Transactive Energy Management with Blockchain Smart Contracts for P2P Multi-Settlement Markets

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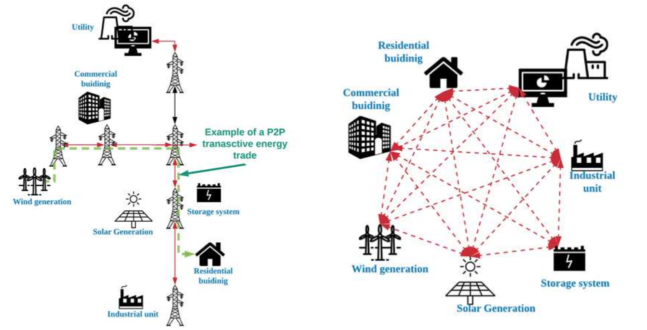
***Abstract*—Integration of renewables and energy storage, leading to rise of prosumers, has created localized bidirectional flows. As the result, the utility demand has decreased and traditional centralized controller can no longer realize the optimal performance of ever growing distribution systems. To achieve scalable control, exploiting the potential of smart loads and Distributed Energy Resource (DER) controllability, a framework for decentralized Peer-To-Peer (P2P) energy management has been developed to manage localized micro-energy markets. Such decentralized management approach could, in theory, sustain diverse prosumer and utility business models. We have been developing an autonomous decentralized management solution that maximizes the benefit of prosumers while protecting utility assets. This P2P energy trading market leverages Blockchain technology and its Smart Contract framework. This paper presents 1) transactive energy market for P2P multi-settlement markets, 2) architecture of blockchain-based energy management system, 3) smart contract design that solves an economic dispatch problem of DERs to maximize the profit of pro/consumers.**

***Index Terms*—Blockchain, Smart Contract, Transactive Energy, Multi-Settlement Market, Peer-To-Peer Transactions, Distributed Energy Resources**

I. Introduction

Power, in traditional energy networks, flows in one direction, from a centralized authority to end-use customers. Digitalization and automation of distribution grid components as well as rapid integration of the intermittent renewable distributed energy resources (DERs) to the grid are changing the electricity sector dynamics and requirements. Due to high volatility and uncertainty of DERs, utmost attention has been required to exploit the abilities of flexible loads and smart meters to increase the system reliability. In order to integrate the flexible intelligent loads and DERs and also to realize grid control scalability, *Transactive Energy (TE)* [1], [2] is emerging to coordinate the operation of modernized and intelligent power systems. Recently, a TE based platform called PowerMatcher was proposed [3] that realizes a market-based control concept for supply and demand matching (SDM) in electricity networks. Another TE approach based on double auction mechanism was suggested in [4], [5] former one for demand response on the operation of an electric power distribution system and latter one for microgrid energy transactions. In those approaches, the trust among the TE agents has been imposed by the central authorities (e.g. utilities) or aggregators as in [6] with appropriate signals and references.

The blockchain protocols have been developed as a foundation of Bitcoin [7] and Ethereum [8] projects. Its application to P2P energy transactions has been conducted as seen in some pilot projects to enable decentralized power trading [9], [10] where the customers can sell surplus energies to their neighbors. The report [11] also discusses many specific requirements of an energy blockchain and provides several practical recommendations to the industry. The decentralized optimization with blockchains in [12] solves the typical power flow problem of minimizing the cost of power obtained from the grid. However, the literature has either focuses on microgrid management or optimal power flow (OPF) solutions over distribution grid, and not provides a comprehensive and consistent mechanism of transactive market structure by fully utilizing smart contract functionalities as well as an architecture to enable the whole market structure.



(a) Energy flows in a distribution grid with active prosumers.

(b) P2P data flows in a multi-settlement transactive market.

Fig. 1. P2P energy trading network over a distribution grid.

We propose a blockchain-based transactive energy management for P2P multi-settlement markets in a distribution grid in which the consumers and prosumers exchange energy directly in the decentralized way through well-designed smart contracts with minimum utility intervention as illustrated in Fig.1. To achieve that, a blockchain-based platform can not only implement faster, trusted, and more secured transactions, but also realize decentralized power trading among customers in a distribution network. In particular, an operational optimization that minimizes the cost of energy buyers is implemented in smart contracts shared among all the blockchain nodes. Also, a decentralized application of our blockchain-based platform features a strategic tool on how much customers could sell/buy to bring the most benefits and savings with the P2P energy trading market.

II. Transactive Energy Market Structure

We propose a multi-settlement pool market, which is similar to what is performed in the wholesale electricity market, but is implemented in the decentralized way using the blockchain technology. The proposed P2P TE market solution provides the following feature and values:

1) Our suggested multi-settlement market is able to provide a competitive market environment for prosumers with intermittent generation using a *forward market* and to guarantee system reliability by implementing a *real-time balancing market*.
2) The suggested market structure provides a space for accommodating comprehensive decision making tools for the prosumers to strategically participate in TE market and maximize their profits.
3) All transactions and data exchanges are conducted through smart contracts shared within a blockchain network and all auction outcomes and energy transactions are authenticated using consensus algorithms.

The overall flow of the procedure of the proposed market is shown in Fig. 2. The detail of each component of the proposed market is described in the following sections.

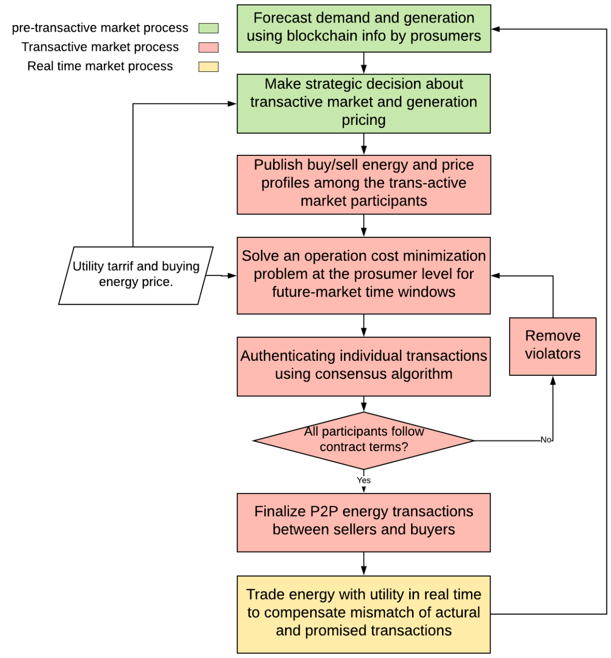


Fig. 2. Flowchart of the proposed market structure.

A. Pre-Transactive Market Process

In the proposed design, at the current time t, the forward market enables TE market customers, defined as *TE nodes*, to trade energy between other nodes for time intervals $T_f = \{t+m, t+m+1, ..., t+m+n\}$. To join this forward market, a consumer node $j \in \mathcal{C}$ should submit their demand profile $\{d_j(t_k)\}$ for each corresponding time interval $t_k \in T_f$, or a prosumer node $i \in \mathcal{P}$ should submit their generation capacity profile $\{\overline{g}_i(t_k)\}$ with selling price $\{p_i(t_k)\}$ for each $t_k \in T_f$. Then, the submitted information is utilized to solve as a decentralized economic dispatch problem written in smart contract where the results of the problem are used for market clearing and TE energy trading. Depending on generation activity of DER, a TE node can be either a prosumer or consumer, thus the set of prosumers $\mathcal{P}$ and the set of consumers $\mathcal{C}$ could vary dynamically. Since these parameters to be published to the market (market information) could impact the benefits and savings of the TE nodes, in the pre-transactive market process in Fig. 2, each TE node should be equipped with an appropriate forecasting and decision making tool to maximize its profit by selecting an optimal strategy to prepare for the upcoming transactive market process.

B. Transactive Market Process

Each TE node must publish market information about its demand or generation decided in the pre-transactive market for each window t_k of the forward market T_f through smart contracts. Therefore, all TE nodes receive the published market information of all the other nodes through updated smart contract at time t for T_f. Although the Utility does not participate in the forward market, the Time-Of-Use (TOU) and Feed-In-Tariff (FIT) are used to limit the energy prices and balance the demand and generation in the forward market. Hence, given the received information for the forward market time windows $t_k \in T_f$, TE nodes should solve the following economic dispatch problem.

$$\min_{g} \quad \sum_{t_k \in T_f} \{ \sum_{i \in \mathcal{P}} (p_i(t_k) + p_{ser}).g_i(t_k) + p_{tou}(t_k).D_U(t_k) - p_{fit}(t_k).G_U(t_k) \} \tag{1a}$$

$$s.t \quad 0 \le g_i(t_k) \le \overline{g}_i(t_k), \quad i \in \mathcal{P} \tag{1b}$$

$$p_{fit}(t_k) < p_i(t_k) < \alpha.p_{tou}(t_k), \quad i \in \mathcal{P} \tag{1c}$$

$$\sum_{i \in \mathcal{P}} g_i(t_k) + D_U(t_k) = \sum_{j \in \mathcal{C}} d_j(t_k) + G_U(t_k) \tag{1d}$$

$$\underline{c}_l \le p_l(t_k) \le \overline{c}_l, \quad l \in \mathcal{L} \tag{1e}$$

where $p_i(t_k)$ is an offered price of a prosumer $i \in \mathcal{P}$ for the forward time window $t_k \in T_f$, $p_{ser}(t_k)$ is the utility charge for infrastructure services, $g_i(t_k)$ is the generation of a prosumer $i \in \mathcal{P}$, and $d_j(t_k)$ is the demand of a consumer $j \in \mathcal{C}$. $D_U(t_k)$ and $G_U(t_k)$ are the energy provided or bought by a utility to balance the demand and generation where

$$D_U(t_k) = \begin{cases} \sum_{j \in \mathcal{C}} d_j(t_k) - \sum_{i \in \mathcal{P}} g_i(t_k) & \text{if } \sum_{j \in \mathcal{C}} d_j(t_k) > \sum_{i \in \mathcal{P}} g_i(t_k) \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

$$G_U(t_k) = \begin{cases} \sum_{i \in \mathcal{P}} g_i(t_k) - \sum_{j \in \mathcal{C}} d_j(t_k) & \text{if } \sum_{i \in \mathcal{P}} g_i(t_k) \ge \sum_{j \in \mathcal{C}} d_j(t_k) \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

$\overline{g}_i(t_k)$ is the generation capacity at time t_k published by a prosumer i. $p_{fit}(t_k)$ is the Feed-in-Tariff (FIT) price when selling energy back to the utility and $p_{tou}(t_k)$ is the Time of

Use (TOU) price, both of them are positive numbers. $\alpha \in [0, 1]$ represents a weight on the TOU. Finally, $p_l(t_k)$ is the power flow on the line $l \in \mathcal{L}$ with its capacity $\overline{c}_l$ and $\underline{c}_l$.

In the course of solving the optimization problem, a *market clearing price* $p^c(t_k)$ is calculated by which all the TE nodes should transact energy. The market clearing price also needs to be bouded by $p_{fit}(t_k) < p^c(t_k) \leq \alpha . p_{tou}(t_k)$. The procedure of deciding the market clearing price is described in the following section with smart contract design.

With the value of the market clearing price, the mechanism of deciding P2P energy transactions also needs to be defined in the smart contract so that TE nodes could exchange Digital Currency with one another. In the transactive market process, after all/several authenticated nodes solving the economic dispatch optimization (1), those nodes publish the results of the solution over the blockchain network. Since those nodes solve the same optimization through a smart contract, their results must be identical, otherwise violators will be removed by a consensus mechanism.

C. Real-Time Market Process

The main objective of this real-time market process is to realize the demand and generation balance to maintain reliable operation of the system. The demands and injected generations by the TE nodes may not be balanced, and thus not identical to the summation of their TE binded transactions due to load and generation uncertainties and the fact that the demands or generations could not be fully bought or sold because of demand and generation imbalance.

After the transactive market process, any inconsistency between P2P energy transactions and real demand and generation is resolved through trading energy with utilities in this real-time market process. The binded transactions are saved in the distributed ledgers, so any TE market nodes including utilities have an access to all the transaction history for any past time windows. This real-time process includes interaction with physical devices such as communications with smart meters. At time t, let the actual generation and demand be $g_i^a(t)$ and $d_j^a(t)$, respectively. For psorumers' side, if $g_i^a(t) < g_i(t)$, they need to buy energy $g_i(t) - g_i^a(t)$ from a utility with TOU price, otherwise the energy $g_i^a(t) - g_i(t)$ is sold to a utility with FIT or stored into a battery. For consumers' side, if $d_i^a(t) > d_i(t)$, they need to buy energy $d_i^a(t) - d_i(t)$ from a utility with TOU price, otherwise the energy $d_i(t) - d_i^a(t)$ should be sold to a utility with FIT unless it is stored into a battery.

III. Blockchain-Based TE Market Components

We discuss three important components for realizing and sustaining the proposed TE market with a blockchain-based platform.

A. Architecture

The overall architecture of the blockchain-based autonomous TE platform is depicted in Fig. 3 where there is a P2P (private) blockchain network, blockchain nodes (Ethereum nodes) with distributed ledgers containing whole

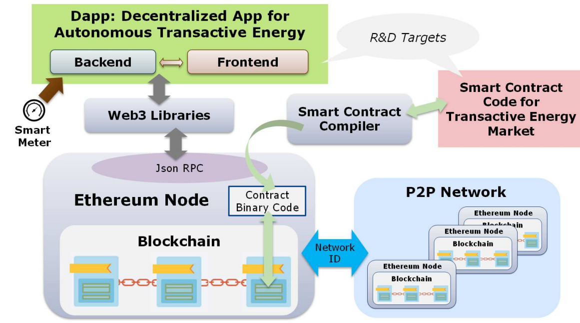


Fig. 3. The architecture for TE market platform.

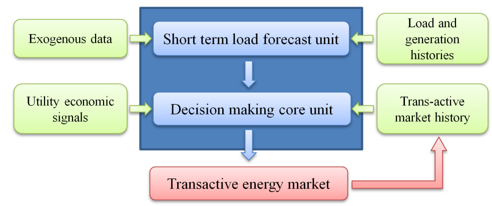


Fig. 4. The proposed TE decision making unit architecture for TE node.

histories of smart contracts, web3 libraries (e.g. web3.js, web3.py) that bridge local/cloud decentralized applications with data and functions of a blockchain node. Our research and development target has been the Decentralized Application, so-called *Dapp*, and Smart Contract Codes for P2P Transactive Energy Management that work with blockchain technologies. Dapp mainly optimizes pre-transactive market process with blockchain history data whereas smart contract codes basically handle transactive market process to solve an optimization problem for all and share data and transactions with all blockchain nodes.

B. Dapp: Decentralized Application

Fig. 4 shows the main components of the proposed decision making unit for the pre-transactive process implemented as Dapp. Since any deviation from the binded transactions should be compensated in the real-time market process by trading energy with utilities, the essential step in order to make an appropriate decision is to provide accurate forecast of the short-term net load profile based on load and generation histories and exogenous data such as climate information. The core module of the proposed decision making unit is responsible for making the best decisions about market information to be published in each window of the forward market T_f using the net load forecast, utility economic signals (i.e TOU, FIT), and transactive historical data.

C. Smart Contract Design

Here is the overall structure of the smart contract we have developed with a list of data and functions.

1) Data: The following items are the overall data stored in the smart contract.

- Current time index and forward market time windows

- Addresses of creator of smart contract, list of authenticated TE nodes, etc.
- List of TE node information including customer ID, PV generation capability, violation flag, etc.
- List of published generation information and its history
- List of published demand information and its history
- List of P2P energy transaction records
- List of real-time utility transaction records

2) Functions: These are the main functions described in the smart contract.

- Giving right to participate in P2P transactive energy market trading only called by an operator
- Posting/modifying generation information in the forward market time frame called by any TE nodes
- Posting/modifying demand information in the forward market time frame called by any TE nodes
- Deciding the market clearing price called by an operator and/or authorized node(s)
- Assigning P2P energy transactions called by an operator and/or authorized node(s)
- Updating real-time transactions called by utilities

These functions are implemented with a contract-oriented language that can run in the blockchain network and nodes. In the smart contract, there are two important functions for achieving P2P transactions over multi-settlement market with the problem discussed in section II-B. One function is about deciding the market clearing price $p^c(_k)$ by which all the nodes transact their energy as written in Algorithm 1. Another function is assigning P2P energy transactions to exchange virtual energy using digital currency as written in Algorithm 2. At each time t, all/several nodes conduct those procedures in the smart contracts for the forward market $t_k \in T_f$.

Algorithm 1 Procedure for deciding the market clearing price.

Initialize the clearing market price $p^c(t_k) = 0$.
Calculate the total energy demand $D_{total} = \sum_{j \in \mathcal{C}} d_j(t_k)$.
Put all prosumer nodes in the list of generators $\mathcal{P}'$ from $\mathcal{P}$ whose offering price is $p_i(t_k) < \alpha.p_{tou}(t_k)$.
while $D_{total} > 0$ **do**
  if $\mathcal{P}' \neq \emptyset$ **then**
    Pick up a node i that has the cheapest price among $\mathcal{P}'$.
    if $D_{total} \leq g_i(t_k)$ **then**
      Set the market clearing price to $p^c(t_k) = p_i(t_k)$.
      $D_{total} = 0$.
    else
      $D_{total} \leftarrow D_{total}(t_k) - g_i(t_k)$.
      Remove the node i from $\mathcal{P}'$ where $\mathcal{P}' \leftarrow \mathcal{P}' - \{i\}$.
    end if
  else
    Set the market clearing price to $p^c(t_k) = \alpha.p_{tou}(t_k)$.
    Break the **while** loop.
  end if
end while
Return the market clearing price $p^c(t_k)$ at time t_k.

Once the market clearing price has been decided, the next step to do with the smart contracts is deciding P2P energy transactions among nodes. The procedure is written in Algorithm 2. Using the market clearing price, all/several TE nodes calculate the trading energy and digital currency that each TE node should receive or send for every interval t_k. After the procedure, authenticated P2P energy transactions S_{P2P} are recorded in the smart contract with the information about current time interval t, forward market time interval t_k, account address of energy sender $addr(i)$, account address of energy receiver $addr(j)$, transacted energy amount $E_{ij}(t_k)$, amount of transferred digital currency $DC_{ij}(t_k) = p^c(t_k).E_{ij}(t_k)$, and market clearing price $p^c(t_k)$. Then, the nodes wait for the next time window $t+1$ to repeat the TE procedures.

Algorithm 2 Procedure of assigning P2P energy transactions.

Initialize the list of P2P transactions $S_{P2P} = \emptyset$.
for each time $t_k \in T_f$ **do**
  Put all consumer nodes at time t_k in the list $\mathcal{C}' \leftarrow \mathcal{C}$.
  Put all prosumer nodes at time t_k in the list $\mathcal{P}'$ from $\mathcal{P}$ whose offering price is $p_i(t_k) < \alpha.p_{tou}(t_k)$.
  Obtain the market clearing price $p^c(t_k)$ at time t_k. (Algorithm 1)
  Initialize temporal energy and demand factors as $g' = 0, d' = 0$.
  Calculate total demand D_{total} and generation G_{total} of all consumers and prosumers at time t_k, respectively.
  if $D_{total} > G_{total}$ **then**
    $\gamma = G_{total}/D_{total}$, $\omega = 1$.
  else
    $\gamma = 1$, $\omega = D_{total}/G_{total}$.
  end if
  while $\mathcal{C}' \neq \emptyset$ **do**
    Break the **while** loop if $\mathcal{P}' = \emptyset$.
    Pick up a consumer node j from $\mathcal{C}'$, then assign $d' \leftarrow \gamma.d_j(t_k)$.
    if $g' = 0$ **then**
      Pick up a prosumer node i from $\mathcal{P}'$, then assign $g' \leftarrow \omega.g_i(t_k)$.
    end if
    while $d' > 0$ **do**
      Break the **while** loop if $\mathcal{P}' = \emptyset$.
      Transacted amount of energy $E_{ij}(t_k) = 0$.
      if $g' > d'$ **then**
        Set $E_{ij}(t_k) = d'$.
        Update parameters as $g' \leftarrow g' - d'$, $\mathcal{C}' \leftarrow \mathcal{C}' - \{j\}$, $d' \leftarrow 0$, $d_j(t_k) \leftarrow d_j(t_k) - \gamma.d_j(t_k)$.
      else
        Set $E_{ij}(t_k) = g'$.
        Update parameters as $d' \leftarrow d' - g'$, $\mathcal{P}' \leftarrow \mathcal{P}' - \{i\}$, $g' \leftarrow 0$, $g_i(t_k) \leftarrow g_i(t_k) - \omega.g_i(t_k)$.
      end if
      Add P2P energy transaction with the following info to S_{P2P}:
      Current time interval t, forward market time interval t_k, account address of energy sender $addr(i)$, account address of energy receiver $addr(j)$, transacted energy amount $E_{ij}(t_k)$, amount of transferred digital currency $DC_{ij}(t_k) = p^c(t_k).E_{ij}(t_k)$, and market clearing price $p^c(t_k)$.
    end while
  end while
end for
Return the list of P2P transactions S_{P2P}.

IV. Simulation and Results

Based on the features above, we could provide Decentralized Application (Dapp) for Customers to make the best decision in selling/buying energy, help customers optimize their battery, provide intelligent engines including unique forecasting methods, In addition, we could provide very well designed Smart Contract for Utility/Operator so that we could help operators to set up optimized values such as usage fee of grid, maintain secure Blockchain and dapp, build Blockchain network with less overhead by building systems from scratch, and set up support of cloud applications for customers.

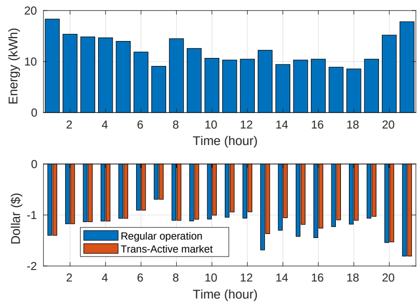


Fig. 5. A consumer's result about hourly demand and corresponding payments based on regular operation and transactive market.

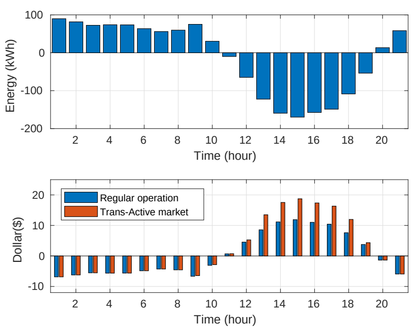


Fig. 6. A prosumer's result about hourly demand/generation and corresponding payments/rewards based on regular operation and transactive market.

In the simulation setup using our blockchain platform, we have used a testing blockchain network called "TestRPC". The smart contract has been developed using "Solidity".

We have created a demo system to simulate the customers behavior with our smart contract and decentralized application design. we perform our simulations on IEEE 33 bus distribution test system. We assumed that 16 nodes of the system join in the proposed transactive market. Also, it is assumed that 8 nodes among the transactive market participant nodes are prosumers due to their excess PV generations during the daily sunny hours. The forward market window size is $n = 4$ starting at the next time index $m = 1$, and thus the time window is $[t+1, t+2, t+3, t+4]$ at each time t. We performed two set of simulations for 21 hours operation. In the first scenario we assume that there is no transactive market while in the second scenario, the selected nodes have this opportunity to participate in the proposed transactive market.

Fig. 5 is the result of a consumer about hourly demand and corresponding payments based on regular operation and transactive market. It shows the saving in electricity cost by 6%. Fig. 6 is the result of a prosumer about hourly demand/generation and corresponding payments/rewards based on regular operation and transactive market. It shows the saving in electricity cost by 1.0% and profit by selling energy to the market by 51%. Both results show potential for both energy consumers and generators to get significant benefit from P2P transactive energy market.

V. Conclusions

In this paper, we have proposed a P2P multi-settlement transactive energy framework that consists of 1) pre-transactive market with an accurate load and generation forecast tool for TE nodes to publish optimal values in the forward market, 2) transactive market that is a blockchain-based decentralized market, which enables TE nodes to trade local energy and digital money directly with one another, and 3) real-time market in which all TE nodes trade energy with utilities to compensate their deviations from the binded transactions for the forward market as well as ensure the system stability. An architecture, decentralized application (Dapp), and smart contracts for our blockchain-based platform have been designed according to the proposed P2P TE market framework with the economic dispatch model demonstrating the benefits for both consumers and prosumers by local energy trading. The TE framework represents a potential to create a steady business model for utilities as infrastructure service providers while provides secured, reliable, and flexible space for prosumers to exploit DERs.

Our ongoing project tries to deal with an enhancement of the decentralized application and smart contract to empower prosumers to utilize our deep-learning and game-theoretical competence to win over the competition in the context of more sophisticated bidding/auction framework defined in the contract.

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