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DOI: https://doi.org/10.1109/jiot.2021.3109613

Publisher: Institute of Electrical and Electronics Engineers (IEEE)

Version: Accepted Version

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VirtElect: A Peer-to-Peer Trading Platform for Local Energy Transactions

Olamide Jogunola, Yakubu Tsado, Bamidele Adebisi and Mohammad Hammoudeh

***Abstract*—An average UK electricity bill is made up of at least 60% service charge, with approximately 22% related to network characteristics including distance charge. This makes distance and network constraints important factors in matching prosumers on any peer-to-peer energy trading platform as assessed in this paper. To realise that, A platform - $VirtElect$, based on a double auction market is developed to support the matching interaction between prosumers. Case studies based on real microgrid data are used to verify the performance of the platform in demonstrating the potential of local energy consumption. Results show that it is possible to balance local energy generation and consumption, with little or no interaction with the utility grid. We also show that local energy trading is not only beneficial to the environment but also leads to a significant amount of cost savings of up to 45%, depending on the number of participants and their ratios on the platform.**

***Index Terms*—Peer-to-peer energy trading, local energy consumption, distance constraints, utility maximisation, network constraints, auction-based market.**

I. Introduction

Peer-to-peer energy trading and sharing (P2P-ETS) platform can provide a market mechanism facilitating mutually beneficial energy transactions between traditional energy consumers that have become 'prosumers' who can both generate and consume their energy. P2P-ETS platform can be implemented to enable the exchange of information and energy among energy traders of different sizes, including prosumers, residential houses, or local distribution networks [1]–[3]. Besides, the platform can assists the system operators to monitor and control the energy integration to the distribution network, for instance, balancing energy supplies and demands.

As such, several pilot energy transaction projects and platforms are currently being trialed in several countries. These include the Piclo in the UK [4], Vandebron in the Netherlands [5], SonnenCommunity in Germany [6], and the Brooklyn microgrid in the US [7]. Some of these projects fit into four P2P-ETS platform models [8]; the retail supplier platform, vendor platform, community microgrid platform, and blockchain platform models.

The Piclo and Vandebron projects utilise online platforms that allow prosumers to select and track the source of the energy they buy. They are representative examples of the retail supplier platform model as they allow suppliers to benefit by gaining a better awareness of their customers and also obtain more value from their distributed energy resources (DER) [1]. SonnenCommunity project is similar to Piclo and Vandebron but with more utilisation of storage systems for battery owners [6]. SonnenCommunity is an example of the vendor platform model that allows the exchange of energy between producers and consumers where the owner of the platform gets a commission for every sale. The Brooklyn P2P-ETS platform is a network of Brooklyn residents and business owners to allow social factor inclusion by encouraging generous prosumers with surplus energy to donate energy to low-income households [9]. The Brooklyn microgrid uses a blockchain model to provide secure decentralised protocols for managing and executing transactions through its smart contracts, thereby classified as a community and the blockchain P2P-ETS platform models.

However, the type of trading rules and controls defined by these platforms have a significant influence on the decisions made by the prosumers. Setting preferences and autonomy to decide the terms of trade are also additional incentives for participating in P2P-ETS platforms [10]. Similarly, to aid in local energy consumption thereby reducing the carbon footprint, distance as a function of the physical location of prosumers is an important factor in matching prosumers on any energy trading platform. For instance, at least 20% of an electricity bill is network cost including distance charge [11]. Besides, other P2P constraints such as price and product divisibility, implementability and network constraints consisting of voltage variation and line losses should be jointly integrated into the energy trading models and platforms as these constraints have their impact on the economic and environmental benefit derived by the grid, prosumers or the community at large.

Compared with the existing P2P-ETS platform designs and models, that considered one or two constraints, the main contributions of this work can be summarised as follows:

- a P2P-ETS platform to support the matching interaction between energy traders is presented. The platform is designed for an implementable hybrid market within the current distribution network integrating diverse solutions for different technical aspects of P2P markets to improve the economic benefit of the prosumers by maximising their social welfare and unitary benefit;
- as environmental emission is mostly determined by the distance energy travels from producers to consumers, as well as a factor in determining the amount paid for energy consumption, distance and network constraints violation charges are implemented on the platform to encourage energy trading with closest neighbours. This highlighted the benefits of local energy consumption to the community and environment;

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This work was supported by ENERGY-IQ, a UK-Canada Power Forward Smart Grid Demonstrator project funded by The Department for Business, Energy and Industrial Strategy (BEIS) under Grant number:7454460.
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- an evaluation of the platform was carried out to show the extent to which the P2P-ETS can benefit prosumers in the network. This is achieved by varying their ratios to determine the optimal mix for maximum benefit.

The remaining sections are as follows. A literature review of P2P energy trading models is discussed in Section II. The development of the energy trading platform '$VirtElect$' is introduced in Section III, the market bids and matching algorithm is presented in Section IV. The performance evaluation of the platform is discussed in Section V. Section VI concludes the paper and discusses future work.

II. Review of P2P Energy Trading Models

Recently, the development of a market framework has been the focus on P2P-ETS where buyers and sellers cooperate to determine the ultimate energy trading contracts [12]–[14]. This development has been shown to reduce battery capacity and energy losses [15]. The related effort focused on the computational properties of the negotiation algorithms [16], the optimised scheduling of energy storage system (ESS) using automated negotiations [17], multi-commodity optimisation of energy traders' resources [18] and prosumers' behavioural patterns based on their bidding strategies. Other market clearing algorithms include the use of distributed optimisation methods [19], consensus-based optimisation [20], dual-based prices like alternating direction method of multipliers (ADMM) [21], reinforcement learning [22] and double-auction for matching prosumers in the market.

In the double-auction market, sellers and buyers report their reservation prices and bids for the efficient operation of the market. This technique has been reported in the literature to achieve the objective of balancing local generation and demand, improves prosumers engagement, and offloading demands at peak time [23]–[27]. For instance, a blockchain-based distributed double auction trade mechanism for energy trading platform is presented in [27] using a co-simulation to interface the energy trading platform and the distribution network layer. This is to assess the impact of P2P trading on the distribution network. Their result suggests that a moderate level of P2P trade does not have significant impacts on network operational performance. Similarly, [28] adopted a sensitivity analysis methodology for the same objective as well as to guarantee energy exchange that does not violate network constraints. A consortium blockchain-based double auction mechanism is proposed in [23] for protecting privacy while trading energy. Also, an iterative double auction mechanism is proposed to solve the electricity pricing and traded quantity in balancing local energy generation and supply. The result showed that the double auction mechanism achieves social welfare maximisation while preserving the privacy of the peers. A similar objective is achieved in [25] for an optimal bidding strategy using a double auction among residential houses. Specifically, utilising the responsive household appliances and ESS, day-ahead and intraday energy management models for residential houses are established for an hour-ahead intraday energy transaction. The authors concluded that the residential demand response schemes and intraday P2P-ETS are effective in managing the uncertainties of load demand and renewable generation.

To reduce peak demand and improve users' participation in local energy trading, the authors of [24] and [26] investigated a data-driven prediction-integration model and Nash bargaining model respectively in their designs of double auction mechanisms. Particularly, [26] designed an incentive mechanism for their energy sharing model to ensure fair benefits to DERS' owners based on their contributions using Pennsylvania-New Jersey-Maryland's capacity market multi-auction structure. Furthermore, Utilising the Rubinstein alternating offers protocol, [29] proposed a bilateral negotiation framework for energy trading in different periods throughout the day. With the use of different negotiation concession algorithms, the prosumers were able to increase their revenue and reduce their costs. These studies, however, did not integrate distance and divisibility constraints between the trading entities to assess their impact on the achieved objectives.

In contrast, the work in [20] proposes multi-bilateral trading with product differentiation based on consumer preferences, i.e., distance. Their results suggest an increased trading cost and a reduction in the maximum power that flows through prosumers on different buses compared to a case without product differentiation. Similarly, [30] proposed a stable matching mechanism and a continuous double auction-based mechanism for P2P trading while accounting for the electrical distance to prioritise trading between peers. The work in [31] proposes exogenous cost allocation including zonal fees and electrical distance fees for cost recovery for the system operator. The exogenous parameter is modelled as an additional cost that might restrict the participation of traders in the market.

While these theoretical studies [20], [30], [31] assess distance as a product differentiation parameter for a decentralised market, here we are assessing its impact in a hybrid market implemented in an energy trading platform. Against this background, this paper advances the current state-of-the-art by considering the distance and network constraints as a major factor in matching peers for energy trading. In addition, to increase profit maximisation, the quantity of energy supplied and demanded can be divided and satisfied by one or more prosumers. This energy and price divisibility feature enables the sale/purchase of different quantities at different prices, offering more control and increase savings. These two factors are achieved by developing a P2P-ETS platform to support the pairing interaction among energy traders. Comparative analysis of this study and other P2P-ETS models is presented in Table I.

III. The Proposed P2P-ETS Platform Design

To enable information exchange among prosumers and to facilitate the monitoring of the distribution network by the utility operators, a P2P-ETS platform is actively needed that incorporates a variety of energy traders. Fig. 1 illustrates interactions on the proposed platform - $VirtElect$, while the following subsections discuss the platform in detail.

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TABLE I: Comparative analysis of representative models of P2P energy trading with this study

P2P-ETS models	Ref.	Year	Objective	P2P-ETS constraints				
				Distance	Divisibility	Network constraints	Hybrid market	Platform
Constrained optimisation	[12]	2020	A decentralized P2P energy trading scheme for electricity markets with high penetration of DERs	×	√	√	×	×
	[32]	2020	A hybrid energy trading scheme for different markets to incorporate prosumers' preferences	×	×	√	√	×
	[31]	2019	An exogenous cost allocation framework including zonal fees and electrical distance fees in P2P electricity market.	√	×	√	×	×
	[33]	2021	A distributed pricing strategy for P2P transactive energy systems considering physical network constraints.	√	√	√	×	×
	[20]	2019	A multi-bilateral economic dispatch and trading with product differentiation based on consumer preferences	√	√	×	×	×
Game theory	[34]	2019	A game-theoretic coalition framework to incentivise prosumers' participation in P2P energy trading	√	×	√	×	×
	[1]	2018	A P2P energy trading platform for a grid-connected low voltage microgrid with trading simulated using game theory.	×	×	√	×	√
Blockchain	[27]	2020	P2P energy trading assessing the impact on the distribution network	×	×	√	×	√
	[35]	2020	A blockchain-based hybrid energy trading market to reduce costs and peak to average ratio of electricity	√	×	×	√	×
Auction theory	[28]	2019	P2P energy trading under network constraints	×	×	√	×	×
	[29]	2020	An automated negotiation framework for energy trading	×	×	√	×	×
	[30]	2021	Electrical-driven P2P energy trading	√	×	√	×	×
This study		2021	A double-auction trading platform for P2P-ETS assessing the impact of distance including violation to network constraints	√	√	√	√	√

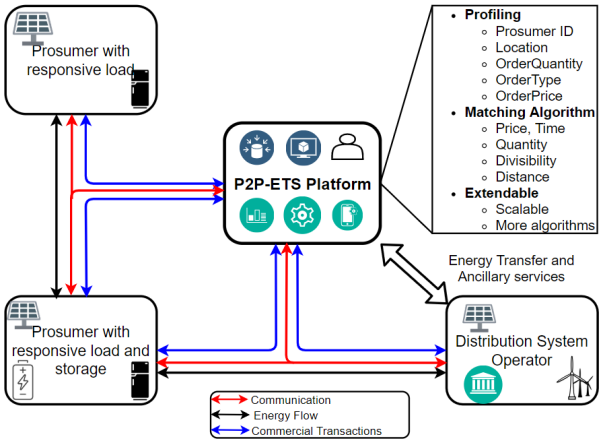

Fig. 1: Interactions of prosumers on the proposed P2P-ETS.

A. P2P-ETS Trading Architecture

P2P-ETS systems can be organised in three fashions, a centralised, decentralised, and a hybrid of both [36]. $VirtElect$ utilises a centralised auction-based market clearing system that is well suited for the current business structure in energy trading. The architecture can also be expanded to a decentralised or a hierarchical/decentralised architecture to serve power industries where multiple communities coexist in a large utility area. $VirtElect$ is a python programming-based P2P-ETS platform that manages local energy transactions in power networks. It acts as the auctioneer with a central market clearing system by only taking in data and providing an intelligent interface for the prosumers, while communication among the prosumers is decentralised. The energy consumption and generation of each prosumer are recorded by their smart meters which serve as the trading agent. The smart meters also facilitate communication with the platform. The $VirtElect$ supports P2P energy trading in a grid-connected microgrid and it consists of consumers, prosumers, and the distribution system operator (DSO), which is also grouped as an energy prosumer on the platform. The DSO is an integral part of the platform that delivers energy to the appropriate prosumer, whilst ensuring network constraints are not violated.

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The electricity grid is made up of the coexistence of multiple communities distributed across different feeders in several locations illustrated in Fig. 2. On the one hand, in a community along the same feeder, trading and sharing within that region will be among prosumers near one another. On the other hand, trading and sharing between prosumers on different feeders will attract more power losses as a result of long distance travelled across substations and cable lines. The following are some considerations that will be taken into account during P2P energy transactions:

- Consumers with no DER can participate and are eligible to only purchase energy.
- Prosumers with DER are eligible to purchase and sell energy.
- The DSO can also buy or sell energy.
- Prosumers with no physical connection to the grid are not eligible to participate in the transaction,
- Regulatory criteria such as minimum electricity capacity and network constraints are integrated to avoid violation or to assign charges as applicable.

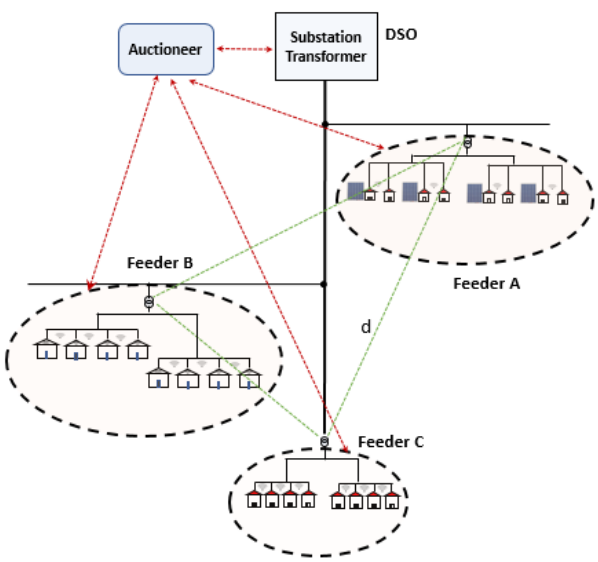

Fig. 2: Local energy consumption, distance charge (adapted from [36]).

B. The Platform ($VirtElect$) Functions

The profiling of each prosumer detailing their preferences including energy price, quantity, and location is stored on $VirtElect$. $VirtElect$ allows the prosumers to place orders for day-ahead energy delivery or intraday trading, based on flexibility and offer prices, with sellers able to respond with when they are available and what services they can provide. There are two predominant forms of intraday trading: discrete auctions and continuous trading. Auction-based intraday markets are cleared at discrete times, while the continuous intraday market is closer to real-time trading as it involves continuous trading throughout the day. Both forms of intraday trading can be adopted with the current methodology of the study by changing the market clearing frequency. The bid information submitted along with the distance constraints of the prosumers, are all taken into consideration before the matching result for the bids and offers is delivered. It is the responsibility of the prosumers to ensure the orders submitted reflect their energy profile needs as the market mechanism only utilises the submitted orders for matching and trading purposes to deter compromising their privacy. The mismatch between the demand forecasting result and the actual demand values in real-time is beyond the scope of this work. Sellers who have some price flexibility will not have any visibility of the buyers' price, so as not to influence their offer prices. Such a system creates market drivers which can bring costs down. A P2P order will contain the following:

- ProsumerID: A unique number assigned to each prosumer.
- OrderID: A unique number assigned to each order placed by prosumers.
- OrderAction: Buy or sell (bid or offer).
- OrderQuantity: Amount of energy (in kWh) to be traded.
- OrderPrice: Bid price or offer price.
- Prosumer role at time t: Indicates the role of a prosumer, either a consumer or a producer at a particular time t.

C. Network Constraints

Energy transactions consider both the monetary transaction and physical electrical power transport through the grid. As a result of the integration of DER to the electrical power network from multiple prosumers, the physical transportation of electrical power is subject to physical network constraints which must not be violated through extensive transactions in the energy network. Studies on physical network constraints and how it impacts energy transactions in the grid network have been carried out. In [36], a platform that considers the system's ability to accommodate DER was implemented by measuring the PV hosting capacity of an electrical power system. They defined a violation as either overloading of power lines and transformers or a voltage set point greater than 1.04 times the nominal voltage. The impact of the transaction on voltage and network capacity was presented in [28] to guarantee an exchange of energy that does not violate network constraints. Other sample models that consider the effect of network constraints like voltage variations, utilisation rate of the lines for congestion control, and system losses, are presented in [31], [37]–[40]. To evaluate the impact of these constraints within this study, the following are defined.

1) Voltage Variations: a transaction that causes voltage variation in the network will not be allowed to proceed. To detect voltage variation issues, we use the relationship between the power injection and the bus voltages to determine the voltage sensitivity coefficients (VSC) as presented in [28], [41]. Using the Nodal admittance matrix Y that describe the linear power system with N buses, the relationship is expressed as (1)

$$S_i = V_i \sum_{j \in N} Y_{ij} V_j \qquad i \in N \tag{1}$$

where V is the vector of voltage magnitudes of the nodes $i, j \in \{1, \cdots, K\}$, $K \bigcup N$. Obtaining the partial derivative of

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the voltages of (1) with respect to the active power P_k of a bus $k \in N$ gives

$$\mathbb{S}_{\{i=k\}} = \frac{\delta V_i}{\delta P_k} \sum_{j \in N} Y_{ij} V_j + V_i \sum_{j \in N} Y_{ij} \frac{\delta V_j}{\delta P_k} \tag{2}$$

A unique solution exist in (2) to compute the partial derivatives of $\frac{\delta V_i}{\delta P_k}$ and $\frac{\delta V_j}{\delta P_k}$. Once they are obtained, the partial derivative of the voltage magnitude can be obtained via

$$\frac{\delta |V_i|}{\delta P_k} = \frac{1}{|V_i|} Re(V_j \frac{\delta V_i}{\delta P_k}) \tag{3}$$

Thus, the changes in the bus voltages based on power changes can be determined using (3).

2) Utilisation Rate: line congestion control can be determined through the line utilisation rate. In estimating the line utilisation rate to assign a charge to the prosumer responsible for using the physical network, a power transfer distribution factor (PTDF) is utilised [28]. PTDF captures the variation in power flow at the buses, reflecting power injection at a bus and withdrawal at another bus. Using the derivative of power injection shift factor (ISF) of [28], the PTDF for a branch (k, l) with respect to power injection and withdrawal at nodes i and j is determined through (4)

$$\phi_{kl}^{ij} = \phi_{kl}^{i} - \phi_{kl}^{j} \tag{4}$$

where ϕ_{kl}^{i} and ϕ_{kl}^{j} are the power injections at i and power withdrawal at j for branch (k, l).

3) System Losses: to associate the losses resulting from the bilateral exchange of energy, a bilateral exchange coefficient (BEC) [28], [42] can be used as expressed in

$$\text{BEC}^{ij} = \frac{\delta P_{loss}}{\delta P_i} - \frac{\delta P_{loss}}{\delta P_j} \tag{5}$$

where $\frac{\delta P_{loss}}{\delta P_i}$ and $\frac{\delta P_{loss}}{\delta P_j}$ are the loss sensitivities to power injection and withdrawal at i and j respectively defined in (6).

$$\frac{\delta P_{loss}}{\delta P_k} = 2RE\left[V^T G \frac{\delta V}{\delta P_k}\right] \tag{6}$$

Here, $\frac{\delta V}{\delta P_k}$ is obtained from (2) and G is the conductance matrix. Equation (6) is termed the loss sensitivity factor (LSF) [43].

Thus, to assess the impact of P2P energy trading on the distribution network operation, the network constraints defined are used. For instance, using the VSC, any transaction violating the voltage variation will not be allowed to proceed. With PTDF, line utilisation rate can be determined, and subsequent charges assigned to the prosumers using the lines to avoid line congestion. Also, the BEC can calculate the system losses as a result of bilateral exchange, charging the prosumer responsible for the loss. The integration of the constraints is implemented within the trading distance charge discussed in section III-D.

D. Trading Distance Charge

Buyers and sellers in the community are grouped based on their location on the feeder as shown in Fig. 2. When a matched buyer and seller are on the same feeder, i.e. feeder A, their transaction proceeds without a distance charge. However, if the buyer and the seller are located on different feeders, i.e., feeders A and B, their transaction attracts a distance charge. The distance charge is implemented such that the further the transacting prosumers are away from each other, the more the distance charge they pay. A preset multiplier determined by the distance between the feeders is applied to the electricity charge. This multiplier is 1 when buyer and seller are on the same feeder. This will encourage trading between prosumers nearby or the same community and also account for losses that can be incurred during cross feeder transactions. To calculate the distance between a buyer and a seller in two different feeders, we use the Euclidean distance presented in [44] for feeder-to-feeder distance calculation expressed in (7)

$$d(a_i, b_j) = \sqrt{\frac{1}{H} \sum_{h=1}^{H} (a_{ih} - b_{jh})^2} \tag{7}$$

where a_i and b_j represent the buyer on feeder A and a seller on feeder B respectively. $h \in H$ are the different network constraint features including voltage variations, network utilisation and system losses defined in section III-C that could impact distribution network during energy transaction.

The distance charge between the seller and the buyer is calculated in (8) as,

$$d_{ch} = 1 + (d \cdot C) \tag{8}$$

where C is a constant vector charged per every kW of transacted energy between the buyer and the seller. An example is demonstrated in Fig. 2, with a cross feeder charge C of $0.002p/kWh$. If prosumer i on feeder A and prosumer j on feeder B are trading energy with an assumed distance of $500m$ apart, the distance charge will be given as $1 + (0.002 \times d(500m)) = 2p/kWh$.

Thus, similar to [28], a third-party entity like DSO validates each matched bid and offer to determine if any network constraint features will be violated. If the constraints will be violated, in case of voltage violation, the trade will not proceed; in case of line utilisation and losses, the charges are incorporated within the distance charge assigned to the trade violating the constraints. This process ensures that energy traders tend to prefer to exchange energy with the closest party to deter excess charge due to network violations resulting from losses and line utilisation.

IV. Market Bids and Matching Algorithm

To develop a P2P-ETS platform, the characteristics of the energy market are first considered. The market has three features: (a) bids are placed at time t_0 for a trading period t_1; (b) The trade proceeds after matching participants, and (c) participants are informed about the value of the traded quantity. The market follows pairwise meetings of participants utilising a double auction market where each prosumer plays an active role to provide bids or offers of their demand or supply.

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A. The Trading Period

In the existing electricity market, energy is bought and sold in a 30 minutes interval. This structure of the market is based on energy generation, consumption, and price that can vary due to [45]:

- Environmental conditions: Since the energy generation focus is on renewable sources, weather conditions affect the generation output of PV panels as well as wind turbines and other renewable sources. A market based on PV panels might increase the trading period during the winter season. Similarly, those based on wind turbines might reduce the trading period during a season with high winds.
- Time of day: The time of electricity usage also affects the market trading period. In the traditional electricity billing, off-peak period usage between 11 pm and 6 am attracts less fee as compared to the peak period, between 4 pm and 9 pm, attracting the highest fee [46]. In addition, the time of the day electricity production for PV panels is highest around noon, which calls for a period trading market.
- Grid balancing: The grid must account for the peak and off-peak electricity consumption periods, and the peak and off-peak generation periods within the design of an energy trading market to enable the balancing of supply and demand.

This paper adopts period-based energy trading and a double auction-based market method, with trading executed at t period. Buyers and sellers submit bids (Table II) into the market during each period t_0 against the next trading period t_1 for intraday energy delivery. An example of a trading period is shown in Fig. 3.

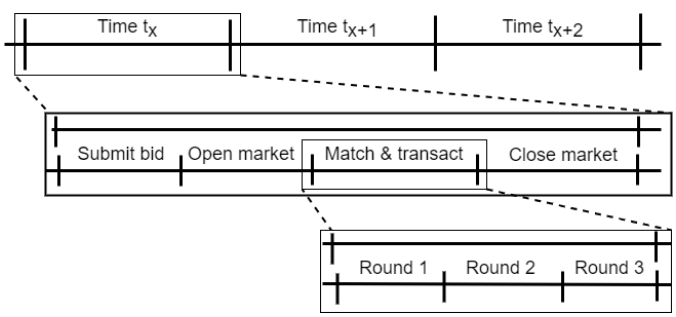

Fig. 3: An illustration of the trading period on the P2P-ETS platform.

The activities at t_x are divided into four segments; submit bid, open market, match a transaction, close market including the settlement and market clearing. Once the market is opened for energy trading, no more bids are submitted. The match and transaction activities could proceed to several rounds depending on the number of prosumers and the quantity of demand left in the market before proceeding to settlement and market clearing.

B. The Matching Phase

The orders submitted to the market are grouped into bids and offer denoted by $N_{\bar{k}} = \{1, \cdots, n_{\bar{k}}\}$, where $\bar{k} = 1, 2,$ denotes the type of group and type $\bar{k}(n_{\bar{k}} \geq 1)$. The dual nature of a prosumer of being a consumer or a producer implies that it can take up either of such roles at a given trading period t_1, submitting either bid or offer at t_0.

TABLE II: Prosumers' market bid structure

Qty. (kWh)	Price (p/kWh)	ID	Role
3.6	14.3	0	Bids
1.8	12	1	Bids
2	14.3	2	Bids
4.2	13	3	Bids
10	14.3	4	Offer (Grid)
2	11	5	Offer
3	10	6	Offer
2.5	13	7	Offer
4.5	10	8	Offer
3	9	9	Offer

The bid price is the maximum price a consumer is willing to pay for $1kWh$ of energy, while the offer price is the minimum price a producer is willing to sell $1kWh$ of energy. For the prosumer to transact, the bid price must be greater than or equal to the offer price. When two prosumers from different groups N_1 and N_2 are matched, they trade over the partition or all of the quantity(ies) of energy associated with the match at that period. For instance, at time $t \in T$, let $i \in N_1$ and $j \in N_2$ be the initially matched prosumers. If their preferences in terms of quantity and price are matched, the prosumers leave the market with the share of the unit price surplus as savings. In the event of unmatched preferences, the algorithm proceeds to the next round (see Fig. 3) where the remaining prosumers in the market are paired with new prosumers until all bids and offers during that trading period are satisfied. However, if any offer remains during the current trading period, the offer is moved to the next open market.

To assess the effect of trading distance, and to evaluate the benefits of local energy consumption, the matching algorithm is evaluated for two scenarios:

1) Matching based on price and quantity: In this scenario, only the price and quantity of energy preference of prosumers are considered in matching the bids and offers. This reference scenario is mostly adopted in the current electricity market system where choice over price and/or source of energy is incorporated.
2) Matching including distance: To evaluate the effect of distance on energy consumption, this scenario incorporated distance charge in the matching phase. As previously discussed that for electricity, transmission losses and other associated costs are largely dependant on the distance travelled making distance an important factor in this work.

C. Matching and Social Welfare Maximisation

With a lot of offers and bids to match, the matching is obtained by solving a market clearing optimisation problem to determine the matched peers and their unitary benefits, i.e. to maximise social welfare [47]. Social welfare is the region where any buyer would pay at most what he was willing to pay and any sellers would receive at minimum the price

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he was willing to sell for. In maximising the welfare of all prosumers in the market, a primal-dual gradient method is utilised in [12] using the first-order method. Result in [12] were evaluated against other traditional distributed algorithms including ADMM, interior point methods and centralised approaches proving its efficiency.

Representing the set of consumers N_1 as N_B, set of producers N_2 as N_S and set of offers from the prosumers as $\mathcal{L}_S = \{S_i, i = 1, \cdots, N_S\}$, with maximum offer quantity of Q_i^G at price P_i^G. Similarly, the set of bids from the prosumers is denoted as $\mathcal{L}_B = \{B_i, i = 1, \cdots, N_B\}$, with maximum bid quantity of Q_i^B at price P_i^B. Thus, the social welfare maximisation problem is expressed as:

$$\underset{\{x_i^S, x_i^B\}}{\textbf{maximise}} \left[\sum_i P_i^B x_i^B - \sum_j P_j^S x_j^S \right] \tag{9a}$$

$$\text{subject to :} \quad \sum_j x_j^S - \sum_i x_i^B = 0 \tag{9b}$$

$$0 \leq x_i^B \leq Q_i^B, \quad i = 1, \cdots, N_B \tag{9c}$$

$$0 \leq x_j^S \leq Q_j^S, \quad j = 1, \cdots, N_S \tag{9d}$$

Equations (9c) and (9d) are the demand and supply levels to optimise the social welfare of the consumers and producers respectively. The solution x^* to solving (9a) as a linear program would only result in a list of matched bids and offers. However, solving (9a) using the dual-Lagrange method gives the complete market clearing. Here, complete market clearing consists of the list of offers (supply and demand, and quantity accepted), achieved through the primal solution and the price at which the market is cleared achieved through the dual solution. Thus, to solve (9a) using the Lagrange multiplier, the following is derived.

$$\underset{\lambda^E, \{v_i^B\}, \{v_j^S\}}{\textbf{maximise}} \left[-\sum_j v_j^S Q_j^S - \sum_i v_i^B Q_i^B \right] \tag{10a}$$

$$\text{subject to :} \quad \lambda^E - v_j^S \leq P_j^S, \quad j = 1, \cdots, N_S \tag{10b}$$

$$-\lambda^E - v_i^B \leq -P_i^B, \quad i = 1, \cdots, N_B \tag{10c}$$

$$v_j^S \geq 0, \quad j = 1, \cdots, N_S, \tag{10d}$$

$$v_i^B \geq 0, \quad i = 1, \cdots, N_B \tag{10e}$$

where $\lambda = \lambda^E$ is the Lagrange multiplier associated with (9b) representing the equilibrium price and $v = [v_1^S, \cdots, v_{N_G}^S \quad v_1^B, \cdots, v_{N_B}^B]^T$ is the Lagrange multiplier associated with (9c) and (9d) respectively. The solution v^* represents the unitary benefits for the various demand and supply offers when the market is cleared at the equilibrium price λ. the market mechanism is summarised in Algorithm 1.

Algorithm 1: The market mechanism algorithm.

```
Function TransactionArray (addsale);
Input: order; bids; offers; quantities; distance charge
Output: sales amount; cost-savings
Open market
for each round do
    for each bid i in orders do
        for each offer j in orders do
            Solve market clearing optimisation (10a)
            for each matched i and j do
                if DSO = Approved then
                    Distance = d(a_i, b_j)
                end
                distance charge = 1+ (0.002 * Distance
                  in meters)
                (bid i, offer j) = (bid i, offer j) *
                  distance charge
            end
            if bid i ≥ offer j && j quantities ≥ i
              quantities then
                Calculate sales quantities
                if bid i ≥ offer j && j quantities < i
                  quantities then
                    Transfer all j quantities to i
                    Transfer excess quantities of i to
                      next round
                end
            end
            Calculate unitary benefits/cost-savings
            Update addsale
        end
    end
    Go to next round
end
Submit successful sales and return to open market
```

V. Evaluation and Result Analysis

To assess the performance of the algorithm and $VirtElect$, the platform development is based on the python programming language. A case of 10 prosumers is first evaluated based on the market bid of Table II. The demand requirement of consumers $0 - -3$ is based on real energy demand data from the 'PECAN street project' [48]. This dataset is for residential households and covers a variety of residential load patterns such as lighting, washing machine, and air conditioning systems, etc., which are used at variable times. As with a realistic power distribution system, the household profiles in the data set vary because the residences' consumption varies. The average peak solar PV output is about $0.4kWh$, the load demand by residential households will determine which household is willing to buy or sell energy. An instance of the data is presented in Fig. 4.

P_{load} represents the energy consumption of the house, P_{grid} is the energy from the grid to balance the consumption, while P_{solar} is the energy generated over 24 hours by the solar PV panels installed on the household roof. Between the hours of $0:00 - -9:00$, the energy consumption for the household is delivered from the grid. Between the hours of $9:00 - -20:00$, the generated solar energy increased sufficiently so that the household energy is mostly delivered by the solar panels, whilst the energy consumed during the remaining hours of the day is delivered by the grid. The total energy received from the grid is the energy submitted as a

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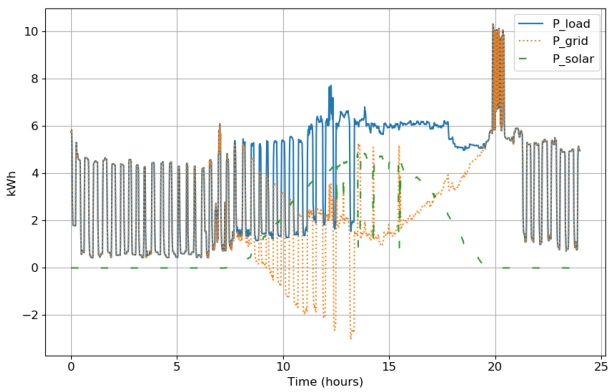

Fig. 4: An instance of a real energy profile of a house used alongside other households in the cases considered.

bid to the market for P2P trade with other prosumers, i.e., consumer 0 profile. In addition, the advertised energy price for the grid is based on the average electricity price for households in the UK.

A. Scenario 1: Matching Based on Price and Quantity of Energy

This section considers the initial matching of prosumers on the platform based on their bid and offer prices as well as quantity demanded and supplied. The result is analysed based on energy demand and supply, and the cost saved by the prosumers.

1) Energy Demand and Supply on $VirtElect$: Fig. 5 shows an example of the matched pairs and the amount of energy traded between each pair after a simulation run. It can be observed that due to the divisibility of the demands, some prosumers, i.e., producer 9, participated in 3 rounds with 3 different paired consumers (1, 3, and 7).

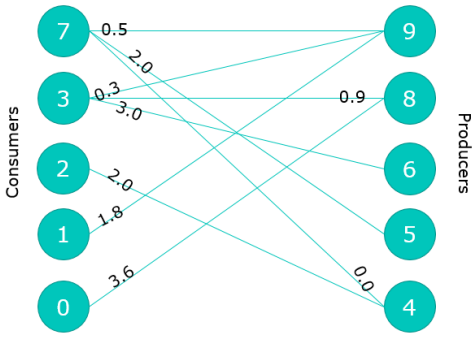

Fig. 5: A graph illustrating the paired prosumers and the amount of energy traded between them.

Fig. 6 shows the result after energy has been traded. In the first round, consumer 0 bought all its quantity demanded from producer 8, consumer 1 from producer 9, and consumer 2 from grid 4. Producer 5 sold all its energy surplus to consumer 7, as producer 6 to consumer 3. In the second round, the demand requirements of consumer 3 have not been met, thus, consumer 3 is paired with producer 8. Producer 8 sold all its remaining energy to consumer 3, while consumer 7 purchased the remaining energy demands from producer 9. Further, the market interactions proceed to round 3, where the remaining demand requirements of consumer 3 are met by producer 9. This shows that all the demands are met by the prosumers on $VirtElect$.

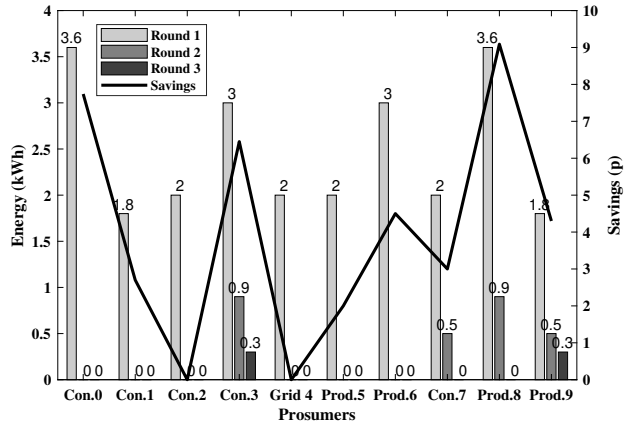

Fig. 6: An illustration of the energy traded between prosumers and individual cost savings.

2) Cost Savings by the Prosumers on $VirtElect$: The economic benefit in terms of cost savings calculation is based on the price difference of the matched partners that traded energy. For instance, consumer 0's $3.6kWh$, with a maximum buy price of $14.3p/kWh$ is supplied by producer 8 with a minimum sale price of $10p/kWh$. The difference in the price equals $4.3p/kWh$, which would be shared as savings for both parties. Thus total savings of consumer 0 by buying $3.6kWh$ of energy from the P2P platform is $7.74p$. This experience relates to other prosumers on $VirtElect$. However, the maximum and minimum bid and offer price for consumer 2 and grid 4 is $14.3p/kWh$, thus, both prosumers when paired did not earn any savings. The cost savings is illustrated in Fig. 6. In addition, it is worth noting that although the grid has the highest amount of energy to sell in the market, it was only able to sell just $2kWh$ of its $10kWh$ total energy. This is a result of its minimum offer price, which is higher than most of the consumers' maximum bid price.

B. Scenario 2: Matching Based on Price, Quantity, and Distance

In this section, the effect of the distance charge is assessed using the segmentation shown in Fig. 2, and mathematical formulations of Section III-D.

The market bid is as shown in Table III, including the location of each prosumer on the distribution feeder. The results are presented based on the energy demanded and supplied as well as the cost saved by the prosumers.

1) Energy Demand and Supply on $VirtElect$: Fig. 7 shows the result after energy has been traded. In the first round, consumer 0 bought all of its demanded quantity from producer 8, as consumer 1 from producer 9. Producer 5 sold all its energy surplus to consumer 7, as producer 6 to consumer 3. Interestingly, consumer 2 was paired with

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TABLE III: Market bid structure and cost savings for Scenario 2.

Prosumer ID	Dist. C (p/kWh)	Feeder Location	Savings (p)
0	2	A	15.48
1	4	B	27.0
2	2	A	3.71
3	4	B	62.4
4	6	C	0.0
5	4	B	8.0
6	2	A	48.0
7	4	B	16.5
8	2	A	29.88
9	2	A	39.21

grid 4, but no trade occurs between them as the far trading distance resulted in extra charges. In the second round, the demand requirements of consumer 3 were not met, thus, consumer 3 was paired with producer 8. Producer 8 sold all its remaining energy to consumer 3, while consumer 2's demand requirements were met by producer 9. Grid 4 was paired with consumer 7, but no trade occurred between them as the far trading distance resulted in extra charges. Further, the market interaction proceeds to round 3, where the remaining demand requirements of consumer 7 were met by producer 9.

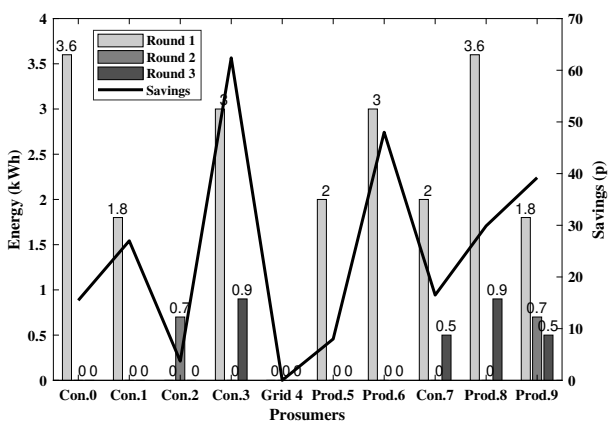

Fig. 7: An illustration of the energy traded between pairs and individual cost savings.

2) Cost Savings by the Prosumers on $VirtElect$: Similarly, using the cost savings calculations described in Section V-A2, the economic benefit in terms of cost savings of consumer 0 by buying $3.6kWh$ of energy from producer 8 on $VirtElect$ is $15.48p$. The cost savings for other prosumers are shown in Table III and Fig. 7. However, the maximum and minimum bid and offer price for consumer 2 and grid 4 is $14.3p/kWh$, but because they are located at different feeders when the two were paired, no trade occurs. In addition, the grid was paired with consumer 7 in the second round, however, no trade occurs between them. Thus, the grid earned $0p$ savings in this scenario. It can be observed that while consumer 2 did not earn any savings in the first scenario because of the paired partner (grid), he earned a total savings of $3.71p$ in this scenario, as a result of declining the grid offer and subsequently being paired with a producer with a lower asking price. These results show that consumers of local energy consumption acquired more cost savings than prosumers that do not trade energy locally.

3) Environmental Impact Analysis: While energy generated from renewable is universally regarded as green energy, energy transmission between consumer and producer might also result in emission losses depending on their distance. This is called transmission and distribution losses. To evaluate the environmental benefit of P2P-ETS, we calculate the total emissions equivalent to generating and consuming energy locally using (11)

$$CO_2 \text{ emissions} = \text{activity data} \times \text{emission factor} \quad (11)$$

The emissions factor calculated by BEIS for electricity generated is $0.23314\ kgCO_2e$, while for transmission and distribution losses is $0.02005\ kgCO_2e$ for the year 2020 [49]. The activity data is the equivalent of electricity consumption and supply in this case. We evaluate the environmental benefit of local energy generation and consumption in the case study given in Table II. The total generation and demand in Table II is $36.6\ kWh$ resulting in a CO_2 emissions reduction of $9.2668\ kgCO_2e$. 92% of the reduced emissions are accustomed to local energy generation and consumption. Factoring transmission distance into the study saves 8% of CO_2 emissions.

C. Scenario 3: Impact of Ratio of Producers to Consumers on $VirtElect$ and Scalability Assessment

Additional assessment is carried out to evaluate the performance and scalability of $VirtElect$ to varying ratios of producers/sellers to consumers/buyers. A range of representative values of demands, supplies, and prices are assigned to the prosumers. For the buyers, the minimum offer price is set between $11 - 14p/kWh$, the quantity of energy demand is set to $1 - 5kWh$, while the sellers' bid price is set to $10 - 15p/kWh$ and the quantity of energy supplies is set to $5 - 10kWh$. Simulations were run for a different ratio of sellers to buyers for 30 participants. Fig. 8 shows the relationship between the total supply, demand, and cost savings against varying ratios of prosumers.

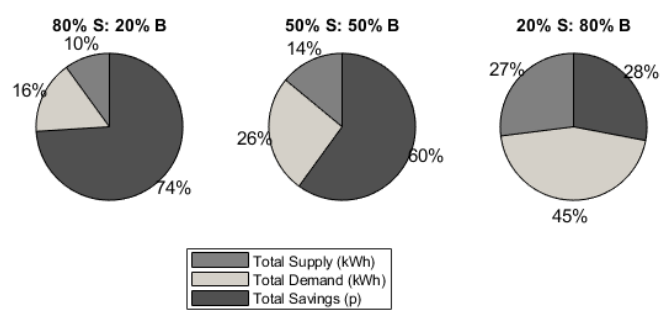

Fig. 8: A pie chart showing the relationship between the total supply, demand, and savings for a different ratio of sellers to buyers.

It can be observed that with a ratio of 80% of sellers to 20% of buyers, the total supply increased with less demand, compared to when there are 20% of sellers on the platform,

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as the total cost savings are a reflection of the volume of trade that occurs on the $VirtElect$. With 80% sellers, the savings is 16% compared to 20% sellers and 45% cost savings. This result emphasises the importance of a P2P exchange of energy, the more the local demand is met by the local supply, the higher the community cost savings.

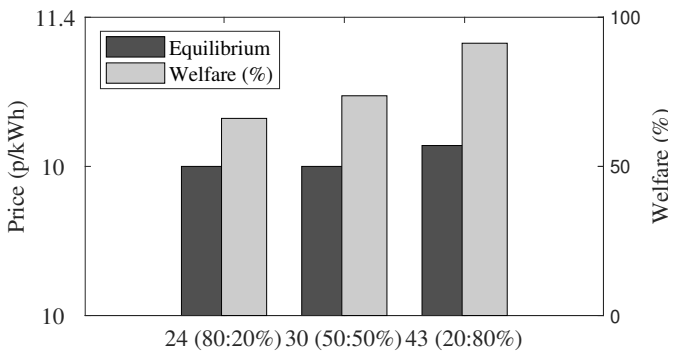

Fig. 9: Relationship between the equilibrium price, quantity, and the percentage welfare for a different ratio of prosumers.

Similarly, Fig. 9 shows the relationship between the equilibrium price, quantity, and the percentage of the maximum welfare against the ratio of prosumers on the platform. It can be observed that for 80% of sellers, the average quantity traded is $24kWh$ at an equilibrium price of $10p/kWh$. However, with 50% of sellers, the traded quantity increased to $30kWh$ which reflects the increase in demand due to the increased number of buyers. In addition, with more buyers on the platform, 80%, the traded quantity, and the equilibrium price increased to $43kWh$ and $11p/kWh$ respectively. This reflects an economic market where an increase in demand and a decrease in supply leads to an increase in the price of the commodity. In addition, it can be observed from the plot that the percentage welfare of the participants increases as the ratio of buyers increases on the platform.

To further demonstrate the scalability of the energy market, Fig. 10 and Fig. 11 show a particular run for 100 participants.

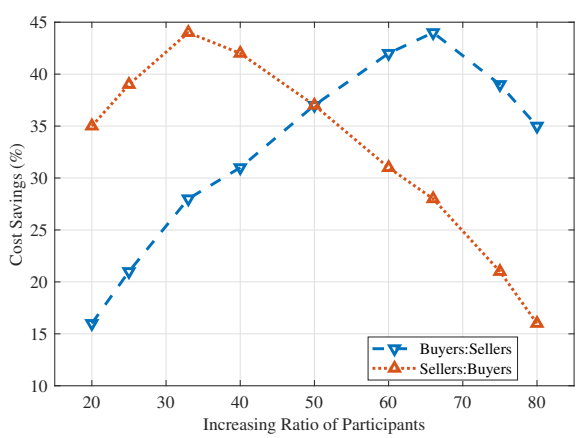

Fig. 10: Impact of different ratios of prosumers to total cost savings.

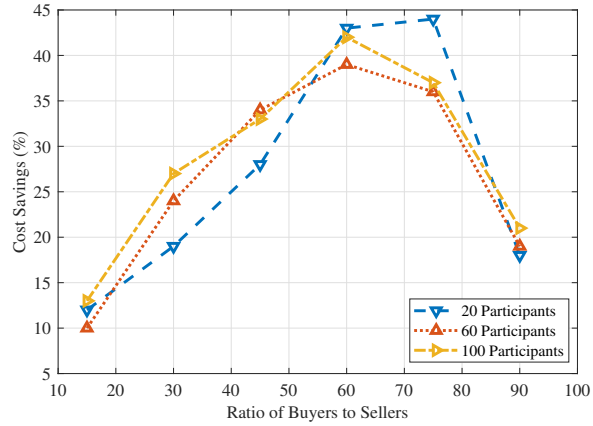

Fig. 11: Impact of different ratios of buyers to sellers for an increasing number of participants and total cost savings.

In Fig. 10, as the ratio of buyers increases against the ratio of sellers, the cost savings increase. However, when the ratio of buyers to sellers exceeds 66%, a decline in cost savings is observed. Similarly, when the ratio of buyers to sellers exceeds 33%, a decline in cost savings was also observed. These results further suggest that the role of prosumers on $VirtElect$ determines the cost savings. Such as fewer savings when there are more sellers than buyers and vice versa. Finally, when utilising the ratio of buyers to sellers for an increasing number of participants, Fig. 11 shows an increase in cost savings. This savings reflect when the buyer to seller ratio ranges between 0% to 60% and declines when the ratio exceeds 60%. This suggests that as the number of prosumers increases, local demands are met, and cost savings increase. However, these cost savings could decline with a disproportionate number of consumers to producers.

To sum, $VirtElect$ can easily be implemented and managed. It has been demonstrated that it is economical for consumers and prosumers in a decentralised energy paradigm where the exchange of energy can be dynamically negotiated to fit individual needs. Thus, reducing the dependency of the central grid and enabling a more competitive environment. This will incentivise further participation in the trading and sharing of locally generated energy. Similarly, the economic benefit to the DSO is realised by balancing local energy generation and consumption through trading. This would assist the grid during peak demand and deter the deployment of generators or high infrastructure to balance and stabilise the system, thus, reducing investment costs.

VI. Conclusion and Future Work

This paper presented the design and implementation of a P2P-ETS platform - $VirtElect$ for local energy consumption and trading. The paper commenced with a description of the platform design that highlighted the interaction between prosumers. Then, the market mechanism used on the platform was discussed for the two used cases considered giving a snapshot of the developed platform interface in the appendix. Simulation results indicate that local energy trading is not only

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beneficial to the environment but also leads to a significant amount of savings by the trading prosumers of up to 45%, depending upon their number and ratio on the platform. Future work will include testing the performance of the platform and market mechanism incorporating more prosumers and functions that will consider more matching resources, preferences and objectives over an extended period. In addition, future work will explore the use of distributed ledger technology to develop smart contracts that can be used to manage trust and transactions on *VirtElect*.

APPENDIX

VirtElect INTERFACE

This section shows the interface of the developed P2P-ETS platform as shown in Figs. 12, 13, 14, and Fig. 15.

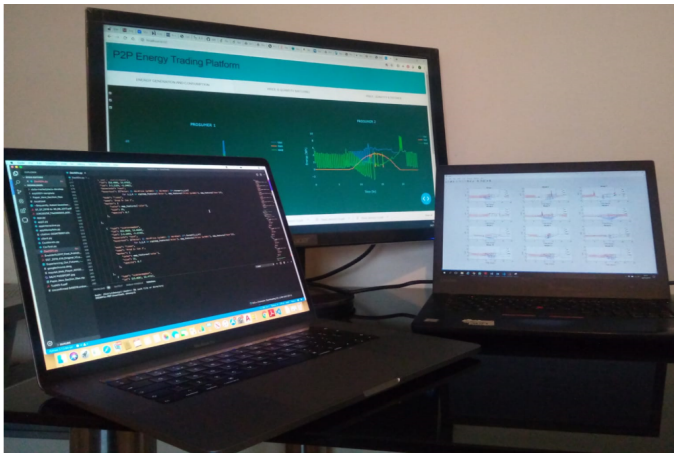

Fig. 12: P2P-ETS platform set-up with connected devices.

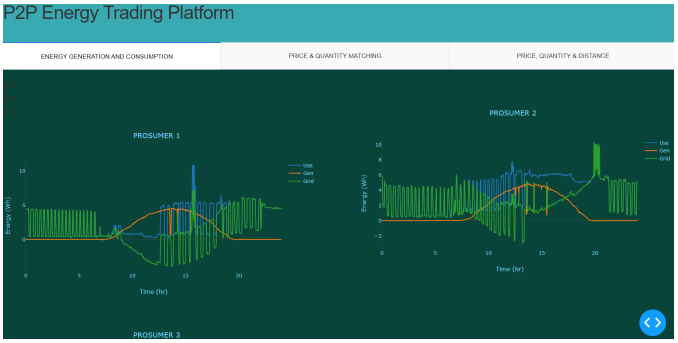

Fig. 13: Prosumers profiling on the P2P-ETS platform.

Fig. 12 shows the overall setup of the connected devices representing prosumer smart meters on the P2P-ETS platform. Fig. 13 shows the received energy profile of the prosumers. This shows details of the energy generated, consumed, and received from the grid as represented in Fig. 4. Similarly, Fig. 14 shows the bid submitted to the market and the location of the market participants. The submitted bid is as represented in Tables II and III and the plot as shown in Fig. 7. Fig. 14 shows the energy transfer between those that trade, as well as the links connecting them on the map.

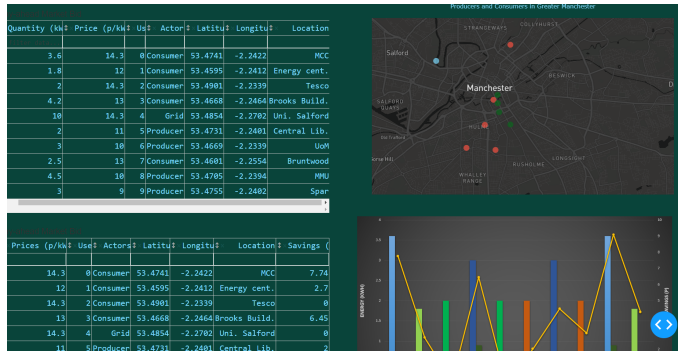

Fig. 14: Market bid and the prosumers' location on the P2P-ETS platform.

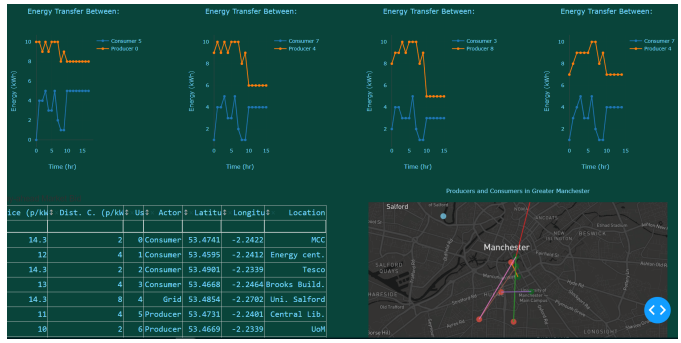

Fig. 15: Energy transfer between prosumers and links connecting trading pairs.

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2021.3109613, IEEE Internet of Things Journal

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