed. Left side of Figure15 shows the OLICoin balance before energy bill settlement. At the bottom of Figure 15, has the section of 'Coin Settlements' where agents can transfer the OLICoins to another account and in return, getting money in euros (currently only OLICoins are transferred, but in future fiat currency could also be transferred by linking it to any banking services). Left side of Figure 15 shows the coin transfer between account # 5 & 8. Account # 5 transferred 500 OLICoins to account # 8 and in return account # 8 will get €5 from account # 5 (as 100OLICoin = €1).


Figure 14: Real-time grid fee in Parent Cell

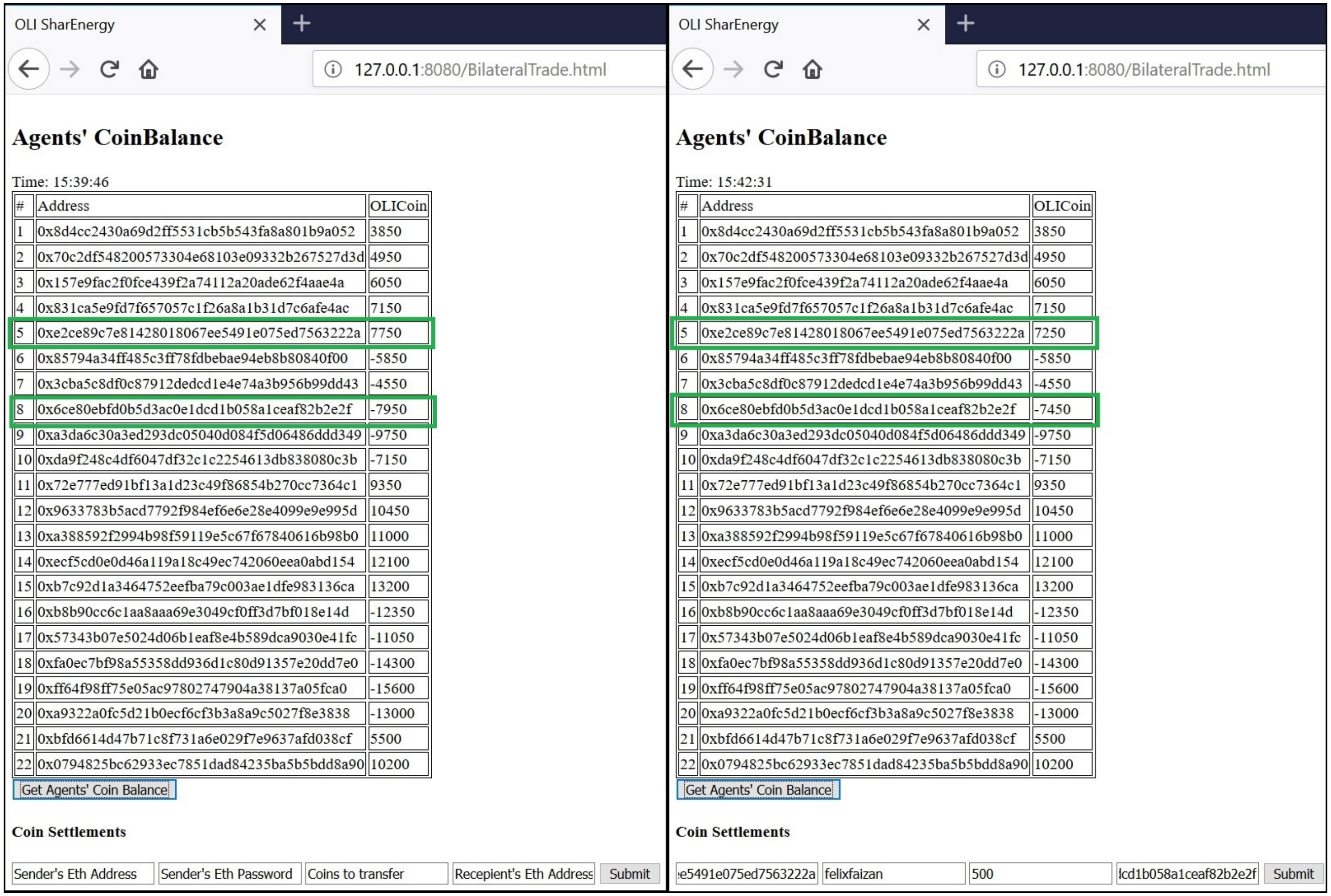


Figure 15: Agents' OLICoin balance - Left: Before trading; Right: After trading

# 4 Conclusion

Due to the decentralized nature of blockchain technology and the problems faced by current electricity market, as discussed in our introductory part. In this manuscript, a simulated model of agents' energy trading using Ethereum private blockchain is created. It is concluded, based on results, blockchain due to its consensus algorithm and decentralized in nature would be a good platform to:

1. Prevent energy grid infrastructure with any downtime due to any attack previously observed on SCADA based energy grid.
2. Facilitate a decentralized energy trading platform, enabling agents to trade energy independently without the need of any third party like energy suppliers.
3. Independent energy billing of agents and their settlements without the need of any third party responsible for energy bill settlements, based on stable priced cryptocurrency tokens on top of blockchain as formulated in this manuscript.

This manuscript is tested with 20 agents trading energy on PoW based private Ethereum blockchain. However, in real world electricity users are in billions that could lead to blockchain network congestion that is previously observed in ethereum public blockchain when cryptokitties were launched (Roberts, 2017). In order to keep the electrical network stable, transaction has to be processed relatively faster. Therefore, despite the blockchain being byzantine fault tolerant, scalability would be an important issue to be addressed to make blockhain practical for energy industry to incorporate a huge number of transactions at a time. Energy Web Foundation's PoA based Ethereum blockchain having the possibility of higher transaction, faster block update speed and environment friendly in terms of less energy requirement for mining compared to Ethereum's Public Blockchain could be a feasible solution (Hartnett, 2018). Still a single network would still be subject to scalability limitations, the theoretical possibility exists to run multiple blockchain networks in parallel. The Polkadot project is currently developing the architecture that enables interconnectivity between multiple Blockchains through a so-called relay-chain, providing a tool to overcome the scalability hurdle through this multi-chain framework (*How Polkadot tackles the biggest problems facing blockchain innovators*, 2018). Utilizing the power of Polkadot, a separate chain can be put in place in each federal state/territory , connected via a single umbrella relay-chain. If necessary, a further division for even smaller market areas can be done. Hierarchies of several blockchains could also enables the storage of data to be concentrated within a specific geographical area, in order to be complied with data sovereignty regulations.

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