Peer-to-Peer Energy Trading and Grid Impact Studies in Smart Communities

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***Abstract*— The rise of peer-to-peer (P2P) marketplace paradigms has transformed existing marketplace models, but the extent to which this approach can be applied to the energy marketplace has yet to be considered. In this paper, we examine existing approaches taken in the application of a P2P paradigm to the energy marketplace, further presenting an approach towards facilitating an online P2P energy marketplace, implementing a prototype P2P web application named *SolTrade*. Furthermore, we submit initial statistics based on simulated transactions facilitated through the platform, which illustrate the physical impact of marketplace transactions on the energy grid. In particular, these results show that, as the number of users rises, the chance of overloading the grid rises, *but* the chance of the grid being unable to sustain itself without an external source of energy falls.**

Index Terms **peer-to-peer economy, web development, energy sharing**

I. Introduction

Photovoltaic (PV) penetration has been growing exponentially in recent years. The accessibility and easy installation of PV enable individual end consumers to become electricity "prosumers" that are capable of producing electricity while consuming it. The distributed nature of PV energy necessitates an innovative business model and architecture that ensures scalability, fairness, convenience, security, and reliability.

Imagine that you could trade solar power with your neighbors. This is different from the traditional model of buying electricity from utility companies. You will enjoy the benefits of setting your own selling or buying prices, choosing cleaner energy resources, saving money or potentially making a profit, and being treated equally as a large power provider. This is the so-called peer-to-peer (P2P) economy.

The P2P economy has been booming recently. Examples include Uber for the taxi industry, eBay for the e-commerce industry, Airbnb for the hotel industry, and Bitcoin for the financial industry. The P2P economy is similar to the economic production model of the pre-industrial age, when everybody was a self-producer. In the modern age, the internet has made the P2P economy much more viable and efficient, as P2P transactions are often facilitated through community-based online services.

While this approach to the energy marketplace has been examined in existing research, the primary focus of this paper lies in the discussion of the implementation of an effective platform for the facilitation of energy transactions in a P2P marketplace as well as an investigation into the impacts that energy prosumers in an energy network have on the power grid in the continual transactions of energy. Unlike pure financial transactions, P2P energy transactions involve physical delivery of electricity and multiple entities in the current power industry. P2P energy trading is still in its infancy, and many questions remain unanswered. What is an appropriate P2P architecture? How do we efficiently match and execute orders in pairs? How do we ensure system reliability? This paper is aimed at developing P2P functionalities with an open-source platform, which facilitates the investigation of the aforementioned questions.

Fundamentally, the implementation of a P2P energy trading platform must consider energy transactions from both a financial *and* an electrical perspective, as energy transactions exist both within the context of monetary transactions, as well as within the context of the physical movement of electrical energy via the grid. In the implementation of this platform, we sought to consider each of these factors.

The remainder of this paper is organized as follows. Related work is discussed in Section II. The P2P trading platform is introduced in Section III. The details of the platform implementation and results are given in Section IV. Section V concludes the paper.

II. Related Work

A. Existing research

Despite the novelty of a P2P based energy marketplace, current research has previously explored the concept from several different perspectives. In their 2018 study, Zhou et al. [1] evaluated P2P energy sharing mechanisms through the use of a multi-agent simulation framework. When creating their simulation, certain parameters are defined to represent individual prosumers (energy producers) as well as the environment in which they trade energy, yielding an objective perspective of the factors that impact the energy marketplace. Leong et al. [2] has designed a virtual energy trading platform to ensure an efficient bidding in the auction and allow consumers and prosumers to physically trade electricity in a P2P model at a microgrid. Similarly, Zhang et al. [3] investigated P2P energy trading through the creation of a simulation, designing an energy trading platform (*ElecBay*) and then simulating prosumer behaviors and actions. Ultimately, the decision to simulate user behavior rather than collect actual data in the field has the potential to create problems in examining P2P energy markets, as simulated behavior often fails to capture the idiosyncrasies of human behavior, pointing to the necessity for future work to be conducted through the use of *non*-simulated behavior.

In terms of work regarding the physical impact of transactions made on an energy network, Guerrero et al. [4] propose a methodology to limit the impact of trading on an energy network, seeking to ensure that network constraints are not violated through extensive transactions taking place on the network. The physical impact of energy transactions on the network is an important factor to consider, as transactions must be *physically* verified before being dispersed into the network.

And, there exist several studies [5] that review existing energy trading platforms currently in development, pointing to the growing interest in the emerging field.

B. Current platforms

Simulation platforms are essential in research on sustainable smart electricity markets as they allow developing and evaluation of the solutions for systems with less cost of experimentation [6]. Several P2P energy trading platforms — while currently open to consumers — are in the early stages of development, providing various examples of existing approaches taken in the field.

The platform *Piclo* [7] seeks to “build a smarter energy grid around the world,” matching the energy supply of prosumers with the energy demands of others. This system allows for a centralized authority to manage the supply and demand of prosumers, alleviating some of the responsibility that could potentially fall to prosumers, such as finding ideal energy offers and making an optimal bid. In this way, the platform *Power Ledger* [8] gives users slightly more flexibility (and thus responsibility), allowing for real-time transactions of energy, recording (as well as verifying) each of these transactions on a distributed ledger (blockchain). The use of blockchain to verify transactions across the grid proves to be a promising technology in the energy sharing field, as a decentralized authority can be used to verify transactions. For example, the *SunContract* [9] platform (recently launched in Slovenia) bases its energy market model on blockchain technology, letting users freely purchase and sell energy to one another, as each of these transactions are verified through the use of blockchain.

While not implementing the use of a blockchain ledger, the *sonnenCommunity* [10] platform consists of prosumers who each own a *sonnenBatterie* used to store their excess energy that can later either be used for themselves or shared with others. In contrast, the company *Vandebron* [11] offers energy generated by third-party suppliers, as users specify which supplier from which they would prefer to receive energy. Although users are technically unable to sell energy through this platform, this model provides an alternative image of novel business models in the energy market.

III. The P2P Trading Platform

A. P2P trading architecture

A P2P system can be organized in a centralized, distributed, or decentralized/hierarchical fashion. Centralized P2P structure is exemplified by Uber and eBay, which provide a centralized communication hub to facilitate P2P transactions and delivery. The centralized platform can perform very fast order matching and execution, but it is also exposed to the risk of single-point failure. The central hub, as the most critical point of the system, is prone to natural and man-made attacks. As a result, any failures could lead to catastrophic consequences for the entire system. In contrast, a fully distributed structure tries to reduce the transaction cost by eliminating the third party and automatically matching orders with peers. Examples include P2P trading of Bitcoin using blockchain technology. However, scalability is a big issue, as the order book has to be stored in each peer node. The reason is the limitation of consensus protocols used in blockchain: every fully participating node in the network must process every transaction. In fact, the blockchain actually gets weaker as more nodes are added to its network.

This paper recommends a decentralized/hierarchical architecture that combines the advantages of both the centralized and distributed models, while avoiding the drawbacks. This decentralized architecture is perfectly suitable for the current business structure in the power industry, where multiple communities coexist in a large utility territory. Note that this design can be expanded to either centralized or distributed architecture, depending on ledger needs.

Fig. 1 depicts this decentralized/hierarchical architecture. First, in a community along the same feeder, P2P communication is enabled through the internet protocol. Neighbors will talk to each other to match the best orders for buying and selling electricity. Any unfilled orders will be submitted to the community node, which talks to other community nodes and tries to match cross-community orders. Any cross-community order execution will be submitted to the substation node for a physical feasibility check so that actual delivery is approved to transmit electricity across different laterals and feeders. Note that the formation of communities is flexible. Under normal conditions, a community usually consists of customers along the same feeder lateral. Under abnormal conditions, where a community experiences physical system failures or communication failures, the customers within that community can join a neighbor community as long as both delivery paths and communication paths exist.

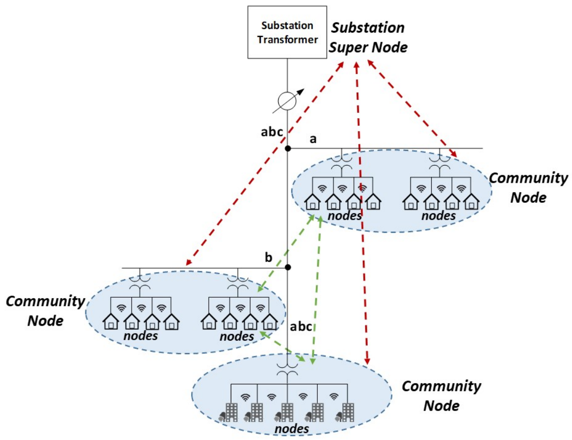

Fig. 1. P2P Trading Architecture

B. Platform functionalities

1) Participant qualification check: Theoretically, anyone who consumes electricity can participate in P2P energy transactions. However, some practical considerations need to be taken into account:

- Customers who have no distributed energy resource (DER) assets are eligible for buying only, and are not allowed to sell. DER assets are equipment or devices that can store or generate electricity, which include but are not limited to PV panels, electric vehicles, and energy storage devices.
- Customers who have no physical connection to the main grid are not eligible to participate in P2P transactions. Isolated customers are not capable of physically fulfilling electricity delivery.
- Regulatory criteria can be set to further ensure normal trading behaviors. These criteria include, but are not limited to, minimum electricity capacity and performance ranking scores.

2) P2P order format: A P2P order contains the following components:

- customerID: A unique number assigned to each customer.
- OrderID: A unique number assigned to each order placed by customers.
- orderAction: Buy or sell (bid or ask).
- orderType: Market order or limit order.
- orderQuantity: Amount of energy (in kW) to be traded in the delivery window.
- orderPrice: Target price for limit orders (market order is fulfilled right away while limit order sets the price limit to buy or sell).

Note that in the attribute orderType, a market order does not have a target price; the best price available will be matched to fulfill the market order. In contrast, a limit order needs to specify the target price. If the target price is not matched, the limit order will be added to the order book.

3) Order matching engine: The order matching engine needs to be implemented in each community node and substation super-node. The orders will be processed in the following way:

- Market orders are processed first, followed by limit orders.
- Buy orders are processed first, followed by sell orders.
- Orders may be fully filled, partially filled or not filled.
- Orders are executed in the priority of "first in first out."

The order books in each community node and substation super-nodes contain all the outstanding orders to be filled. The order books are updated frequently, i.e., whenever there is a status change due to incoming orders or expired orders. Fig. 2 gives an example showing how the order book is updated once new orders come in. Initially, there are four customers with outstanding orders to be filled. After 2 minutes, customer 5 enters a market order to buy 8 kW. This market order is immediately matched with 7 kW from customer 4 and 1 kW from customer 3. At 10:03, customer 6 enters a limit order to sell 4 kW for at least 1.9 cents/kW. This order is matched with customer 1 and the order book is updated accordingly (i.e., 4 kW is deducted from customer 1's order).

4) Physical system feasibility check: A physical feasibility check is conducted before execution of any order. Orders that are paired within the same community will be executed automatically. Orders that are paired across communities will be submitted to the substation super-node for approval. The approval process will be prioritized according to the "first come first served" rule. If the feasibility check is not passed, the orders will remain open in the order book. Physical constraints include voltage limit, branch current capacity, voltage regulator tap change, and capacitor bank capacity.

IV. Platform Implementation and Results

The developed P2P energy trading platform is named *SolTrade*. For the creation of the *SolTrade* energy trading platform, we used the *Flask* web framework in tandem with styling templates from *Bootstrap*, using *SQLAlchemy* to service requests to our *SQLite* database. The database serves to store several models that represent users, groups, energy requests, energy offers, and (previously) energy bids. The platform supports user registration and verification letting users select the grid in which they live, as well as a dashboard where users can: make requests for energy, view other users in their grid, and examine statistics relating to energy transactions within their grid. These statistics include: request history, total energy traded on the grid, as well as total energy purchased on the grid (Fig. 3).

Through the use of the Fig. 3 interface, users can directly interact with their grid, allowing them to request energy as well as view statistics related to energy transactions taking place within their network.

A. Energy Grid Simulation

In order to examine the impact of energy transactions on the *physical* energy network, a simulated energy grid was created to model the grid in which energy transactions were being facilitated. The open source Python library *PandaPower* was used to model the network. More specifically, a *Kerber Vorstadtnetze* network (Fig. 4) provided by the library was used,

Fig. 2. Order book dynamics

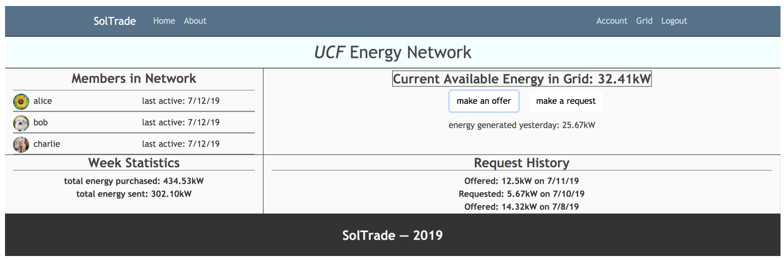

Fig. 3. The dashboard allowing users to interface with the grid, implemented with a first-price sealed bid auction model.

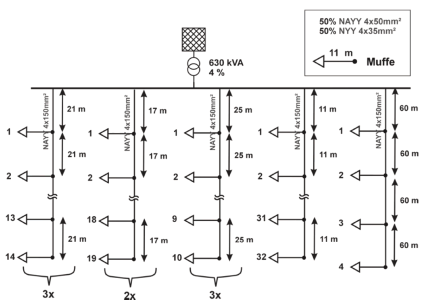

Fig. 4. A diagram of the *Kerber Vorstadtnetze* network in which transactions were facilitated.

which features an open ring, meshed network topology. This network further features a high building density (conducive to modeling a residential grid) as well as a high number of loads per transformer station. While this network was used for the purposes of our research, other simulated network models could be further used to measure the impact of energy transactions on a power system.

The *PV hosting capacity* of the network was used as a basis to determine whether or not a transaction was physically valid on the network. The hosting capacity of an electric power system refers to the ability of the system to accommodate distributed energy resources (DERs), such as distributed solar, energy storage, and electric vehicles. To evaluate the hosting capacity of this network, a *violation* is defined as either an overloading of power lines and transformers or a voltage set point of greater than 1.04 times the nominal voltage. If any of these criteria are met, then the network can be seen as unable to accommodate the current transaction, even if the transaction is financially sound.

B. Transaction Simulation

To investigate the physical impact of transactions on the energy grid, user energy transactions were simulated via a Python script, with statistics gathered as a result of these simulated transactions. Throughout the simulation, the two primary statistics that are examined are the number of days where the network was *violated* and the number of days where the network was not *sustainable*. In this context, sustainable refers to a single day where the excess energy produced by users within the network is enough to provide for users who have an energy deficit at the end of the day. To calculate whether a given user had a net deficit or surplus of energy at the end of each day, both the average daily energy production of a solar panel and the average daily energy need of an American household [12] were multiplied by a uniform distribution for each user, resulting in either a deficit or surplus of energy depending on the energy production and need of the given user.

The trading strategy defined for each user was relatively naive, yet sought to allow all users in need of energy to be able to obtain energy from other energy producers in their network if a surplus of energy were available. Essentially, each user in need of energy requests from the network the amount of energy of which they are in need, and if either a single other user is (or combination of other users are) able to provide this energy to the user in need, the energy is provided, and then traded on the network. These transactions were run over a series of *five* iterations (each with an increased number of users) of 31 days, with data collected for each of these iterations.

C. Results

In running the energy transaction simulation between users, the relationships between number of users and number of

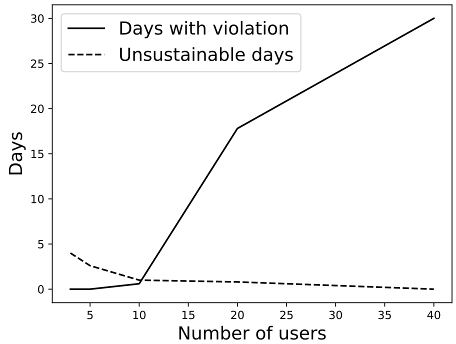

Fig. 5. The number of users vs. number of days with violations and days where the grid was unable to sustain itself.

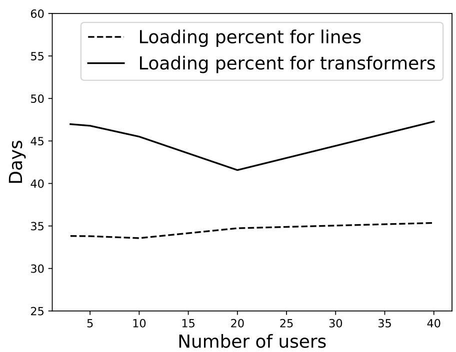

Fig. 6. The number of users vs. loading percent for lines and transformers.

network violations and number of users and number of unsustainable days were both examined. Fig. 5 presents the negative relationship between these two variables.

The data seems to show that as the number of users in the network rises, the number of violations rises, but the number of unsustainable days falls. The possible solution for this would be solar power curtailment if the number of users exceeds the hosting capacity of the grid. Furthermore, the relationship between number of users and loading percentages for both lines and transformers was considered which is shown in Fig 6. The loading percent seems to fluctuate back and forth as the number of users increases, though with a distinct upward trend, as reflected in the increase in number of violations.

Interestingly, the data gathered through our series of simulated energy transactions reveals the trade-offs that come when adding and recruiting an increasing number of users to a P2P energy trading platform. While the rise in number of users allows for a more sustainable network, this rise seems to be directly responsible for the number of violations that occur within the network, lowering the probability of a valid transaction in the network.

V. Conclusion

In this paper we implemented a platform to simulate energy transactions in a P2P marketplace considering both financial and electrical perspective. By using the collected data, we also investigated how the number of users of the platform affect the power grid in terms of sustainability and reliability.

While the concept of a P2P energy marketplace has gained traction in recent years, there is still a need for further research to be carried out in the investigation of this novel paradigm. Future work in the field could concern itself with examining the hosting capacity of an energy network through the use of *non*-simulated energy transactions and *non*-simulated energy demand and production.

Enhancing the power system modeling framework, implementing advanced trading algorithms and multi-agent learning platform are other future direction for this work. The application of machine learning to P2P energy trading remains a possible direction of research in this area, as the behavior of energy platform users and prices could be analyzed — and ultimately predicated — through the use of machine learning algorithms. Such approaches could further be concerned with limiting the impact of users on the energy network while still providing requisite energy amounts to users in need. This research also disregarded the existence of utilities, which could impact results as an outside producer of energy may be able to offer more affordable energy to users in need.

Acknowledgements

The support for this work was provided by the National Science Foundation REU program under Award No. 1852002. Any opinions, findings, conclusions, and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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