A Vehicle-to-Vehicle Energy Trading Platform Using Double Auction with High Flexibility

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***Abstract*—The rapid growth of the Electric Vehicle (EV) deployment contributes to zero-emission transport but puts great pressure on the power grid. This paper proposed a Vehicle-to-Vehicle (V2V) energy trading platform for EV charging that allows EVs with surplus electricity to provide electric energy for the exhausted batteries of other EVs. The platform applied the Double Auction (DA) mechanism allowing multiple vehicles to conduct energy transactions simultaneously. The price, availability and amount of the traded electricity can be continually adjusted with high flexibility. The final trading price was determined by the k-factor rule so that balances the profits of all participants. A case study was performed by using the EV data collected from a public car park in the UK. Financial benefits of all participants were increased significantly and the energy consumption from the power grid was reduced by using the proposed trading mechanism. These potential reductions in EV running costs encourage the development of the EV market.**

Keywords—V2V energy trading, electric vehicle, double auction, k-factor.

I. INTRODUCTION

In recent years, there is a dramatic growth in the number of Electric Vehicles (EVs). The sales of EVs made up 10.7% of the UK car market in 2020 [1], and the UK Government committed to decarbonize transport further by phasing out the sale of new petrol and diesel vehicles by 2030, with all new cars and vans to be zero emissions by 2035 [2]. Such a large number of new-registered EVs put tremendous pressure on the current power grid. In the UK, the energy consumption of EVs was around 21.6 TWh (million kWh) in 2020 [3], and the number keeps growing.

Concerns have been raised that the current Vehicle-to-Grid (V2G) energy transaction will hardly satisfy the rapidly growing demand of EVs in the future. However, EVs can be served as the mediator to carry and exchange energy with other vehicles, e.g. EVs with surplus electricity can transmit electric energy for the exhausted batteries of other EVs. As a result, the Vehicle-to-Vehicle (V2V) energy trading platform has been proposed for the EV charging. It allows energy transactions between vehicles, thereby reducing the peak demand of the power grid and balancing the distribution of energy resources. The impact of the V2V trading will be even more significant if concerns the rapid development of residential solar PV systems.

The V2V trading is a multiple-buyer versus multiple-seller trading problem. It commonly adopts the Double Auction (DA) pricing mechanism to allow multiple traders to offer or accept transactions during the trading period [4]. Many researches have been conducted to use DA method to maximize the overall social welfare, i.e., the sum of the utility of all auctioneers. In [5]-[8], the DA mechanism was combined with the blockchain technology for different trading scenarios. The blockchain-based DA mechanism did not require a trusted third party to complete the trading [5] and showed great advantages in the trading privacy and security [6]. In [7], a DA-based game theoretic approach was proposed, which let buyers adjust amounts of demanded energy according to verification of the electricity price and sellers achieve the maximum social warfare. A flocking-based DA method was proposed in [8], and the successful trading reaches 80% within neighborhoods. However, the blockchain-based DA mechanism was not effective for transactions of a small number of participants [9]. The Multi-Units Double Auction (MUDA) mechanism was proposed in [10]-[12]. It reduced the time cost of the trading so that increased the flexibility of the experimental design [10]. However, the final trading price of the MUDA mechanism was determined by the participants' asks and bids at specific trading points. To prevent cheaters from manipulating the trading market, those asks and bids at trading points were sacrificed even if they met transaction requirements [11]. Additionally, the Iterative Double Auction (IDA) [13] and Continuous Double Auction (CDA) mechanisms [14][15] were developed and applied for different trading scenarios. Both IDA and CDA allow participants to bid/ask repeatedly, so that to financial profits can be maximized by iterations. However, IDA and CDA mechanisms were not efficient for small-scale civil energy trading.

This paper proposes a V2V energy trading platform for EV charging. The platform applied the DA pricing mechanism that allowed EV users to trade electric energy with each other directly. The final trading price was determined by the k-factor rule so that the financial profits of all participants were balanced. In addition, the platform enabled participants to change their reservation bid/ask prices, energy amount and available trading time flexibly. By changing trading details, the maximum profits of each participant can be determined. A case study was conducted by using the historical EV charging data in a public car park in the UK. The maximum economic profits of participants were searched by changing the reservation prices and available trading time. By using the V2V platform, the running cost of EVs was reduced.

The paper is organized as follows. Section II introduces the V2V energy trading platform, including the architecture, the DA mechanism and the k-factor rule. The mathematical formulation of the trading procedure is also presented.

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Section III presents the case study and the simulation results. The conclusion is arranged in section IV.

II. V2V Energy Trading Platform

The V2V energy trading platform collects buyer and seller data and uses the DA to decide transaction pairs. The DA mechanism is a process of buying and selling goods with multiple buyers and sellers [4]. Buyers and sellers provide their reservation bid and ask prices to the third-party market platform, and the platform determines the clearing price of the trading by matching their needs. The DA allows participants to negotiate and trade with each other, so that it is especially suitable for the multiple-buyer versus multiple-seller problem. Fig. 1 shows the architecture of the proposed V2V platform.

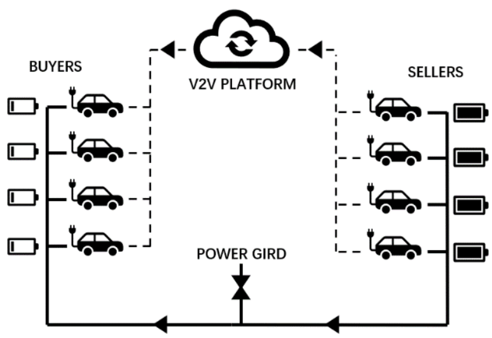

Fig. 1. Architecture of the V2V energy trading platform.

The V2V energy transactions are conducted in public car parks at scheduled times. Both buyers and sellers can get energy trading details through the platform, such as the clearing price, amount of energy and trading location, etc. In addition, participants can modify trading details before the gate closure in each trading circle, so that they can obtain the largest economy benefits by using appropriate auction strategies. However, the trading will fail if the amount of energy is unbalanced or the bid/ask price is unmatched. In this case, EVs will be charged from the power grid instead. Platform fee is required for each successful V2V transaction due to the installation and maintenance cost.

The trading procedure includes four steps. It first collects the buyer and seller data, sorts the data according to the bid/ask price and available amount, and calculates the final trading price. Once the transactions are completed, the trading cycle will be cleared.

A. Step 1: inputs

Buyers and sellers will naturally acquire attributes after participating in the V2V energy trading. Attributes includes the reservation bid/ask price, i.e., the preferred trading price, the amount of energy and the available trading time. Table I summarizes key parameters in each clearing circle.

TABLE I. Key Parameters In Each Clearing Circle

Parameters	Descriptions
$B=\{b_1,b_2,...b_i\}$	The set of i buyers
$S=\{s_1,s_2,...s_j\}$	The set of j sellers
$R_b=\{R_{b1},R_{b2},...R_{bi}\}$	The reservation bids of buyer (i.e. the highest bid that a buyer could offer)
$R_s=\{R_{s1},R_{s2},...R_{sj}\}$	The reservation asks of seller (i.e. the lowest price that a seller could accept)
$X_b=\{X_{b1},X_{b2},...X_{bi}\}$	The amounts of demands from buyers
$X_s=\{X_{s1},X_{s2},...X_{sj}\}$	The amounts of supplies from sellers

The full-day trading period T consists of 48 slots, that each slot is a transaction clearing circle equaling to half of hours. Parameters shown in the table are updated every 30 minutes.

$$T=\{t_1,t_2,...t_{48}\} \tag{1}$$

B. Step 2: order the input data

The platform orders buyers' and sellers' attributes based on two rules:

1) Price first rule: The reservation bids/asks submitted by buyers and sellers are ordered accoding to prices. The reservation bids from buyers are sorted in a decreasing order, while the reservation asks from sellers are sorted in an increasing order.

$$R_{b1} \geq R_{b2} \geq ... \geq R_{bn} \tag{2}$$

$$R_{s1} \leq R_{s2} \leq ... \leq R_{sm} \tag{3}$$

2) Time first rule: Considering the situation that different buyers/sellers submit their reservation bids/asks with same prices at same time slot, the time first rule is proposed and applied. Traders are sorted in chronological order, that the buyer/seller who submitted the bid/ask earlier takes the higher position.

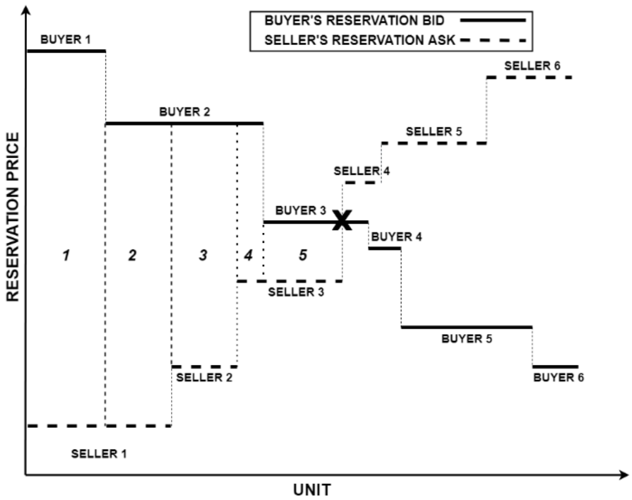

Fig. 2. Multiple buyers trade with multiple sellers in double auction.

The price curve constituted by the sorted reservation bids/asks is called buyer's/seller's curve as shown by Fig. 2. The intersection of the buyer's and seller's curve is the trading clearing point, i.e. the cross in Fig. 2. Transactions on the left side of the point are successful V2V transactions, while the rest of the participants (right side of the point) are failed due to the unmatched asks and bids. Assuming the buyer at the trading clearing point is buyer x (b_x), and the seller is seller y (s_y), there are two situations at the intersection, which are:

$$Case\ 1: R_{bx} \geq R_{sy} \tag{4}$$

$$Case\ 2: R_{bx} < R_{sy} \tag{5}$$

These two cases describe the conditions of the last successful reservation, which not affects the trading process. The following chapter will take Case 1 as example.

C. Trading and bill calculation

In the V2V energy trading, the number of transactions is not necessarily equal to the number of buyers and sellers. A buyer can buy energy from multiple sellers, and a seller can trade with multiple buyers. The blocks divided by dashed lines in Fig. 2 indicate successful energy transactions, that the transaction numbered 2, 3 and 4 refers to a trading with one buyer and three different sellers. The energy amount of demand from buyers X_{bi}, and the energy amount of supplies from sellers X_{sj} are denoted by Eq. (6) and Eq. (7), where m is the number of seller that buyer i traded with and n is the number for the seller j.

$$X_{bi}=\sum_{m=1}^{M} X_{bi}^{m} \tag{6}$$

$$X_{sj}=\sum_{n=1}^{N} X_{sj}^{n} \tag{7}$$

K-factor rule is the pricing mechanism applied in the proposed V2V platform. The rule is denoted by Eq. (8). In the equation, P represents the final trading price, b refers to the reservation bid from buyers, s refers to the reservation ask from sellers, and K is the pricing factor.

$$P=K\cdot b+(1-K)\cdot s \tag{8}$$

When K is 1, the final trading price equals to the buyer's bid price. In this case, the rule is equivalent to giving the buyer a favorable right to make the bid while the seller can only accept or reject the trading. Similarly, setting $K = 0$ effectively grants the seller the first-ask right. The final trading price equals to the seller's ask price. When $K = 1/2$, the rule determines a final trading price by splitting the difference between the participants' offers. Both buyers' and sellers' offer carry equal weight in determining the trading price [16]. The application of the k-factor rule enables the platform to balance the price between the buyer and seller-side market.

The final trading price (C_k) of each energy transaction is determined by using $k = \frac{1}{2}$, as shown in Eq. (9).

$$C_k=\frac{|R_{bi}+R_{sj}|}{2} \tag{9}$$

The cost of the buyer i in time slot t, F_{bi}^{t}, is represented by Eq. (10), where α is the ratio of the platform fee charged from the buyer, m represents transactions that buyer b_i with multiple sellers.

$$F_{bi}^{t}=(1+\alpha)\cdot\sum_{m=1}^{M}(X_{bi}^{m}\cdot C_k) \tag{10}$$

Similarly, the income of the seller j in time slot t, F_{sj}^{t}, is denoted by Eq. (11), where β is the ratio of the platform fee charged from the seller, n indicates transactions that seller s_j with multiple buyers.

$$F_{sj}^{t}=(1-\beta)\cdot\sum_{n=1}^{N}(X_{sj}^{n}\cdot C_k) \tag{11}$$

Then, the total transaction amount for the day of the buyer i (F_{bi}) and seller j (F_{sj}) are represented are obtained, shown as Eq. (12) and Eq. (13) respectively.

$$F_{bi} = \sum_{t=1}^{T} F_{bi}^{t} \tag{12}$$

$$F_{sj} = \sum_{t=1}^{T} F_{sj}^{t} \tag{13}$$

D. Trading circle clearing

For participants, actions such as changing the price and amount, should be made 5 minutes before the end of the time slot. When all transactions in the slot t are solved, the trading circle is cleared. The platform automatically moves to the next cycle, and the unsolved transaction reservations in the previous cycle are retained and processed in the next time slot.

III. CASE STUDY

A case study was performed to evaluate the proposed trading platform by using the historical EV data. The data were collected from a public car park in the UK. 15 EVs were selected to be participants of the trading, which were divided to 7 buyers and 8 sellers. The real-life data recorded the energy consumption, start charging time and end charging time of charging events of each vehicle. The remaining electricity was also available measured by the on-board sensor. By randomly generating the reservation bids/asks, the data used for the case study was generated as shown in TABLE II. The ratio of the platform fee charged from buyer α is 0.1, and for seller, β equals to 0.15.

TABLE II. THE DATA IN CASE STUDY

Buyer				
ID	***Time Start***	***Time End***	***Reservation Bid (£/kWh)***	***Demand (kWh)***
1	10:33	11:43	0.15	40.3
2	12:40	13:19	0.13	16.4
3	13:14	13:55	0.125	17.7
4	13:39	13:55	0.145	8.1
5	14:03	14:58	0.15	20.4
6	15:37	17:05	0.115	17.3
7	17:04	18:32	0.125	25.6
Seller				
ID	***Time Start***	***Time End***	***Reservation Ask (£/kWh)***	***Demand (kWh)***
1	10:39	09:11 (+1)	0.095	21.6
2	12:16	11:39 (+1)	0.11	27.4
3	13:11	08:00 (+1)	0.105	33.5
4	13:52	07:06 (+1)	0.075	35.9
5	14:07	07:21 (+1)	0.075	28.7
6	15:03	08:26 (+1)	0.08	19.1
7	16:18	14:33 (+1)	0.10	37.2
8	18:06	12:50 (+1)	0.13	35.7

A. Results of Total Bills

The costs of buyers and incomes of sellers are simulated by using the proposed V2V energy trading platform. Fig. 3 shows the comparison between the V2V and V2G transaction costs of 7 buyers throughout the day. Each column represents one energy transaction. Columns with slashes represent costs of buyers using V2V transactions, while solid columns indicate potential costs of buyers with V2G transactions. The difference between two types of columns showed buyers saved money by the V2V energy trading.

Similarly, Fig. 4 represents 8 sellers' incomes in the day transaction. Almost all V2V transactions made more profits than V2G except the trading in the time slot 12:00 – 12:30. According to the figure, there was no V2V result in that slot, which means there is no available buyer for the seller so that the seller traded to the power grid instead. In general, sellers obtained greater profits by conducting V2V energy trading than V2G transactions.

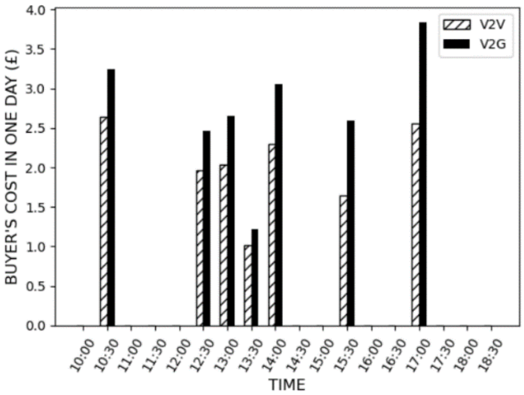

Fig. 3. Buyers' costs within one day.

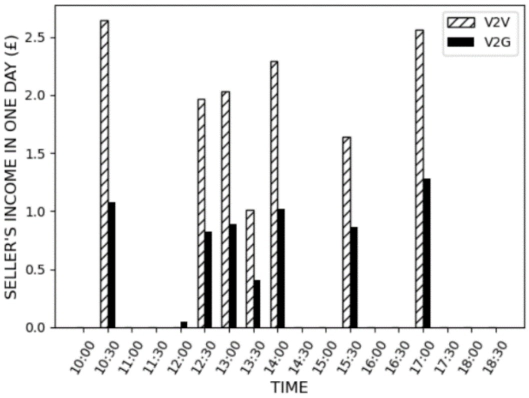

Fig. 4. Sellers' incomes within one day.

The total costs and incomes of buyers and sellers are shown in TABLE II. The profit of the platform is presented.

TABLE III. THE CASE STUDY RESULTS

Parties / Costs/Income (£)	Buyer	Seller	Platform
V2V	15.58	12.04	3.54
V2G	19.07	6.36	-
Difference	3.49	5.68	-

B. Results of Benefit Maximization

The V2V energy trading platform allows buyers and sellers to modify the reservation price, amount of energy and trading slot before the closure gate. Participants can gain higher profits by appropriate trading strategies. In this paper, changing reservation price and changing energy amount are the two strategies applied to increase profits.

1) Changing reservation price in the same time slot

Changing reservation prices legitimately is one of strategies to maximize trading benefits. The seller 3 and buyer 3 were taken as examples to analyze benefit variations with the price changing. Fig. 5 shows costs of the buyer 3 in different reservation bids.

According to the figure, the cost was zero when the bids were lower than 7. This is caused due to that the bid price was too low in the current trading slot that were unable to match any seller's ask. Thus, the V2V energy trading is not conducted. The gap between 10.0 to 10.5 £/kWh was caused by the priority shifting. In that case, the bid price was too high to keep the buyer's priority to trade with another seller, so that the buyer was rearranged to the second priority according to the higher reservation ask. In general, the total cost increased as the bid price increased. Buyers obtained higher returns by compressing the price, but excessively lowering the price facing a risk of transaction fails.

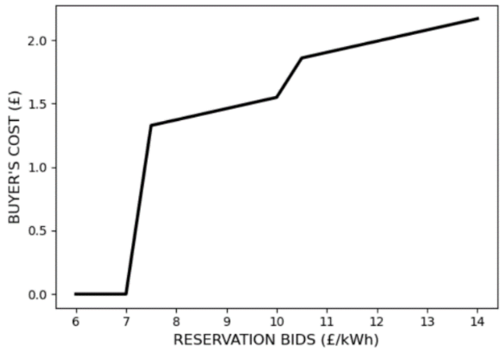

Fig. 5. Costs of buyer 3 in different reservation bids.

Fig. 6 shows the potential incomes of the seller 3 with different reservation asks. Similar to Fig. 5, each sharp trop of income represents the seller was reordered to the lower priority due to the higher ask price. However, in each transaction, the higher the ask price the buyer submitted, the higher income obtained. In general, increasing reservation ask price is a method to achieve higher benefits. However, risks of losing the current priority of trading rises correspondingly.

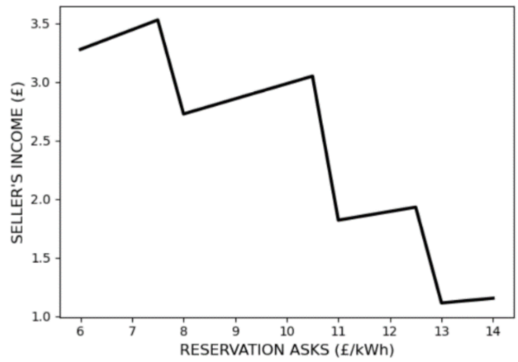

Fig. 6. Incomes of seller 3 in different reservation asks.

In general, it is possible for participants to obtain more economic benefits through the V2V transactions by changing reservation price in the same slot. The good strategy for buyers (sellers) is decreasing (increasing) reservation prices while maintaining higher transaction priorities.

2) Separating amount of energy to trade in different time slots

Separating energy into different parts to trade in different time slots is another strategy to obtain better benefits for buyers and sellers. Here used buyer 1 and seller 1 as examples to evaluate potential benefits. The energy was divided into two parts and traded in different time slot. The first time slot *T1* is between 10:30 and 11:00, while *T2* is randomly chosen. Fig. 7 shows costs of buyer 1 when trading in different time slots.

According to Fig. 7, with the traded energy amount increased in *T1* and decreased in *T2*, the total cost of the buyer 1 experienced a slight increase first, and then fell sharply after reaching a peak. The sharp fall was caused by two reasons: the reservation price of the matched seller in time slot *T2* was higher than that in *T1*, or there was no matched seller in *T2*. In this case, the reason is the former one.

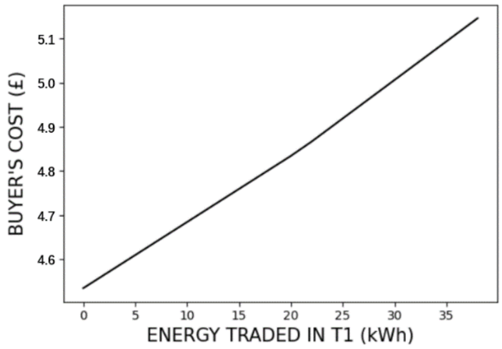

Fig. 7. Costs of buyer 1 in different time slots.

Fig. 8 presents incomes of seller 1 trading in different time slots. The curve of incomes keeps increasing with the amount of energy traded in *T1* increases and *T2* decreases. This is because there was no matched buyer to trade in time slot *T2*, hence the more energy traded in *T1*, the greater income the seller 1 obtained.

Overall, separating energy into different parts to trade in different time slots can raise buyers' (sellers') economic benefits. This strategy increases the matching possibility for sellers (buyers) with lower (higher) reservation price, and disperses the risk of transaction failure.

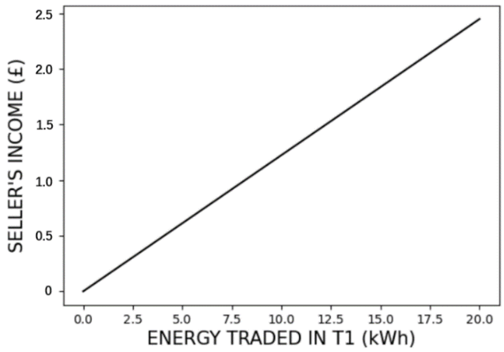

Fig. 8. Incomes of seller 1 in different time slots.

IV. Conclusion

This paper proposed a V2V energy trading platform using double auction with high flexibility. It provided an economical feasible solution for V2V energy trading. The trading rule and procedure were established based on the analyzation of different supply and demand relationships. A billing calculation was conducted on basis of maximize buyers and sellers' economic benefits. Finally, a generic model using double auction as pricing mechanism was established, and the V2V energy trading platform was performed to EV energy transaction in communities located in the UK. The platform was given a high degree of flexibility, letting participants to choose the most cost-effective trading strategy by modifying trading price, time and amount of energy. The result of the case study proved that the current V2V energy trading platform can bring economic benefits to all participants. With the positive effect of the platform, the running cost of EV is reduced and more distributed energy source is exploited, and the pressure of the power grid caused by growing number of EVs can be reduced. This constitutes a virtuous circle to improve the uptake level of zero-emission transportation.

In future work, the loss and cost of the energy during transmission will be considered, along with the impact of the verification of the electricity price.

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