Investigate Centralized and Decentralized Information Infrastructure for Future Electricity Market

by

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DEDICATION

To My Parents

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I want to express my deepest appreciation in this section to those who directly or indirectly contributed to the completion of this work:

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ABSTRACT

The power grid is undergoing a transformation from a monopolized control system to a more decentralized one. Distributed renewable energy generation, responsive loads, and distribution automation are posing a new challenge to the traditional centralized control method. To address these challenges, we propose two innovative centralized and decentralized solutions for the information infrastructure of the future electricity market. For the centralized approach, we investigate the applications of an open-source control system platform VOLTTRON in the areas of building control and electric vehicle charging. For the case study, we implement the VOLTTRON platform to solve the economic dispatch (ED) problem. The VOLTTRON platform is used as a central message bus and 16 single-board computers are used to simulate distributed generators and dispatchable loads. For the decentralized approach, we propose an innovative Bitcoin-style distributed transactional model “Bit-Energy” using radically different Internet-of-Things technologies (Blockchain and Ethereum’s smart contract). “Bit-Energy” enables transparent, auditable, and peer-to-peer energy transactions between active market participants. We implement a highly efficient buyer/seller matching algorithm. Case studies demonstrate the accuracy, robustness, effectiveness, and scalability of the proposed Bit-Energy platform under various operating conditions.

Key-words: Smart Grid, Electricity Market, Distributed Control, Multi-Agent System (MAS), Internet-of-Things (IoT), Bitcoin.

CHAPTER 1: INTRODUCTION

There have been few changes to our current grid structure since its birth in the 1890s. The aging grid structure is struggling to keep up with the needs of the twenty-first century. The demand for electricity in U.S. have been increasing 2.5 % annually over the last twenty years [1]. As more electric vehicles (EVs) and hybrid electric vehicles (HEVs) are expected to hit the road in the next few years. The increase in power demand is only going to be rising faster. As the demands increase, the generation of electricity is also becoming more decentralized. Large coal and oil based power plant are being replaced by renewable energy generation devices and power plants. Solar and wind generation have large variation over time. House hold small renewable generation device owners will also have the need to sell their excrescent energy back to the grid. Therefore, renewable energy generation will create more Distributed Generation (DG) over the grid. These new DGs post challenges on load balancing and energy storaging. The traditional one way information and electricity flow structure no longer fits this new application. A new grid infrastructure which supports bidirectional power and information follow is urgently needed [2].

To cope these challenges, the concept of smart grid has emerged as the next generation electric power system [1]. Smart grid is defined as an electricity network that monitors and manages the transport of electricity from different generation sources to meet end-users' demands. It uses digital and other advanced technologies [3]. It is a distributed automated energy delivery network which allows two-way flows of electricity and information [2]. The Smart Grid is like an energy internet, it’s a combination of controls, automation, computers and new technologies and equipment [4]. The advance in digital, sensing and information technology helps forms the concept of smart grid. These new technologies allow the smart grid to cope with the electricity demand of the twenty-first century. Smart grid will be a great solution for the DG problem. With its ability to provide real-time generation information to the system operators, smart grid can manage generation and demand balancing with great system flexibility and stability [3].

The power system is taking the transformation from a single-purposed power distribution system to a multi-purpose power and information exchange network. The information infrastructure of the power grid will have an ever-increasing importance in the future power system.

The information infrastructure for the future smart grid can be generally divided into two parts [1]. The first part is a local part, in which the information flows from sensors, devices and different electrical appliances to a smart meter. In this part, the information flows within the customer level. The second part connects the local smart meters to the utility’s data center. The information flows from the customer level to the utility level.

The smart grid and its advanced information infrastructure is an ideal power distribution system for the future. However, it will take a considerable amount of time to convert the existing power system to a netwide smart grid.

Therefore, we proposed a hybrid power grid system. In this hybrid system, new technologies are applied on local power system and micro-grids. The concept is to cooperating local decentralized control and free market exchange system to the legacy centralized system. This hybrid system concept is fully compatible with the existing electricity grid. As most part of the grid keeps its current statues, this localized hybrid system can provide the much-needed technology support for neighborhoods and micro-grids that have its own generation devices hence the need to trade energy locally.

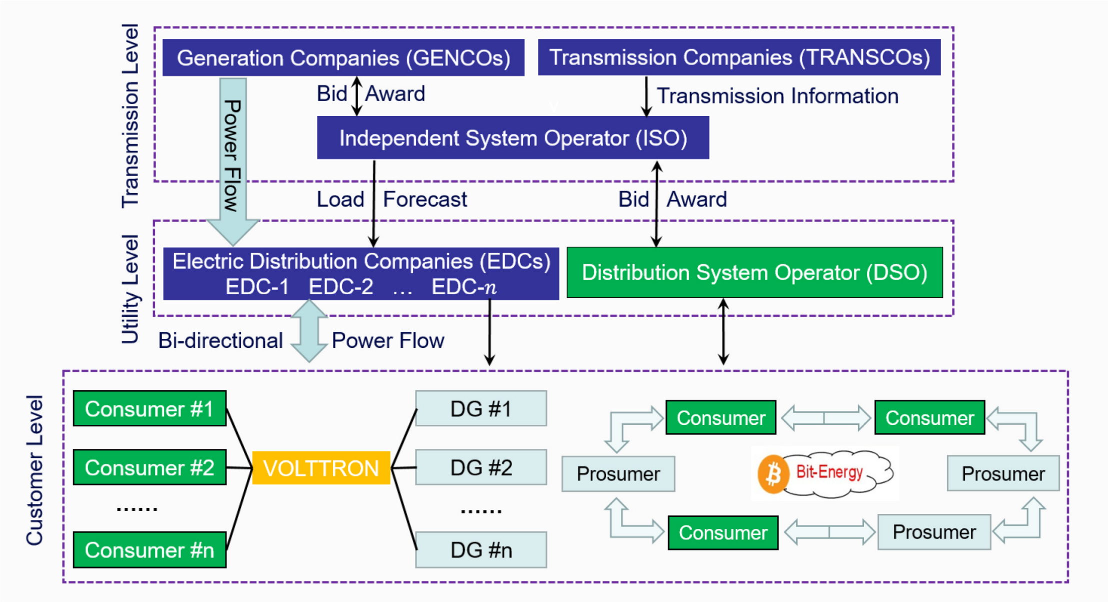


Figure 1: A hybrid and competitive electricity market

Our investigation is conducted in two part. The first part focus on localized control. The applications and advantages of using an agent-based platform VOLTTRON is stated. A simulation is conducted by using the platform and 16 single-board-computers to solve a demand-response problem in a micro-grid. VOLTTRON platform is served as a local centralized message exchange center, where the data from the 16 nodes of players are collected and exchanged. The second part focus on a localized competitive electricity market. The blockchain technology are used to construct a secure decentralized electricity free market, where peer-to-peer electricity trade are enable without any third party or intermediary.

CHAPTER 2: CENTRALIZED APPROACH VOLTTRON

The power grid is undergoing a transformation from a monopolized control system to a more decentralized one. Many new distributed issues such as renewable energy generation, responsive loads and automation in the distribution system are posing a new challenge to the traditional centralized control method [4]. A new group of agent-based software platforms is emerging to cope with this new challenge. Software agents can make local decisions based on information provided by other agents or online sources. This capability suits the decentralized control demand of the future smart grid.

2.1. Introduction to VOLTTRON

VOLTTRON is an open-source control system platform developed by the U.S. Department of Energy (DOE) at the Pacific Northwest National Laboratory (PNNL). The platform provides services such as resource management, agent code verification and directory services [5]. These services allow the platform to manage different assets within the power system. In the large scale, VOLTTRON can manage assets within smart grids, achieve demand response matching, assist with energy trading and record grid data. In a smaller scale, VOLTTRON can be a good platform for the operation and optimization of large commercial buildings.

VOLTTRON has the potential to play an important role in both the commercial and academic realm [6]. VOLTTRON allows researchers to quickly test new control methods on a multi-agent environment and can serve as an ideal platform for rapid-prototyping of new control applications. In addition, the open-source nature of the platform frees developers from any license issues. Such openness also reflects VOLTTRON's ability to merge with other platforms and software. Moreover, due to its agent mobility service, VOLTTRON agents can be transferred from platform to platform.

The concept of an agent is defined as a computer system capable of autonomous action in a situated environment [7]. An agent can react to information sent by the operator, the environment or other agents in real time. VOLTTRON's agents are generally divided into three classes [5]. Platform agents serve as service providers in the platform. Cloud agents serve as bridges between the platform and other remote platforms. Control agents control the actual hardware devices.

Figure 2 shows the basic components of the VOLTTRON platform. The message bus in the center allows agents in the platform to exchange information by publishing and subscribing to topics. The mechanism of the "publish" and "subscribe" paradigm will be discussed later in the case study section. Drivers are connected to the control objects and their controllers. Drivers, loggers and an archiver send a copy of the data to the historian in the cloud for backup.

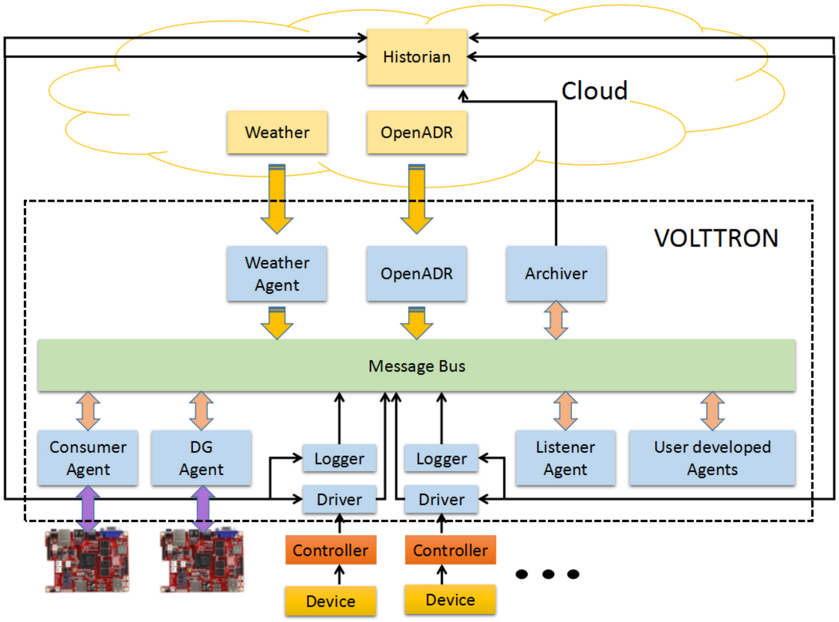


Figure 2: Basic principle of VOLTTRON

2.2. Application of VOLTTRON

This section discussed different applications of the VOLTTRON platform. The two main areas of VOLTTRON applications are building control and electric vehicles charging.

2.2.1. Applications in buildings

Worldwide, buildings cover a major part of energy consumption and greenhouse gas (GHG) emissions. Up to 40% of the total energy in the United States is consumed by buildings, which also constitute 38% of the GHG emissions of the country [6]. Considering the fact that the future smart electricity market will most likely have dynamic pricing, an implementation of up-to-date sophisticated building automation systems (BASs) with VOLTTRON could have a large impact on reducing energy consumption, GHG emissions and operation costs of buildings.

A distributed agent-based control platform is a natural fix for building control:

- VOLTTRON allows different kinds of easy access. Different communication protocols, such as BACnet, Modbus, and OpenADR, are supported by the platform, making it an ideal platform to combine the information of different assets with multiple communication protocols.

- VOLTTRON gives timely feedback and runs a real-time control cycle.

- Agents can be easily installed and uninstalled on the platform in a manner similar to that used with app stores. This allows the corresponding devices to join and leave the platform easily.

- A VOLTTRON system can be implemented in a low-cost credit-card-sized single board computer such as Raspberry Pie or Cubieboard, making it easy to implement.

The software nature of the agents allows VOLTTRON developers to program them to do a variety of tasks. Any complex control algorithm can be easily implemented into a control agent. A scalable supervisory control algorithm for the heating, ventilation, and air-conditioning (HVAC) system in large buildings using generalized gossip and the VOLTTRON platform is proposed by Chinde [8]. They divided a large-scale building into several different zones and used a distributed optimization method to reduce energy consumption. They also developed an optimization agent in VOLTTRON to run the simulation. VOLTTRON then served as both a control center and a message bus, with devices connected to VOLTTRON through BACnet.

VOLTTRON is a command-line-based system suitable for developers, as it gives developers greater freedom to modify the agents and achieve a wide range of functions. But being command-line-based also makes it unfriendly to users with little programming experience. A building management system with a graphical user interface (GUI) would have a much greater advantage than a system without one. Thankfully, VOLTTRON's open-source nature also makes it an ideal software framework to build upon.

Developers at Virginia Tech built a Building Energy Management Open Source Software (BEMOSS) platform based on the VOLTTRON platform [9]. Their platform aims at the optimized control of small- and medium-sized buildings and can control loads in buildings and implement demand response to save operation costs. The platform consists of multiple layers, with VOLTTRON being the core component of the operating system and framework layer. One of the highlights of their system is the user interface layer. The user can choose between different comfort levels associated with different costs.

2.2.2. Applications in Electric Vehicles and Smart Grids

As the world's fossil fuel starts to run out, in the near future, electric vehicles (EV) will start to replace conventional vehicles and play a greater role in transportation. Most designs of the currently running utility grid do not consider large amounts of electric vehicles charging at the same time. Using VOLTTRON as an agent-based distributed control would have serval advantages:

- The control is conducted locally, thus reducing the complexity for the utility to conduct long distance central control.
- Distributed control is more robust, meaning a single point of failure won't imperil the whole system.
- The real-time nature of the system ensures a fast response to local condition changes.

The potential of VOLTTRON's application in integrating electric vehicles and the smart grid is discussed in [5]. They built a demo with a smart home that has three EV chargers. Three types of agents were developed within the platform to share and broadcast the information, determine charging priority of the EVs within the local region and provide a user interface to record the charging data. Such a system determines when to charge an EV based on three main factors: 1) The expected time of departure 2) The charge needed and 3) Regional information, such as the power available. The order of the priority is also determined by these factors through different agents of different households. This VOLTTRON-based system not only reduces the cost for EV owners to charge their vehicles, but also provides information to the utility and helps them manage load and demand more easily.

As the percentage of EV ownership increases in densely populated urban areas, large EV charging decks will start to appear. These large charging facilities can be created by converting existing parking structures. Imagine a large-scale implementation of VOLTTRON and its impact on EV charging. The platform can provide distributed control over larger parking decks.

Utilities and parking deck owners can also use VOLTTRON to solve demand response problems and adjust their prices accordingly.

VOLTTRON can also be used to solve demand response problems in smart grids. The generation of energy is becoming more decentralized with more and more renewable energy generation devices being installed in homes all over the Unitized State. The electricity market of the future will be a dynamically priced free market. The traditional centralized control method has become unsuitable to control such a fast-changing system, meaning the decentralized control method and system will play a greater role from now on. In particular, the VOLTTRON system can be a low-cost solution for local neighborhoods to regulate and control renewable generation devices.

2.3. Related Software

Many other multi-agent platforms and decentralized control software are also available. This section gives a brief introduction to these systems and compares them with VOLTTRON. The Java Agent Development framework (JADE) is a distributed middleware system. It has a flexible infrastructure which allows easy add-on of new modules [10]. The communication model of JADE is implemented based on FIPA specifications and follows a peer-to-peer paradigm [11]. Each player in the smart grid is represented by a container, and each container can host multiple agents. One platform will have one main container and many peripheral containers. The main container hosts two special agents which facilitate agent communication [12]. The peripheral containers are instances of a runtime environment in JADE. The JADE platform and its agents are coded in Java. In addition, JADE has a graphical user interface (GUI) for debugging, which makes it more user-friendly than VOLTTRON. It also has an interface with Matlab Simulink, which allows developers to directly test their Simulink model in an agent-based platform.

ZEUS is a developer tool for building collaborative multi-agent applications. Its agent establishing technology allows users to rapidly develop multi-agent systems. The ZEUS toolkit consists of three basic component groups: an agent component library, agent building software and utility agents [13]. Each agent is made of multiple basic parts that allow it to exchange and handle messages, schedule reactions and store data. Like JADE, ZEUS is also a Java-based system and is FIPA compliant. The key advantage of ZEUS is that it modularizes the functions of an agent, so that a developer can simply choose the functions needed from the classes in the agent component library. ZEUS has a GUI and a runtime environment for programming and debugging agents, making it an ideal user-friendly tool for starters. One limitation of the ZEUS platform, however, is the lack of detailed documentation [7].

Mortar.io is an open-source platform for building automation. It provides services and applications to monitor and control different assets in a building [14]. Similar to VOLTTRON, Mortar.io uses a publish/subscribe architecture for message exchange; however, the pub/sub architecture for Mortar.io is different from that of VOLTTRON. Instead of publishing and subscribing to topics as agents do in VOLTTRON, Mortar.io's pub/sub architecture publishes or subscribes to an address or a node. The Mortar.io system consists of multiple layers, each of which provides a unique function from communicating with a control object to exchanging messages between agents to providing service and a user interface.

Compared to the software mentioned above, VOLTTRON has its own advantages and drawbacks. Unlike JADE and ZEUS, which are generalized agent platforms designed to be used in multiple domains, VOLTTRON is specifically designed for the smart grid. VOLTTRON's smart-grid-facing design makes it easily compliable with the existing communication protocol in buildings and smart grid control. Its suitability for use with multiple protocols also gives VOLTTRON the advantage of much better hardware driver support [7]. JADE and ZEUS's agents are restricted to being programmed in Java. Although most of

VOLTTRON's agents are written in Python, VOLTTRON does allow agents to be written in other languages. The mobility service even allows agents from other platforms to be transferred into VOLTTRON. Compared with Mortar.io, a software specifically designed for building automation, VOLTTRON has a wider range of applications in the smart grid. VOLTTRON's agent platform nature also makes it more flexible and more suitable for developers.

That said, VOLTTRON has some shorting comings as well. Its lack of a GUI makes developing VOLTTRON agents harder for beginners. Additionally, VOLTTRON can only be used in power industry applications.

2.4. VOLTTRON Implementation

An actual implementation case of VOLTTRON is presented in this section. The demonstration uses the VOLTTRON platform as a message bus. Decentralized generators and consumers are simulated by 16 single-board computers.

2.4.1. Problem Formulation

This section gives a brief introduction to the consensus based distributed algorithm proposed in [15]. Details regarding the modeling of the consumers and DGs are provided. The multiple constraints of the formulation are also discussed. The algorithm aims at solving the economic dispatch (ED) problem and maximizes the welfare for both the consumers and the distributed generators (DGs).

The ED problem is a short-term resource management problem in which the DGs should satisfy the load requirement of the smart grid in an optimized cost-effective way. This section formulates the ED problem with the definition of the consumers' utility function and the DGs' cost function.

A) Utility and Cost Functions

Equation (1) denotes the utility functions of the consumers. Each consumer's behavior is reflected as the parameters σ $\$/kWh2$ and ω $\$/kWh$.

$$U_j\left(P_j^{Load}\right) = \begin{cases} \omega_j P_j^{load} - \sigma_j\left(P_j^{load}\right)^2 & P_j^{load} \leq \omega_j/2\sigma_j \\ \frac{\omega_j^2}{4\sigma_j} & P_j^{load} \geq \omega_j/2\sigma_j \end{cases} \tag{1}$$

The DGs are modeled by a quadratic mathematical equation. Each DG is customized by its unique set of parameters of α $\$/kWh2$, β $\$/kWh$ and γ $\$/h$. P_i^{Gen} denotes the power generated by DG number i.

$$C_i\left(P_i^{Gen}\right) = \alpha_i\left(P_i^{Gen}\right)^2 + \beta_i P_i^{Gen} + \gamma_i, \quad i \in S_G \tag{2}$$

The objective function maximizes the summation of the utility functions (1) and minimizes the summation of the cost functions (2). Therefore, it aims to maximize the profits for both the consumers and the DGs. The objective function is shown below:

$$\text{Min}\left(\sum_{i \in S_G} C_i\left(P_i^{Gen}\right) - \sum_{j \epsilon S_D} U_j\left(P_j^{load}\right)\right) \tag{3}$$

Grid constraints such as power losses and transmission capacity are not considered in this model. One constraint that is considered, however, is the power balance between consumption $\sum_{j \epsilon S_D}\left(P_j^{load}\right)$ and aggregated generations $\sum_{i \in S_G}\left(P_i^{Gen}\right)$.

$$\sum_{j \epsilon S_D} P_j^{load} = \sum_{i \in S_G} P_i^{Gen} \tag{4}$$

The constraints of the maximum capacities of consumers and DGs are also considered. These two constraints are as shown below:

$$0 \leq P_i^{Gen} \leq P_{i,max}^{Gen} \quad i \in S_G \tag{5}$$

$$0 \leq P_j^{load} \leq P_{j,max}^{load} \quad i \in S_D \tag{6}$$

B) Distributed Algorithm for Economic Dispatch

When it comes to optimization problems such as economic dispatch, a consensus-based distributed algorithm can provide a great optimized solution. In this approach, the optimized consensus can be reached by information exchange between agents within a local network or platform. A consensus is reached if and only if the value of the states of all agents are equal[16][17]. The consensus reached is based on a common agreement between all the agents within the platform. Equation (6) is the Laplacian potential for a graph. It represents the virtual energy stored in a graph[18].

$$\mathcal{L}_{\mathcal{P}} = \sum_{i,j} \mathrm{a}_{i,j}\left(\mathrm{x}_j - \mathrm{x}_i\right) = 2\mathrm{x}^T\mathrm{Lx} \tag{7}$$

This virtual energy stored in a graph shows the level of total disagreement among all agents in the platform. A consensus can only be reached by agent communication. If network-wide communication is not available, an agent should at least be able to communicate with its neighboring agents. A general consensus means there is no disagreement among all the agents. Therefore, in this optimal solution we have $\mathcal{L}_{\mathcal{P}} = 0$ or $\mathrm{x}_j = \mathrm{x}_i$.

The consensus in this paper is considered a zero-power mismatch consensus. The total power mismatch in the system is considered the kind of virtual energy mentioned above. According to the definition of Laplacian potential, this virtual energy must be minimized in order to reach consensus. The consensus condition is shown in (7).

$$\Delta\mathrm{P}_1 = \Delta\mathrm{P}_2 = \cdots = \Delta\mathrm{P}_n = 0 \tag{8}$$

This equation means the power mismatch of the entire system estimated by every DG in the system equals zero. The agents' single-integrator dynamic property is considered and is defined as a standard linear consensus protocol (8).

$$\dot{x}_i(t) = \sum_j a_{ij}(x_j - x_i) \tag{9}$$

2.4.2. Implementation Demo

In this demo, the VOLTTRON message bus is implemented on a Linux desktop PC with an FX-4100 CPU @ 3.60GHz, 8-GB RAM memory. The nodes in the system are simulated by a cluster of low-cost credit-card-sized single board PCs (Cubietruck) with an All Winner Tech SOC A20 processor, ARM® Cortex™-A7 Dual-Core.

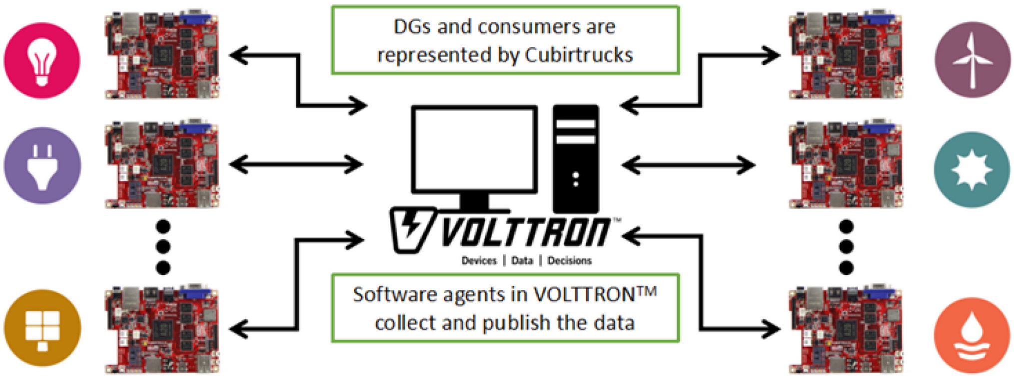


Figure 3: An overview of the implementation

This case study is a demo for a consensus-based distributed algorithm proposed in [15]. The algorithm uses a consensus-based approach to solve the ED problem of distributed generators. The consensus-based method allows local agents to iteratively exchange information through two-way communication channels. Each agent adjusts its output accordingly with the information it receives. In the end, a global optimal decision can be reached. This section focuses on the details of the technical approach of the simulation. The simulation consists of 16 nodes, 10 of which are consumers and 6 of which are DGs. Each node is represented by a Cubietruck.

2.4.3. The VOLTTRON Message Bus

The VOLTTRON software is installed on a desktop PC with a Linux operating system. By following the VOLTTRON user guide [19], the prerequisite software was installed and the system is set up.

Two VOLTTRON software agents are designed to collect and forward the information from the Cubietrucks. The consumer software agent collects information from the 10 Cubietrucks representing the 10 consumer nodes. Similarly, the DG software agent collects information from the six DG nodes. Both software agents receive the data through universal asynchronous receiver/transmitter (UART) serial communication with the Cubietrucks. The software agents in VOLTTRON are designed to scan the serial ports from the data, with the scan and publish operation designed to run in a loop. The design references the concept of the heartbeat of the “listener agent.”

The “listener agent” is one of the sample agents in the VOLTTRON user guide [19]. The listener listens (subscribes) to all messages published in the message bus and publishes a copy of these messages. The listener is a good tool for debugging in the message bus. It can also be used as a base platform to develop more complex agents. The heartbeat of the listener is the time gap between two scan and publish operations. It is implemented by a publish heartbeat function within the software agents. The new agents used in this paper use a similar heartbeat function with a much faster heart rate. The reason for a much faster heartbeat rate is that it allows our consumer and DG software agent to collect data much faster and achieve real-time simulation. The received information is then converted to the VOLTTRON message format and published in the message exchange bus. Both agents are written in Python with the guiding of the VOLTTRON user guide [19].

The received information is then converted to the VOLTTRON message format and published in the message exchange bus. Both agents are written in Python with the guiding of the VOLTTRON user guide [19].

The information is exchanged in the VOLTTRON message bus following the “publish” and “subscribe” paradigm. Each VOLTTRON message has a topic. A topic can have multiple subtopics, following the format “topic/subtopic/subtopic/….” For example, the consumer software agents publish the data from consumer one following the topic format of “Data/consumer /consumer1.” Consequently, a DG who is interested in getting only the information from consumer one can subscribe to the topic of “Data/consumer/consumer1.” If the same DG is also interested in the information other consumers send, it can subscribe to a higher-level subtopic, “Data/consumer,” to receive all the data sent by the consumers.

2.4.4. 16-nodes of the Cubietruck Setup

Cubietruck is the third generation of Cubieboard. Cubieboard is a small credit-card-sized single-board computer produced by the company Cubietech. All 16 Cubietrucks used in this simulation have the Ubuntu 12 operating system installed. The code for the simulation is written in Python. Each Cubietruck will receive the data needed from the message bus. The simulation is then run and output is produced and sent to the message bus. All the connections between the Cubietrucks and the desktop computer that hosts VOLTTRON are connected by mini-USB cables. In order to extend the host machine’s number of USB ports, two USB hubs are used. Figure 3 shows an actual setup of a cluster of Cubietrucks. The parameters that characterize DGs and the consumers are selected randomly.

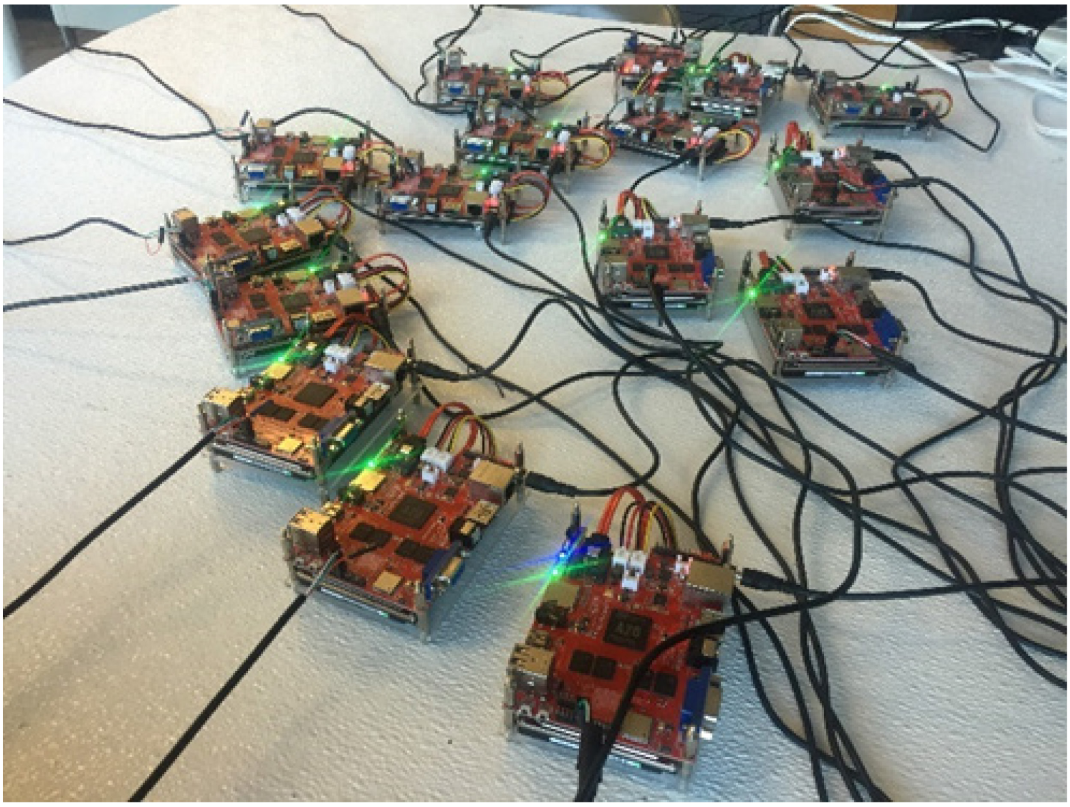


Figure 4: 16-nodes of the Cubietruck Setup

2.5. Implementation Steps

This section briefly lists the implementation steps of this demo system.

- VOLTTRON is installed on a Windows laptop by following the steps in the user guide [19]. The system hosting VOLTTRON is a Linux Virtual Machine (VM) run by the software Virtual Box.

- Porotype agents for the system are developed and tested on the Windows laptop

- The formal VOLTTRON platform is then installed on a Linux desktop, which serves as the host machine.

- Serial communication between the host desktop computer and the Cubietrucks is achieved by changing the system parameters and running a Python test script. The connections between the Cubietrucks are UART to USB lines, where the UART ends are connected to the Cubietrucks.

- For the purpose of the demo, the simulation is conducted in Matlab Simulink and translated into multiple Python scripts. These Python scripts are then run in the 16-node Cubietruck setup.
- Final debugging is done with the host machine and the Cubietrucks. The heartbeat frequency is tuned to an optimal level to ensure the VOLTTRON platform provides a timely response

2.6. Results

The results are shown in Table 1. The DGs are labeled as G1, G2, ..., G6 and the consumers are labeled as L1, L2, ..., L10. Nodes DG3, DG5 and L4's corresponding power outputs and demand are zero. The simulation results were validated by a centralized approach benchmark. After 42 iterations, the system reached the converging point. The total generation matched the total load, with both being around 421 kW. The incremental cost converged to 7.371 \$/kWh. This rate of convergence is considered a fast one.

Table 1. The experimental test results

Node	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	DG1	DG2	DG3	DG4	DG5	DG6
Output (kW)	52.4	58.9	54.9	0.0	32.2	40.8	71.8	39.1	40.6	30.2	106.6	124.4	0.0	89.8	0.0	100.2

Total Generation (kW)	Total Load (kW)	Lambda ($/kWh)	Iteration Number
421.0	421.1	7.37	42

CHAPTER 3: DECENTRALIZED APPROACH BIT-ENERGY

The power and energy industry is undergoing through a reconstruction from a monopolistic electricity market to a more open and transactive one [20],[21]. The next-generation grid should be a level playing field in terms of electricity transactions, where all customers should have an equal opportunity [22].

3.1. Introduction

The Public Utility Regulatory Policies Act of 1978 led to the creation of the Independent System Operator (ISO) in the United States [23]. The growth of ISOs creates a broader, more competitive wholesale electricity market for bulk independent power producers. However, ISOs only deal with large blocks of aggregate load or generation at the transmission level, and do not reach down into the distribution systems or, more importantly, the customers.

Although electricity market deregulation has been under way since the United Kingdom opened a Power Pool in April 1990, competitive forces in the U.S. retail electricity market have been largely silent since the early-2000s California electricity crisis. In today's retail market, customers have limited "energy choice" or participation, i.e., the ability to choose their supplier from competing electricity retailers.

The recent development of distribution system operators (DSOs) opens new possibilities of coordinating, monitoring, and controlling short-term or real-time delivery of electricity at the distribution level [24]-[27]. In the United States, most DSO development efforts [28],[29] are underway in NY, CA, HI, MA, and MN (at the state regulation and policy level). The vital necessities of DSO can be categorized in three major items: (i) the need for an efficient and fair retail market; (ii) the opportunity for all customers at distribution levels to actively participate; and (iii) the need for improved distribution system reliability. Recently, some U.S. retail electricity providers (e.g., NY, PA, TX, NJ, CO, and CA) have started to allow a small number of residential/industrial customers to offset their electric cost by selling excess self-generated power back to the utility grid.

While DSO plays a very important role (i.e., grid operator and market operator) to ensure an efficient and re-liable delivery of electricity in a centralized manner, some customers are expecting a higher degree of "energy choice" so that they can directly share or exchange electricity with their neighbors. In-spired by the recent explosion of Bitcoin-style transactional models, there are new possibilities to explore a fully distributed peer-to-peer energy transactional platform at distribution levels, as a perfect complement to the aforementioned DSO-based centralized market. This was simply not possible in legacy energy market.

3.2. Related Work

After the birth of Bitcoin and Blockchain in 2008, researchers are trying to combine the blockchain technology into different aspects of our lives. There are several relevant projects from the industry that combines the concept of the blockchain with the power system.

Transactive Grid is an energy market platform developed by LO3 Energy [41]. Transactive Grid used the secure blockchain network to achieve peer to peer energy transaction. By combining it with their previous project Brooklyn Microgrid, they implemented the system in President Street and had a successful test run to sell electricity of local solar panel owners to their neighbors [51][52].

Filament built an experimenting project based on blockchain in Australia. They combined the technology of IoT, mesh networks and blockchain to create a “taps” device to allow power poles to communicate with each other [53]. The result will be a more secure and flexible electricity grid network, in which electricity can be redirect to other parts of the network if one part of the network is down. If implemented, this technology would significantly reduce blackouts.

Create by a group of volunteers, SolarCoin is a new cryptocurrency based on Bitcoin technology [54][55]. SolarCoin’s main propose is to create an incentive to encourage people to buy renewable electricity. The different between SolarCoin and other cryptocurrencies is that, instead of created by mining, each SolarCoin is generated by the production of one MWh of solar electricity from a photovoltaic system [57][58].

Grid Singularity, a Vienna-based startup, is exploring the blockchain to create a secure energy transaction platform [60]. Their aim is to create a key to enable the current electricity market to take a sustainable transform to a fully distributed energy market model. Key functions include energy data analysis and benchmarking, smart grid management, green certificates trading, and energy trading validation [59]. Grid Singularity has already implemented a test run with their smart payment system in South Africa. South Africa uses prepaid electricity system, where users must pay their electricity upfront. Their system allows uses to buy their electricity with Bit-coin in remote areas and save them a trip when a blackout happens [61].

3.3. Bit-energy Concept

Figure 5 shows the proposed Bitcoin-style distributed transactional model for a completive electricity market. Figure 6 illustrates its integrated role.

The major contributions of Chapter 3 are summarized as follows:

1) Explore a fully distributed peer-to-peer energy transactional platform "Bit-Energy" at distribution level as a perfect complement to the DSO-based centralized electricity market;

2) Develop a computerized transaction protocol "Smart Contract" that executes the terms of a contract among active market participants; and

3) Evaluate the performance of the proposed "Bit-Energy" platform using an open-source, cryptographically secure, and distributed application platform-Ethereum.

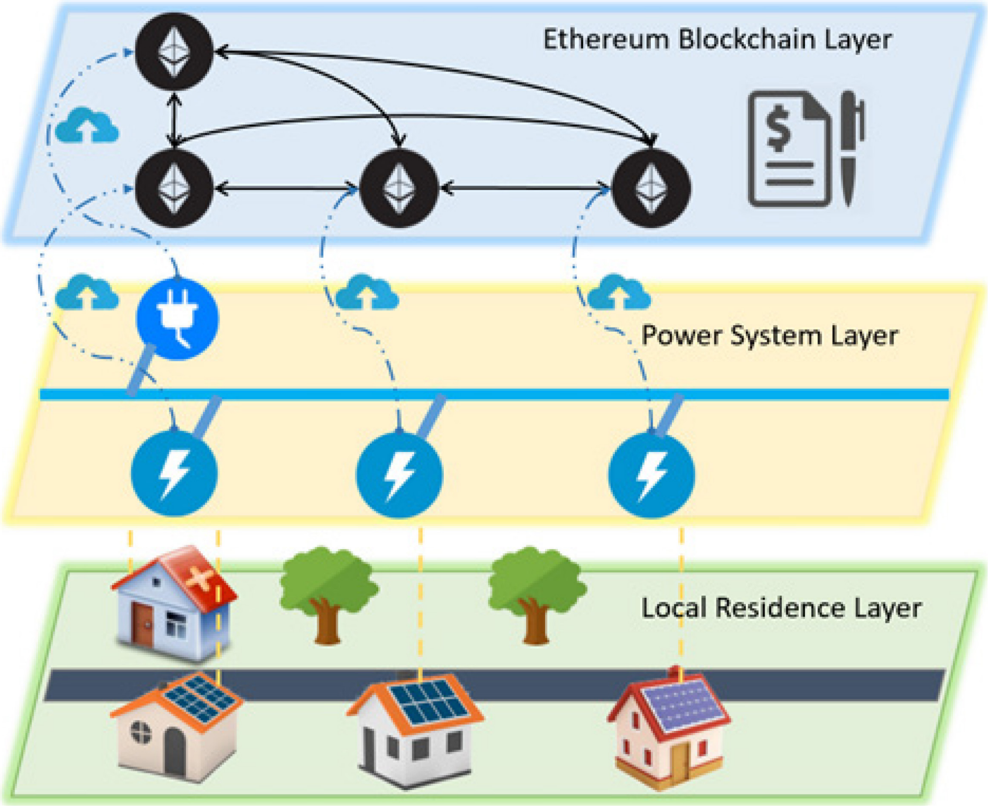


Figure 5: An illustrated Bitcoin-style distributed transactional model for a completive electricity market

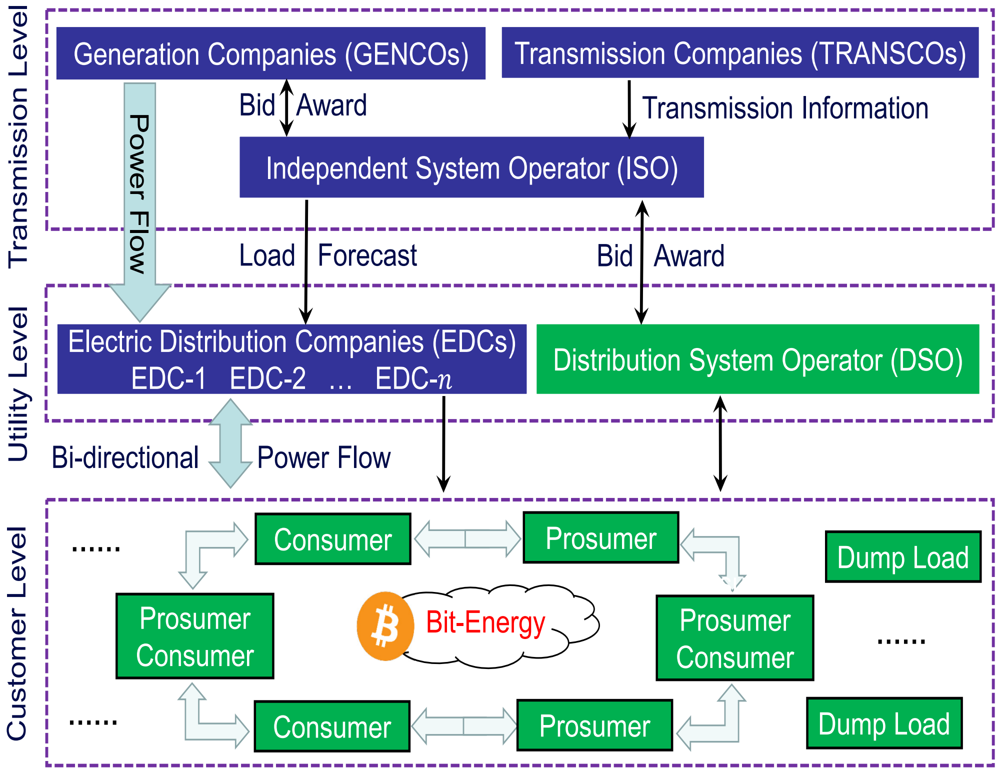


Figure 6: The role of Bit-Energy in a completive electricity market

3.4. Internet-of-things and Blockchain

The competitive information technology industry is thriving and evolving while providing a wide range of innovative services and products. The boom of the IoT [29] provides great opportunities for our nation's economic growth, cost reduction, and job creation [30]-[32]. The IoT is especially relevant to power systems [33]-[35], since it provides systems to gather and act on energy and power-related information in an automated fashion. For example, with advanced metering infrastructure devices connected to the Internet backbone, electric utilities can not only collect data from end-user connections, but also manage other distribution automation devices such as transformers.

In addition, inspired by the concept of the IoT, there has been a growing interest in Transactive Energy [36] and the Energy Internet. Some initial efforts [37]-[43] have been made in some pilot projects (e.g., Olympic Peninsula Project, AEP gridSMART Demo, Pacific Northwest

Smart Grid Demo, and Brooklyn Microgrid). Our envisioned retail electricity market consists of hundreds of thousands of consumers and prosumers. The vision we promote will require the equivalent of the concept of IoT. The integration and adoption of the emerging IoT concepts and technologies are a potentially viable solution where some customers can sell and buy energy in a fully distributed fashion.

In our proposed electricity market framework, the peer-to-peer energy transactions will be verified by network nodes and recorded in a public distributed ledger called the Blockchain. The Blockchain enables trustless networks so that end-users can buy/sell electricity locally even though they do not trust each other. Blockchain is a distributed database built for the cryptocurrencies such as Bitcoin. Blocks are the basic component in a Blockchain. A block in is the collection of relevant pieces of information [45]. Only one block can be generated at a time. Each newly generate block contains a timestamp prove from the previous block. Faster reconciliation can be achieved by avoiding a central intermediary (e.g., DSO). In essence, Blockchain is a cryptographically secure list of transactions that can be stored and updated on every participating consumer and prosumer. Since the energy transaction data will be replicated and shared among a network of end-users, data privacy is a critical matter. A distributed consensus mechanism is needed to guarantee agreement on transactions. In this paper, we are focused on a private Blockchain network where all the market participants are whitelisted.

Bitcoin: Bitcoin was introduced among with the Blockchain in 2008 by Satoshi Nakamoto. Bitcoin is the first cryptocurrency, a decentralized virtual currency [44]. The mechanism of the Blockchain allows bitcoins to be transferred peer-to-peer without any third-party validation. As shown in Figure 7, the validating process is done by blocks in the Blockchain. Bitcoin can be trade worldwide, trading and exchanging bitcoin can take place at anywhere with an Internet connection.

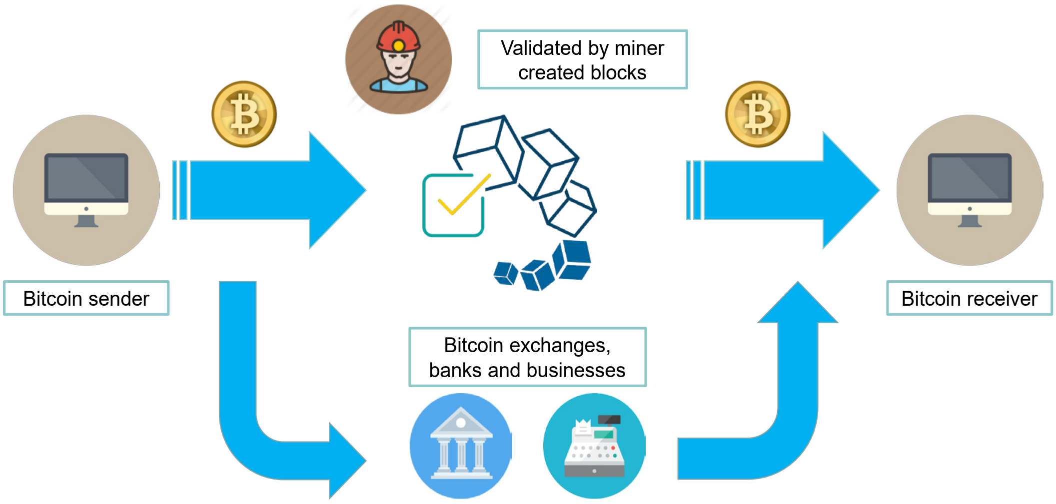


Figure 7: An illustrated cash flow of Bitcoin

Mining: Mining keeps the Blockchain 'alive' and 'running'. Mining is a constant validating process of Blockchain. By mining the Blockchain keeps its consistence and completeness [45],[46]. Each new transaction is broadcasted through the Blockchain by the new blocks created in the mining process. Every client within the Blockchain can set their device into mining mod. Within the mining mod the device will provide part of its computational power to create new blocks for the Blockchain. As shown in Figure 8, each of these new blocks contains a cryptographic hash pointing to the previous block [44].

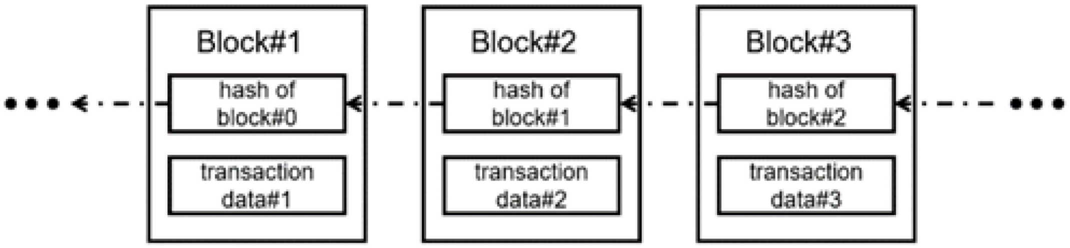


Figure 8: The working principle of blockchain

3.5. Smart Contract

Smart contract: A smart contract is a multi-party digitally signed, computable agreement. A software agent can act as a virtual third party by execute and enforce terms within the contract [47],[48]. Smart Contracts are scripts stored on Blockchain with a unique address. In this paper, we will design a Smart Contract that enables peer-to-peer energy transactions automatically, per user-defined criteria. Once a client triggers a Smart Contract, it executes independently and automatically in a prescribed manner on every node in the Blockchain network.

For example, a Smart Contract is defined as: (i) a “posting” function allowing sellers to post units of X into the contract (Prosumer α is willing to sell electricity); (ii) a “trade” function that sends μ units of X in exchange for 30 units of Y (Prosumer α is willing to sell electricity at 30 cents per kWh); and (iii) an “update” function that allows change or withdrawal of all the assets that the post in the contract holds. The “posting” and “update” functions are written in a way that only Prosumer α can call it. Then, consider that Prosumer α calls her “posting” function and posts 3 units of X to the contract. This transaction is recorded on the Blockchain. Then Consumer β, who is willing to buy electricity, call the contract’s “trade” function and sends a transaction contain 90 units of Y in exchange for 3 units of X. This transaction is also recorded on the Blockchain. The revenue (90 cents) is then deposited to prosumer α’s account.

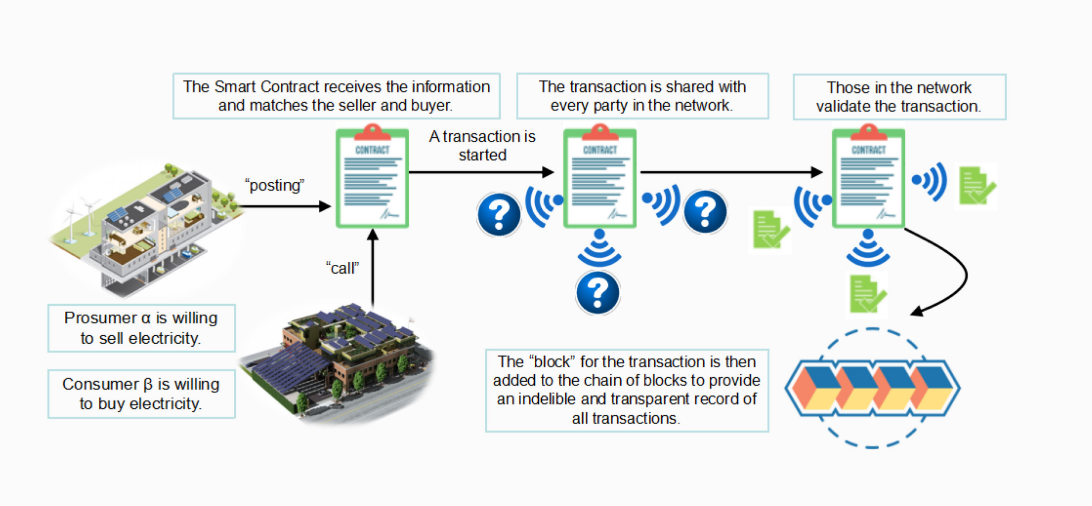


Figure 9: The working principle of smart contract

The envisioned Bit-Energy is inspired by the rapidly growing interest around Bitcoin but brings more challenges and opportunities that have not been explored yet. While Bitcoin is just a decentralized virtual currency, Bit-Energy is subject to Kirchhoff’s circuit laws, which adds physical constraints on top of financial transactions. For example, Prosumerα paying Consumer β for one additional kWh of electricity does not assert that this amount of electricity flows directly from α to β. Additional power injection at node α may also contribute to the change of total power losses. On the other hand, electricity distribution companies (EDCs) must play a critical role in maintaining power balance while allowing peer-to-peer energy transactions between α and β. Bit-Energy allows and promotes a certain level of local energy transaction for the following two major reasons:

1）More customer choices: While typical consumers can still purchase electricity from utility grid (e.g., EDCs), they can directly share or exchange electricity with their neighbors.

2）Less power line loss: Peer-to-peer energy trading at local levels can reduce the need of long distant transmission, ultimately decrease the transmission/distribution losses.

3.6. Simulation Case Study of Bit-energy

In this simulation, all software simulations are conducted in the Ethereum Blockchain environment on a laptop PC with an Intel® Core™i7 CPU @ 2.60GHz, 16-GB RAM memory. Ethereum is a decentralized platform built upon the ideas of Bitcoin and Blockchain. With its unique programming language ‘Solidity’, developers can create decentralize applications (D-apps). These applications can have functions such as markets, data registries of a corporation or a voting board [49]. Geth is a command line based interface tool for implementing and running an Ethereum node [50]. It’s an ideal tool for Ethereum developers and D-apps programmers. In this paper, Geth is used to construct a private Ethereum Blockchain.

In this paper, we start with a small residential area of four customers. Three of them are assumed to own local generators (e.g., roof-top solar panel). In other words, they can sell the energy surplus by “posting” at the smart contract. All the posting will form a “selling list” in the smart contract. This information will be available for all the clients in the contract. The consumer defines the needed amount of electricity and the maximum price it is willing to pay. The smart contract will automatically rank multiple local sellers in order of their offers and go down the table until the needed amount of electricity matches the supply. In addition, the distribution line constraints are pre-programmed into the smart contract. In our case studies, the proposed smart contract has the following major functionalities:

- Balance transfer: A direct transfer of virtual tokens (i.e., money) between prosumers and consumers.

- Sell/Post: Prosumers post the amount of energy they are willing to sell and the associated selling price.

- Buy: Consumers post the amount of energy they are willing to buy and the associated purchase price.

- Update: Revise/delete the post.

Figure 10 shows the flowchart of the abovementioned buyer/seller matching algorithm in the smart contract.

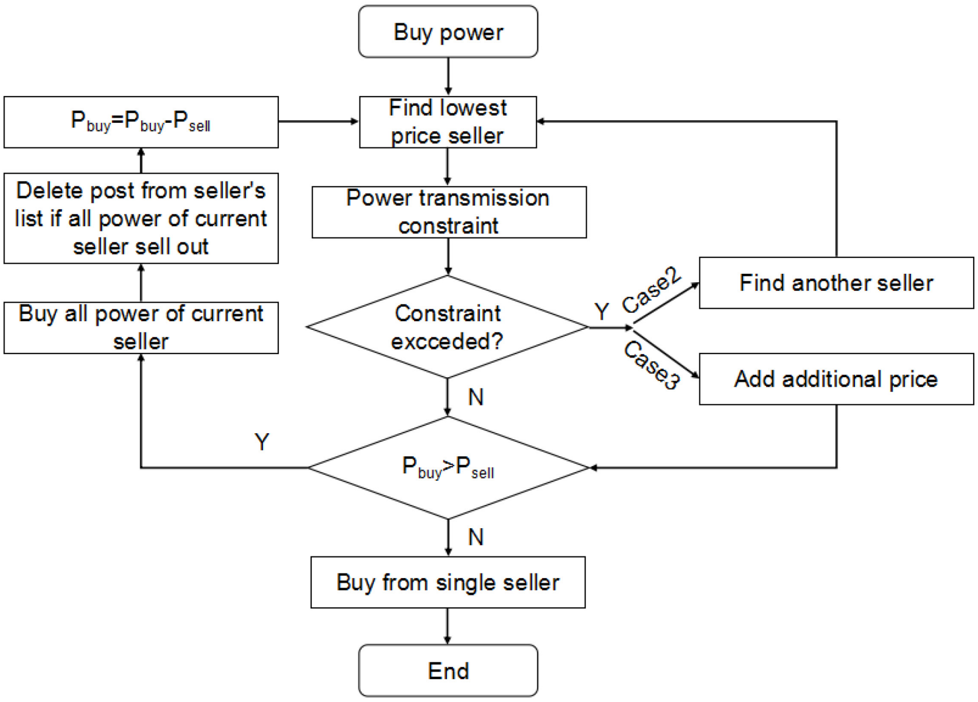


Figure 10: Buyer/seller matching process

When the buyer submits her purchasing information to the smart contract. The contract will go through the selling list and find the lowest priced seller. Once the lowest priced seller is found, the power flow constraints (e.g., line congestion) will be checked. If the constraints are violated, the contract will loop back and find another seller (Case Study II) or take the penalty price into consideration and check the lowest price again (Case Study III).

Once the match is found, the contract will check if the seller's posting amount P_{sell} can satisfy the demand of the buyer P_{buy}. If not, the contract will empty the selling post and delete the post. The buyer demand will be subtracted by the seller's posting amounts. The contract will then find a match for another seller. The transaction can be made if the contract can find enough matching sellers to fulfill the energy demand of the buyer.

For the sake of simplicity, in our case studies, each Ethereum account is assigned with an initial amount of $10 worth of virtual tokens. Each prosumer has 50 kWh of surplus electricity to sell.

3.6.1. Case I

In this case, no distribution line congestion is considered. In other words, each consumer or prosumer can transmit any amount of electricity they prefer. Each of the prosumer posts some of her surplus electricity with a price on the selling list within the smart contract. The consumer make a request of buying 8.0 kWh of electricity and a maximum acceptable price of 10 cents/kwh to the smart contract. The results are shown in Table 2.

Table 2. Case I results

	Before Transaction				After Transaction			
	Balance (cents)	Power (kWh)	Post		Balance (cents)	Power (kWh)	Post	
			Amount (kWh)	Price cent/kWh			Amount (kWh)	Price cent/kWh
C_1	1000.0	50.0			921.28	58.0		
P_1	1000.0	50.0	6.0	9.82	1058.92	44.0		
P_2	1000.0	50.0	7.0	9.90	1019.80	48.0	5.0	9.90
P_3	1000.0	50.0	8.0	9.97	1000.0	50.0	8.0	9.97

The consumer C_1 brought 6.0 kWh of electricity from the first prosumer P_1. Because P_1 had the lowest selling price. All P_1's electricity is sold out, then the contract deletes P_1's post and matches the second prosumer P_2. C_1 purchases another 2.0 kWh of electricity from P_2.

3.6.2. Case II

The power line constraints are considered in this case study. Once the constraint between the buyer and the seller is exceeded, no more electricity can be transmitted between them. For better comparison between case studies I and II, the posting and buying set up is the same as case study I. The constraints between the consumer C1 and three prosumers are 5 kWh, 10 kWh, and 5 kWh, respectively.

Table 3. Case II results

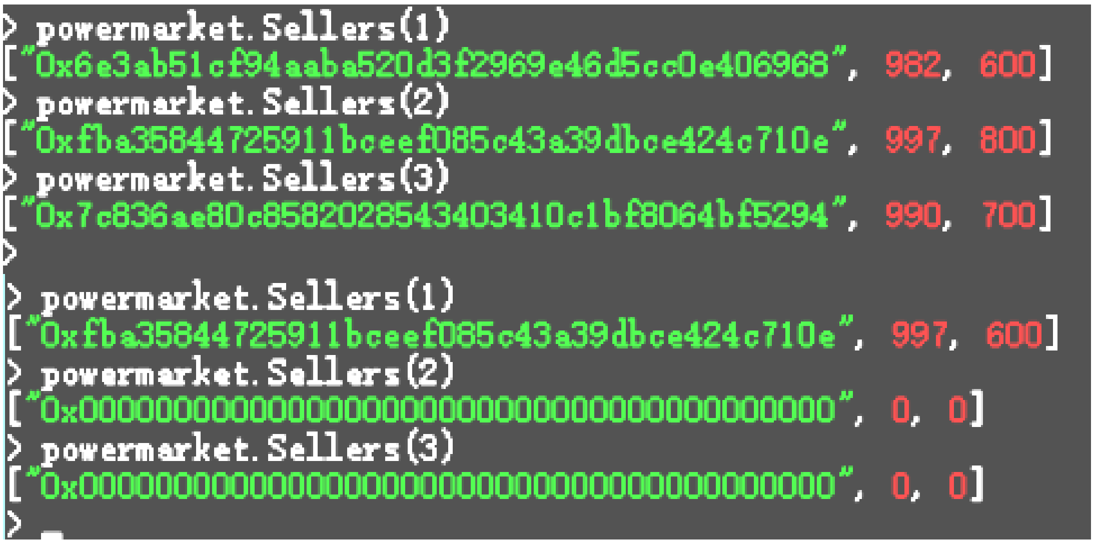
	Before Transaction				After Transaction			
	Balance cents	Power kWh	Post		Balance cents	Power kWh	Post	
			Amount kWh	Price cent/kWh			Amount kWh	Price cent/kWh
C_1	1000.0	50.0			921.20	58.0		
P_1	1000.0	50.0	6.0	9.82	1049.10	45.0	1.0	9.82
P_2	1000.0	50.0	7.0	9.90	1029.70	47.0	4.0	9.90
P_3	1000.0	50.0	8.0	9.97	1000.0	50.0	8.0	9.97

As shown in Table II, the smart contract locates the seller with the lowest price P_1. Because of the line constraint between C_1 and P_1, C_1 only allows to buy 5 kWh from P_1. The rest of the power demand is brought from the second matched seller P_2.

3.6.3. Case III

EDCs must play a critical role in maintaining power balance while allowing peer-to-peer energy transactions. Please note that EDCs still own and operate the distribution grid infrastructure. In this case study, the power line constraints are regulated by introducing a penalty function. Once the power flow constraints are violated, additional price will be charged to the associated prosumers. The additional revenue from this payment strategy will be automatically disbursed to different EDCs. For the sake of simplicity, the penalty price is set as +0.1 cent/kWh in case study III.

The posting amount of the prosumers stay the same as case study II, but the power demand of the consumer is increases to 15 kWh. The consumer's maximum acceptable price is still 10 cent/kWh. The constraints are the same as case study II.



```
> powermarket.Sellers(1)
["0x6e3ab51cf94aaba520d3f2969e46d5cc0e406968", 982, 600]
> powermarket.Sellers(2)
["0xfba35844725911bceef085c43a39dbce424c710e", 997, 800]
> powermarket.Sellers(3)
["0x7c836ae80c8582028543403410c1bf8064bf5294", 990, 700]
>

> powermarket.Sellers(1)
["0xfba35844725911bceef085c43a39dbce424c710e", 997, 600]
> powermarket.Sellers(2)
["0x0000000000000000000000000000000000000000", 0, 0]
> powermarket.Sellers(3)
["0x0000000000000000000000000000000000000000", 0, 0]
> _
```

Figure 11: Data in Geth

Figure 11 shows two screenshots of the results in the Geth command window. The first six lines of code show the status of the selling list after the sellers post their information and before the purchasing transaction happens. The next six lines show the status of the selling list after the transaction. The hexadecimal numbers in green are the Ethereum account addresses of the sellers. The red numbers indicate the prices and the selling amounts.

Table 4. Case III results

	Before Transaction				After Transaction			
	Balance cents	Power kWh	Post		Balance cents	Power kWh	Post	
			Amount kWh	Price cent/kWh			Amount kWh	Price cent/kWh
C_1	1000.0	50.0			851.74	65.0		
P_1	1000.0	50.0	6.0	9.82	1059.02	44.0		
P_2	1000.0	50.0	7.0	9.90	1069.30	43.0		
P_3	1000.0	50.0	8.0	9.97	1019.94	48.0	6.0	9.97

The detail result for case study III are shown in Table III. First, 5 kWh of electricity is brought from P_1 with a price of 9.82 cent/kWh. Secondly, P_1's constraint is violated and the penalty price is added. Accordingly, the price becomes 9.92 cent/kWh. P_2 becomes the lowest priced and sells all 7.0 kWh of electricity in the post, the post is deleted. Thirdly, P_1 becomes the lowest one again and sells out all the electricity left in the post with a constraint exceeded price. Finally, P_3 sold 2.0 kWh to satisfy the 15.0 kWh total demand.

CHAPTER 4: CONCLUSION AND FUTURE WORK

4.1. Conclusion

This study was inspired by the new challenges posed by the future smart grid and the trend of internet of things (IOT) technology, emphasizing the necessity of interconnection and communication between the devices and assets in the grid. The vision of the proposed retail electricity market is inspired by the rapidly growing and dynamic electronic commerce (E-commerce) industry that provides consumer-to-consumer sales and services via the information infrastructure. The key attributes of E-commerce are interoperability, open standards, and massive consumer participation. In a similar paradigm shift, the electricity market must be open standards-based, and must support open innovation. In this thesis, we proposed two innovated solutions in the customer level of a hybrid power system structure.

For the centralized solution, we investigated an open-source agent-based platform, VOLTTRON. First, we gave a brief overview of VOLTTRON and explained how it will be an essential tool in the future smart grid. Second, we summarized the existing projects related to VOLTTRON. We also discussed the advantages of using VOLTTRON in different aspects of the smart grid. Third, we compared VOLTTRON with other similar types of software platforms and discussed their advantages and disadvantages compared with each other. Finally, we gave a brief introduction to the consensus-based distributed algorithm in [15], and provided a detailed case study of the implementation of the algorithm using VOLTTRON.

For the decentralized solution, we proposed an innovative Bitcoin-style distributed transactional model, “Bit-Energy,” to enable transparent, auditable, and peer-to-peer energy transactions between active market participants directly without a central intermediary (e.g., DSO) using radically different IoT technologies. The proposed distributed platform is fully compatible with the existing distribution grid infrastructure. Case studies demonstrate the accuracy, robustness, effectiveness, and scalability of the proposed distributed platform.

4.2. Future Work

In future work, we plan to further explore our two centralized and decentralized control and market systems. For the centralized part, we plan to investigate more functionalities of VOLTTRON by conducting simulations related to building controls and EV charging controls. For the decentralized part, we will further investigate the computational/communication overhead of the proposed Bit-Energy platform under a wider variety of scenarios. One system we have started working on is a reward and penalty system called “Envoi-coin”. Envoi-coin will be assigned or deducted from a consumer depends on whether he chose to buy from a renewable source or not. We are also trying to combine our system with Home Emissions Read-Out (HERO), a real-time emission read out software development by researchers at Wayne State University. The goal is to adjust the amounts of award or penalty the consumer receives accordingly with local read out from HERO and relevant government standards.

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