Shafiekhani M
Cardiff University
School of Engineering

Zhou Y
Cardiff University
School of Engineering

Qadrdan M
Cardiff University
School of Engineering

Wu J
Cardiff University
School of Engineering

SUSTAINABLE ENERGY

Development of a Multi-Community Peer-to-Peer Electricity Trading Mechanism

Peer-to-peer electricity trading allows individual energy producers and consumers to trade electricity directly with one another. They can be managed as a single unit in the form of an energy community. However, in this study, a multi-community peer-to-peer electricity trading mechanism was developed to enable excess electricity from renewable sources to be traded between multiple communities. For this purpose, two energy communities were considered, in which there are generation and storage technologies such as PV panels, wind turbines, energy storage systems, and flexible and non-flexible loads. A Bill Sharing method was adopted to determine the price of electricity traded between different peers within each community and between the two communities and the suppliers. The efficacy of the proposed peer-to-peer electricity trading in decreasing the cost of satisfying the electricity demand in the communities was investigated. The proposed model reduces the average daily electricity costs by 64% compared with the case without peer-to-peer electricity trading.

Keywords:
P2P electricity trading, flexible load, heat pump, renewable energies, multi-community system.

Corresponding author:
ShafiekhaniM@cardiff.ac.uk

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INTRODUCTION

Worldwide? approximately 50 billion tonnes of greenhouse gases are emitted annually, almost 75% of which are related to the electricity sector [1]. Total GHG emissions in the UK in 2020 were 405 million tonnes. 27% of the greenhouse gases emissions was from transport sector, 21% from electricity supply, and 17% from businesses (as the three most polluting sectors). The total emissions are nearly 50% lower than in 1990 which is significant progress towards the UK's goal of reaching net-zero emissions by 2050 [2].

The increase in the share of Distributed Renewable Energy Resources (DRER) is a response to policies and incentives aimed at reducing emissions and addressing global warming. However, this increase in DRER poses challenges, such as managing the variability and intermittency of renewable sources, as well as integrating DRER into the existing power grid. To address these challenges, peer-to-peer (P2P) electricity trading has the potential to offer a solution. P2P trading allows customers to trade excess electricity generated from their DRER directly with each other, which can help balance the grid. This causes consumers to appear in the role of prosumers. By providing a means for customers to participate in energy markets, P2P trading can also help democratize the energy system. While P2P trading is not a complete solution, it offers a promising approach to address the challenges associated with the increase in DRER and can help promote a more sustainable and resilient energy system. A prosumer is an electricity customer who could also generate electricity. The excess electricity can be fed back into the grid and/or be traded with other prosumers. New marketplaces and business models are required to enable/empower prosumers and market participants [3,4] to minimize the costs of the entire system as well as their own costs.

LITERATURE REVIEW

There are various P2P electricity trading mechanisms, such as Supply Demand Ratio [3-7], Mid-Market Rate [8,9], and Bill Sharing [10-12]. These P2P pricing mechanisms have been utilized in various research with different objectives.

A method has been developed in [3] to examine the effects of Distributed Energy Resource ownership on the benefit of each participant in the form of a single community microgrid in the P2P trading market. The Supply Demand Ratio method was used to calculate the P2P trading prices in this study. An energy management method is proposed in [4] that integrates demand-side management into the P2P electricity trading problem. Demand side management offers flexibility for community residents to participate in the P2P electricity market. They use a uniform pricing and electricity-allocation mechanism based on the Supply Demand Ratio method to ensure that every household within the community residents can participate fairly in P2P electricity trading. A smart bidding strategy is developed in [5] for a community of smart homes with different distributed energy resources, battery, electric vehicle, and smart appliances (thermal and electrical loads). The proposed algorithm involves a double auction mechanism, in which bidding occurs between the prosumers and consumers based on Supply Demand Ratio and real-time pricing. A deep learning-based P2P transaction method combined with Supply Demand Ratio is proposed in [6], which uses a data-driven approach to build a transaction behaviour model to optimize the energy consumption plans and P2P bids of prosumers in the community. The Supply Demand Ratio pricing mechanism has been utilized in [7] to develop an approach to optimize the charging/discharging schedule of battery energy storage systems in the microgrids of prosumers based on an energy router-based energy sharing structure.

A joint Mid-Market Rate-based P2P electricity and carbon allowance trading mechanism for a small building community is proposed in [8]. It claims to address (1) the increasing penetration of renewable energies and the complicated operation of coupling multi-energy sectors; (2) the lack of integration of the energy market and carbon emission trading scheme; and (3) privacy concerns in the energy system. The authors in [9] formulate P2P trading as a multi-agent coordination problem and propose a multi-agent deep reinforcement learning method to address it. They also utilize the Mid-Market Rate pricing mechanism to enable electricity trading among peers. Some studies have used the Bill Sharing method for P2P electricity trading.

Some studies have used Bill Sharing mechanism for P2P electricity trading. Two mechanisms are proposed in [10] to construct a stable grand coalition of a single community prosumers to adequately incentivize them to participate in P2P trading. The first involves a benefit distribution scheme, whereas the second involves a pricing mechanism based on the Bill Sharing method. The operational costs of an individual household and community are optimized in [11] using the Bill Sharing method for various degrees of PV penetration in the form of a P2P electricity trading problem. A systematic index system is developed in [12] to evaluate the performance of various P2P electricity-sharing mechanisms, such as the BS, Mid-Market Rate, and Supply Demand Ratio methods and three different technical indexes, i.e., energy balance, power flatness and self-sufficiency were investigated. The flaw in the BS method used in all these studies is that only the cost and income of buying and selling electricity from/to the supplier are considered. For example, when the community has excess electricity, the amount of excess electricity is sold to the supplier, and the income is divided between the producer peers. Consumer peers do not pay for their consumption and producer peers are not paid for supplying electricity within the community.

Here, we develop a multi-community P2P electricity trading mechanism in a multiple-community system as Fig. 1. In this structure, each community can compensate for its needs from other communities as well as suppliers.

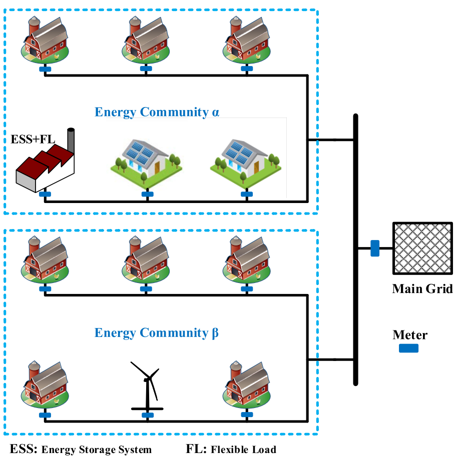

Fig. 1. Multiple-community structure.

FORMULATION OF A P2P ELECTRICITY TRADING PROBLEM

The P2P electricity trading was formulated as an optimization problem with an objective function to minimize the cost to all communities conducting P2P electricity trading (Eq. 1):

$$Cost = \sum_{k=1}^{K}\left(\sum_{t=1}^{T}\sum_{n=1}^{N} P_{k,n,t}^{Im}\,\lambda_{k,t}^{Im} - \sum_{t=1}^{T}\sum_{n=1}^{N} P_{k,n,t}^{Ex}\,\lambda_{k,t}^{Ex}\right) \tag{1}$$

where, $\lambda_{k,t}^{Im}$ [£/kWh] and $\lambda_{k,t}^{Ex}$ [£/kWh] represent electricity import and export prices in the community at time , respectively. The amount of electricity imported by peer n in community k at time t, is denoted by $P_{k,n,t}^{Im}$ [kW]. The amount of electricity exported is denoted by $P_{k,n,t}^{Ex}$ [kW]. n is the index of peers and k is the index of communities. $P_{k,n,t}^{Im}$ and $P_{k,n,t}^{Ex}$ are calculated by Eqs. 2 and 3.

$$P_{k,n,t}^{Im} = D_{k,n,t} + P_{k,n,t}^{Ch} + FL_{k,n,t} - M_{k,n,t}, \forall k\epsilon K, \forall t\epsilon T, \forall n\epsilon N \tag{2}$$

$$P_{k,n,t}^{Ex} = G_{k,n,t} + P_{k,n,t}^{Dch} - M_{k,n,t}, \forall k\epsilon K, \forall t\epsilon T, \forall n\epsilon N \tag{3}$$

The electricity demand of peer n in the community k at time t is denoted by $D_{k,n,t}$ [kW]. Furthermore, the generation of peer n in the community k at time t is denoted by $G_{k,n,t}$ [kW]. The instantaneous overlapping of consumption and generation of peer n in community k at time t is denoted by:

$$M_{k,n,t} = min(D_{k,n,t} + P_{k,n,t}^{Ch} + FL_{k,n,t}, G_{k,n,t} + P_{k,n,t}^{Dch})$$

Air-source heat pumps have been considered as the Flexible Load (FL) [13]. They enable prosumers and also Energy Storage Systems to provide flexibility and exchange electricity with suppliers or other prosumers in response to P2P electricity trading prices. $FL_{k,n,t}$ [kW] represents flexible load's consumption of the nth peer in community k at time t. Details regarding the formulation of the Flexible Load can be found in [13].

$P_{k,n,t}^{Ch}$ [kW] and $P_{k,n,t}^{Dch}$ [kW] are positive variables and denoted the battery charging and discharging power of the nth peer in community k at time t. Details regarding the formulation of the Energy Storage System can be found in [13].

BILL SHARING METHOD

The Bill Sharing method is a cost sharing method that each peer inside a community pays for its individual electricity use. This cost is shared according to individual peer's total electricity consumption and export. The electricity use is calculated for individual peers. We have developed the BS's formulation used in literatures for multi-community systems. In the multi-community system, there is a coordinator that has access to all data of all peers and solves the optimization problem, which is related to the day-ahead market. By solving the P2P electricity trading problem by the coordinator, the energy exchanged between peers and communities and their prices are determined. In fact, exchanges between peers and communities happen simultaneously. The formulation of the Bill Sharing method is stated in Eqs. (4) and (5). $\lambda_{k,t}^{BS}$ [£/kWh] is the base price and it is assumed to be equal to Smart Export Guarantee (SEG) tariff rate [14] (a fixed payment for sending electricity to the grid which has been used in the UK since 1 Jan 2020) in this paper. $E_t^{S_kC_k}$ [kWh] represents the amount of electricity from a supplier to the community k at time t. $\lambda_t^{S_kC_k}$ [kWh] shows community k's supplier price at time t. $E_t^{C_iC_k}$ [kWh] represents exported electricity from community i to community k at time t. $E_{k,t}^{Im}$ [kWh] and $E_{k,t}^{Ex}$ [kWh] show total electricity imported and exported by community k at time t, respectively.

CASE STUDY AND RESULTS

There are two energy communities: α and β as shown in Figure 1. In community α (k =1), there are 15 peers (n = 1, 2, ..., 15)), and in community β (k =2), there are 18 peers (n = 1, 2, ..., 18)). Figure 2 shows predicted generation, and demand of the communities and Fig. 3 shows the suppliers prices, and SEG tariff rate. Each community has got its own supplier. As Figure 2 shows, in the first 12 hours, there was excess electricity in community β, and this situation occurred for community α from 9:00 to 17:00. The SEG tariff rate is equal to 5.5 pence in the system [14]. There is an Energy Storage System in community α with a capacity of 100 kWh/50 kW. The proposed model is simulated using CPLEX solver in GAMS software.

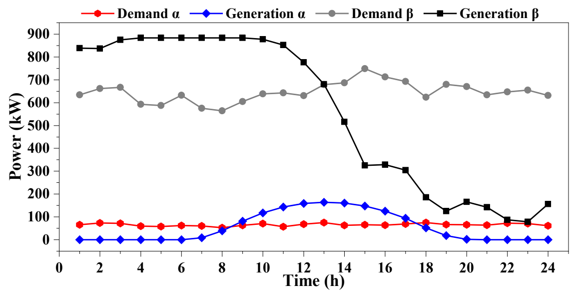

Fig. 2. Predicted generation and demand of communities.

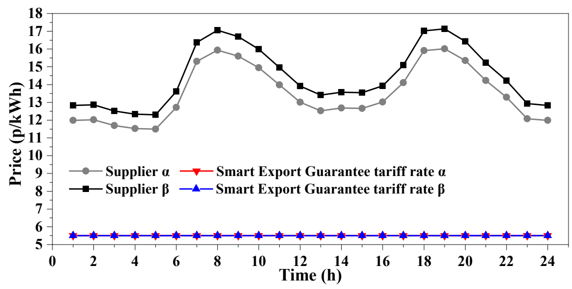

Fig. 3. Market prices

Figure 4 shows P2P prices in both communities. As is clear from Eqs. (4)-(5), the minimum import and export prices in each community are equal to the base price ($\lambda_{k,t}^{BS}$). The minimum import price in each community occurs when a community does not import electricity from its supplier or other communities. Community β has not imported any electricity from the supplier or community α during hours 1:00 to 13:00, so its peer's import price is equal to the base price. This happened to the community α during hours 9:00–18:00. Community β has been importing electricity from community α and its supplier since hour 14:00, so during these hours, the import price has exceeded the base price (red line in Fig. 4). Community α imports electricity from Community β during hours 1:00 to 8:00 and imports electricity from the supplier during hours 19:00 to 24:00, so the import price has exceeded the base price during these hours.

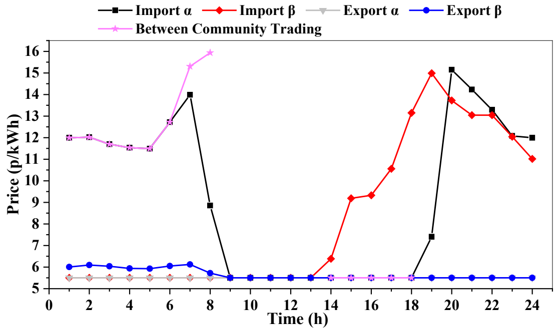

Fig. 4. P2P prices.

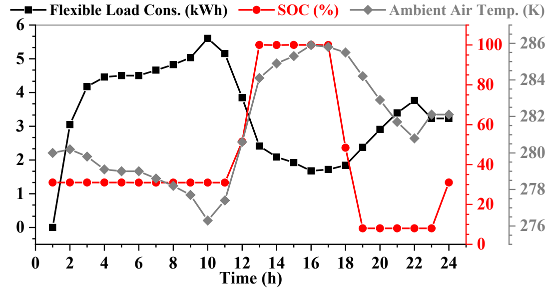

Fig. 6. SOC of the ESS and FL's consumption.

As it is clear from Eq. (4), the export price in each community depends only on the amount of electricity exported to another community and the export price. In the first eight hours and hour 13:00, community β exports electricity to community α, and during hours 14:00 to 18:00, community α exports electricity to community β. The between-community prices during these hours are illustrated in Fig. 4. Community α exports electricity to community β only during hours 14:00 to 18:00, so only during these hours its export price can exceed the base price; however, considering that the between-community prices are equal to the base price during these hours, the export price in this community is equal to the base price. It should be noted that during the hours when community α does not export electricity to community β, the export price is equal to the base price. Community β exports electricity to community α during hours 1:00 to 8:00 (blue line in Fig. 5), and the between-community price is higher than the base price during these hours (purple line in Fig. 4), so the export price in this community is higher than the base price (blue line in Fig. 4). Because community β does not export electricity to community α during other hours, the export price is equal to the base price.

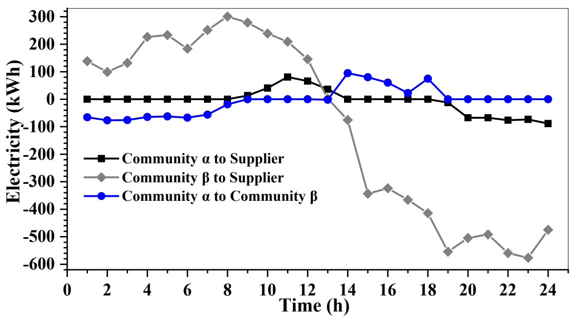

Fig. 5. Trading electricity in communities

The ambient air temperature and power consumption of the flexible load are presented in Fig. 6. It is known that as the temperature decreases, the amount of electricity consumed to maintain the inside temperature of houses within a comfortable range increase. The state of charge of the ESS is also shown in this figure. The Energy Storage System is charged at 12:00 and 13:00, because during these hours, the community α faces an excess of electricity. During hours 18:00 and 19:00, the Energy Storage System discharged all its electricity because during these hours, the community faced a deficit of electricity. Finally, it's charged at hour 24:00 to reach the initial state of charge.

The total cost of the studied system is £599.66. In order to verify the advantage of between-community trading, another model was also solved without between-community trading. In that case, the total cost is £651.47, which is 8.6% higher than with community-community trading. In order to reveal the effect of P2P electricity trading compared to the traditional market, another model was also solved in the form of a traditional market, and the total cost in this case is £1646.68, which is almost triple that of the P2P case.

CONCLUSIONS

This paper describes a multi-community P2P electricity trading mechanism in a local electricity market. The Bill Sharing method, which is a cost-sharing method, was developed as the pricing mechanism for this structure. It was found that P2P in a multi-community system with between-community trading capability reduces the total cost of the electricity by 64% compared with the case without P2P electricity trading. It was also found that without between-community trading in the same system, the cost increases by more than 8%.

Conflicts of interest
The authors declare no conflict of interest.

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