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Impact of Energy Imbalance on Financial Rewards in Peer-to-Peer Electricity Markets

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ABSTRACT Peer-to-peer electricity markets allow small producers and consumers of energy to trade directly. Energy imbalances, the difference between predicted and actual supply or demand for energy, may be higher in peer-to-peer markets than in traditional markets. High energy imbalances could increase the total cost of the electricity system, both inside and outside the peer-to-peer market, because the system operator must take expensive corrective actions at short notice. This paper examines the effect of imbalance charges on peer-to-peer electricity markets. A new symmetric imbalance charge mechanism is proposed which penalises market participants irrespective of the direction of their energy imbalance. The symmetric imbalance charge mechanism provides a financial incentive for peer-to-peer market participants to reduce their energy imbalances. For illustrative purposes, this paper uses a simulation to show that the current imbalance charge mechanism in Great Britain does not provide a financial incentive for peer-to-peer market participants to reduce their energy imbalances. The imbalance charge is close to zero under the current British imbalance charge mechanism when averaged over hundreds of settlement periods or more. When subject to the symmetric imbalance charge mechanism, the simulation shows that peer-to-peer market participants are given a strong financial incentive to reduce their energy imbalances. Finally, this paper discussed how the symmetric imbalance charge mechanism could be implemented only within the bounds of a peer-to-peer market, or within the whole electricity system.

INDEX TERMS Electricity market, energy imbalance, energy market, imbalance charge, imbalance price, peer-to-peer.

I. INTRODUCTION

Distributed generation is becoming a ubiquitous part of electricity systems. For example, the total installed capacity of distributed solar photovoltaic (PV) generation with an individual installed capacity of 5 MW or less per installation in Great Britain increased from 16 MW in January 2010 to 7,362 MW in January 2021 [1]. Feed-in tariff schemes are often the only way distributed generators can be compensated for exporting energy. For example, in Great Britain the Smart Export Guarantee scheme is the only revenue stream for distributed generators with a capacity less than 5 MW [2]. Peer-to-peer (P2P) electricity markets offer an alternative by allowing distributed generators to sell directly to consumers, without the need for an intermediary such as an energy supplier. Direct sale of electricity between distributed generators and consumers represents a significant change in how electricity markets function. The current codes and standards which govern electricity markets will not necessarily be appropriate for P2P markets. This paper proposes a symmetric imbalance charge mechanism which provides P2P electricity market participants with a financial incentive to minimise their energy imbalances. To demonstrate the effectiveness of the symmetric imbalance charge mechanism, it is contrasted with the current British imbalance charge mechanism.

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A. ENERGY IMBALANCES AND IMBALANCE CHARGES

In liberalised electricity markets, such as those found in Britain and much of Europe, competitive wholesale market trading is followed by a monopolistic balancing mechanism run by a system operator to ensure energy supply and demand are matched [3]–[5]. Trading in the wholesale market is based on market participants' predictions of their supply and demand for energy. Errors in these forecasts, known as energy imbalances, are corrected by the system operator in the balancing mechanism.

Imbalance charges compensate the system operator for their costs in the balancing mechanism [3]. Imbalance charges are paid by market participants to the system operator in proportion to their energy imbalance.

Different regulatory regimes place balancing responsibility on different parties. In Britain and much of Europe, balancing responsibility is placed on individual market participants, by requiring them to balance their position in wholesale markets as far as possible [3]–[5]. In other regulatory regimes the system operator manages the cumulative energy imbalances of all market participants, which will be lower than the sum of the magnitude of individual imbalances, e.g. the PJM region of the USA [6]. It is debatable which balancing mechanism design is most efficient. In this paper we assume that we are in a regulatory regime that places balancing responsibility on market participants. That is the case for Great Britain, used in our comparative case study. Section II provides a full description of imbalance charges in Great Britain.

B. ENERGY IMBALANCES IN PEER-TO-PEER ELECTRICITY MARKETS

Peer-to-peer electricity markets are likely to exist, at least initially, as sub-elements of traditional electricity markets. The most developed P2P market models are relatively small markets that only contain small energy producers and consumers [7]. Peer-to-peer markets in this form cannot supplant traditional markets. Therefore, it is likely that P2P markets will be subject to the codes that govern traditional electricity markets, including those concerning balancing responsibility.

Existing P2P market literature focuses on optimising the internal working of P2P markets [8]. While this work is valuable, if P2P markets are to exist the internal design of the markets must account for the regulations to which they are subject. The regulations must also account for P2P markets [9]. Literature which compares the profitability of traditional and P2P electricity markets finds that participants are more profitable in P2P markets [10]–[12]. However, most of the literature examining P2P electricity market design assumes participants can accurately predict their supply and demand for energy [12]–[17]. In reality this is unlikely to be the case [18], [19]. Therefore, P2P market participants will be subject to imbalance charges. When taking the retail market price and feed-in tariff, market participants are not subject to imbalance charges. The additional cost of imbalance charges is neglected by the cost models in the current literature. This means that profitability in real-world P2P markets is likely to be lower than modelled in the current literature.

Pilot projects of P2P markets tend to be run in regulatory sandboxes [20]. These sandboxes exempt the pilot projects from much of the regulation of electricity markets, including imbalance charges [21]. Therefore, pilot projects have not provided evidence of the energy imbalance which could be expected from P2P markets, or of how imbalance charges would affect P2P markets.

A recent set of P2P market literature has examined how energy imbalances in P2P market could be minimised through optimal scheduling of flexible resources [11], [22]–[29], or the use of real-time markets [30]–[34]. However, these markets do not completely eliminate energy imbalances and therefore an imbalance charge mechanism would still be required. The symmetric imbalance charge proposed in this paper would complement P2P market designs which minimise energy imbalances by providing an external financial incentive to market participants who reduce their energy imbalances.

C. OUR CONTRIBUTION

Many current imbalance charge mechanisms, including the one in Britain, are audit and fines based [35]. These imbalance charge mechanisms do not provide a direct financial incentive for market participants to minimise their energy imbalances, but fine participants who do not [36]. While this audit and fines system is workable for the relatively small number of market participants which exist in current wholesale energy markets, even relatively small P2P markets could dramatically increase the number of balance responsible parties [37]. This dramatic increase in the number of balance responsible parties which could accompany the introduction of P2P energy markets necessitates a rethink of how market participants are incentivised to minimise their energy imbalances.

In this paper we propose a symmetric imbalance charge mechanism which provides a financial incentive for market participants to minimise their energy imbalances. This financial incentive removes the need for an audit and fines based enforcement system and is therefore more appropriate for the large numbers of balance responsible parties which can be expected with the advent of P2P energy markets. The symmetric imbalance charge mechanism proposed in this paper differs from the current British imbalance charge mechanism [3], and others discussed in recent academic literature [38] in that market participants are charged the imbalance charge irrespective of the direction of their energy imbalance. This provides a strong financial incentive for market participants to minimise their energy imbalances. A full description of the symmetric imbalance charge mechanism is provided in Section III.

We present a Monte Carlo simulation of households with PV acting in a P2P energy market to demonstrate the contrast in financial incentives between our proposed symmetric imbalance charge mechanism, and the current British imbalance charge mechanism. This simulation shows that the imbalance charge is a significant proportion of profit in P2P markets when energy imbalances are high, but falls significantly when energy imbalances are reduced. This significant change in imbalance charges proportionate to energy imbalances shows that P2P market models must consider energy imbalances in their market costs.

Previous literature has shown that if P2P market participants were subject to imbalance charge mechanisms such as the one which exists in Britain today, they could game the system to financially benefit from the imbalance price [39]–[42], described as malicious behaviour throughout the remainder of this paper. We model two types of malicious behaviour in our Monte Carlo simulation and demonstrate that market participants cannot benefit by gaming our proposed symmetric imbalance charge mechanism. This inability to game the system is important as it further removes the need for an audit based enforcement system of balancing responsibility.

The rest of the paper is structured as follows. Section II provides a mathematical derivation of imbalance charges as they currently exist in Great Britain. Section III provides a mathematical derivation of the symmetric imbalance charge mechanism. Section IV provides detail of the methodology and data used. Section V provides the results of our model and analysis of the results. Finally, Section VI provides concluding remarks. Additional supporting results data are provided in Appendix A.

II. IMBALANCE CHARGES IN GREAT BRITAIN

In Great Britain, imbalance charges are governed by the Balancing and Settlement Code (BSC) [3]. BSC parties are responsible for predicting their supply and demand for energy, and putting contracts in place to buy or sell excess energy. After gate closure, the system operator takes over responsibility for balancing supply and demand for energy.

The system operator, National Grid ESO in Britain, uses the balancing mechanism to keep the supply and demand for energy in balance during the settlement period. Generators and demand response operators acting in the balancing market submit bids and offers to increase or reduce their supply or demand for energy during a settlement period. Bids to increase supply or reduce demand have a positive price, i.e. the system operator must pay. Offers to reduce supply or increase demand have a negative price, i.e. the system operator will be paid. Bids and offers are selected by the system operator through merit ordering. The system operator's energy balancing costs are covered by an imbalance price paid by BSC parties proportionate to their energy imbalance.

The imbalance price, λ^k_{imb}, for a settlement period, k, is set at the marginal cost of the balancing mechanism [35]. The imbalance price is therefore the price of the most expensive balancing action, bm, from the set of balancing actions during that settlement period, BM. This incentivises BSC parties to take all actions to reduce energy imbalances which cost less than it would cost the system operator. This idea, that the party who can take the balancing action for the lowest cost should take it, minimises the total system cost.

$$\lambda^k_{imb} = \max_{bm \in BM} \left\{ \lambda^k_{bm} \right\} \tag{1}$$

The imbalance price is normally positive, although it can be negative [43]. If all balancing mechanism actions the system operator has ordered during a settlement periods are reductions in supply or increases in demand then the cost of the marginal balancing mechanism action might be negative.

Market participants responsible for energy imbalances (BSC parties) must submit the amount of energy they have bought or sold for a settlement period to the system operator before the beginning of that settlement period, a point called gate closure [35]. This submission by a market participant, i, is the final notification volume, $E^{i,k}_{fnv}$. The energy imbalance, $E^{i,k}_{imb}$, is the difference between the final notification volume, $E^{i,k}_{fnv}$, and net exported energy, $E^{i,k}_{exp}$. The final notification volume, $E^{i,k}_{fnv}$, and net exported energy, $E^{i,k}_{exp}$ are both positive for export and negative for import. The energy imbalance, $E^{i,k}_{imb}$, is positive when the market participant exports too little or imports too much energy, and negative if they export too much or import too little energy.

$$E^{i,k}_{imb} = E^{i,k}_{fnv} - E^{i,k}_{exp} \tag{2}$$

The imbalance charge incurred by a BSC party during a settlement period, $C^{i,k}_{imb}$, is the energy imbalance of that BSC party during the settlement period, $E^{i,k}_{imb}$, multiplied by the imbalance price, λ^k_{imb}. Figure 1 shows a timeline of energy trading in Great Britain.

$$C^{i,k}_{imb} = E^{i,k}_{imb} \lambda^k_{imb} \tag{3}$$

The imbalance charge, $C^{i,k}_{imb}$, is positive when a BSC party's energy imbalance, $E^{i,k}_{imb}$, is in the same direction as the imbalance of the whole grid. If the whole grid has a deficit of energy the system operator must pay generators to increase their supply of energy, or pay loads to reduce their demand. Therefore the imbalance price, λ^k_{imb}, will be positive. BSC parties who have a deficit of energy during a settlement period have a positive energy imbalance, $E^{i,k}_{imb}$. These BSC parties will receive a positive imbalance charge. Conversely, if a BSC party has an imbalance in the opposite direction to the whole grid, they will have a negative imbalance charge, paid by the system operator to the BSC party.

The system operator's revenue, R^k_{SO}, is based on the net energy imbalance. There is a single imbalance price for each settlement period. Any BSC parties who have an energy imbalance in the opposite direction to the whole grid will be paid the imbalance charge. Therefore, the system operator will only receive the imbalance charge proportionate to the net imbalance in the system. So, from equations 1 and 3 the system operator's revenue is the sum of the imbalance charges over the set of market participants, I.

$$R^k_{SO} = \sum_{i \in I} C^{i,k}_{imb} \tag{4}$$

$$= \sum_{i \in I} E^{i,k}_{imb} \cdot \max_{bm \in BM} \left\{ \lambda^k_{bm} \right\} \tag{5}$$

The principle of paying BSC parties who have an imbalance in the opposite direction to the whole grid is based on the idea that their imbalance is beneficial and therefore they should be compensated. Although these BSC parties have provided a service to the grid, they did not do so intentionally. Balancing market participants who adjust their supply and

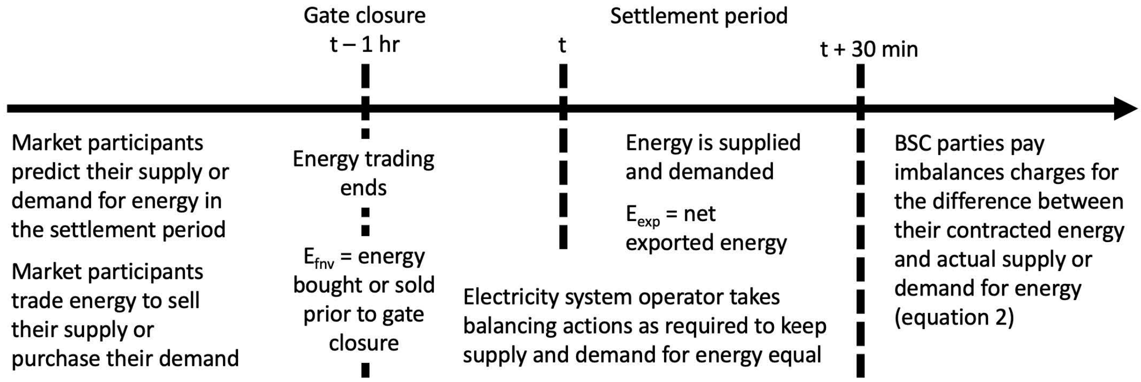

FIGURE 1. **Timeline of energy trading in Great Britain.**

demand at the request of the system operator to balance the grid are compensated separately.

III. SYMMETRIC IMBALANCE CHARGE MECHANISM

To encourage P2P electricity trading, we propose a new method for calculating imbalance charges. This symmetric imbalance charge penalises all energy imbalances, irrespective of whether they are in the same direction as the imbalance of the whole grid. Where the purpose of many current imbalance charge mechanisms is to recuperate energy balancing costs, the symmetric imbalance charge also aims to provide an incentive for parties to reduce their level of imbalance. This financial incentive is provided through the imbalance price, without the need for a separate levy. We specify three criteria which any new imbalance charge mechanism must meet to be compatible with P2P electricity markets:

1) *The total imbalance charge must equal or exceed the energy balancing costs of the system operator:* The imbalance charge is the only mechanism by which the system operator is compensated for their energy balancing service. Therefore it is important that any change to the imbalance charge maintains the system operator's revenue.
2) *The imbalance charge must provide an incentive for P2P market participants to reduce their energy imbalance:* Implementing measures to reduce energy imbalance is expensive. For example P2P market participants could install energy storage or flexible loads. Therefore a financial incentive must be provided.
3) *The imbalance charge must be low enough that a P2P market is beneficial over a traditional electricity market:* If imbalance charges are high enough to eliminate profits in P2P electricity markets, then participants will revert to traditional energy markets.

The P2P market price is effectively bounded by the retail market price, charged by energy suppliers, and the feed-in tariff. If the P2P market price is above the retail market price for a sustained period, market participants will switch to purchasing energy from the retail market. If the P2P market price falls below the feed-in tariff, market participants will switch to selling energy through the feed-in tariff. Market participants must be able to agree to a price within this range that is beneficial to both the buyer and seller.

If the imbalance charge is larger than the difference between the retail market price and the feed-in tariff, it will prevent P2P markets from being possible. For simple P2P markets which only trade energy, the P2P market may still function with a single price. However, P2P markets which use dynamic pricing to balance supply and demand of energy form the bulk of the current literature [13]–[16], [44]. Markets with dynamic pricing may require a wider band of allowable market prices. The size of imbalance charge which would prevent P2P markets from functioning therefore depends on the aim and design of the market.

Under the symmetric imbalance charge mechanism, market participants would be charged the imbalance price, λ^k_{imb}, irrespective of whether their energy imbalance is in the same direction as the whole grid. The imbalance price has a lower bound of the highest market price for that settlement period. This combination of always charging the imbalance charge, and the imbalance price always being equal to or above the highest market price prevents market participants gaming the imbalance system for their benefit, as discussed further in Section III-B.

$$C^{i,k}_{imb} = \begin{cases} \left|E^{i,k}_{imb}\right| \cdot \lambda^k_{imb}, & \text{if } \lambda^k_{imb} \geq \max\left\{\lambda^{i,k}_{P2P}\right\} \\ \left|E^{i,k}_{imb}\right| \cdot \max\left\{\lambda^k_{P2P}\right\}, & \text{if } \lambda^k_{imb} < \max\left\{\lambda^{i,k}_{P2P}\right\} \end{cases} \quad (6)$$

Under current imbalance charge mechanisms, the system operator's revenue is based on the net energy imbalance. Under the symmetric imbalance charge mechanism the system operator's revenue is based on gross imbalance. Therefore the imbalance price, λ_{imb}, can be reduced while maintaining the system operator's revenue. Section II provides a derivation of the system operator's revenue under the current British imbalance charge mechanism. The revenue of the system operator under the symmetric imbalance charge mechanism is the sum of the imbalance charges. Note for equations 7 through 12 only we use subscript 'sym' when refer to the symmetric imbalance charge mechanism and 'cur' when referring to the current British imbalance charge mechanism.

$$R^k_{SO,sym} = \sum_{i\in I}(\left|E^{i,k}_{imb}\right| \cdot \lambda^k_{imb,sym}) \tag{7}$$

The aim is to calculate the imbalance price at which the system operator's revenue is maintained. Therefore equating the system operator's revenue under the current imbalance charge mechanism from equation 5 with the system operator's revenue under the symmetric imbalance charge mechanism from equation 7…

$$\sum_{i\in I} E^{i,k}_{imb} \cdot \max_{bm\in BM}\left\{\lambda^k_{bm}\right\} = \sum_{i\in I}(\left|E^{i,k}_{imb}\right| \cdot \lambda^k_{imb,sym}) \tag{8}$$

Substituting in equation 1…

$$\sum_{i\in I} E^{i,k}_{imb} \cdot \lambda^k_{imb,cur} = \sum_{i\in I}\left|E^{i,k}_{imb}\right| \cdot \lambda^k_{imb,sym} \tag{9}$$

Defining the ratio of imbalance price under the symmetric mechanism to the imbalance price under the current British imbalance charge mechanism as α…

$$\lambda^k_{imb,sym} = \alpha \cdot \lambda^k_{imb,cur} \tag{10}$$

Therefore, substituting equation 10 into 9…

$$\sum_{i\in I} E^{i,k}_{imb} \cdot \lambda^k_{imb,cur} = \sum_{i\in I}\left|E^{i,k}_{imb}\right| \cdot \alpha \cdot \lambda^k_{imb,cur} \tag{11}$$

$$\alpha = \frac{\sum_{i\in I} E^{i,k}_{imb}}{\sum_{i\in I}\left|E^{i,k}_{imb}\right|} \tag{12}$$

Since $\sum_{i\in I}\left|E^{i,k}_{imb}\right| \geq \sum_{i\in I} E^{i,k}_{imb}$, the imbalance price, λ^k_{imb}, under the symmetric mechanism will always be less than or equal to the price under the current British imbalance charge mechanism. These calculations assume that the bids and offers in the balancing market remain the same under both mechanisms.

A. NET BENEFIT OF A PEER-TO-PEER MARKET

To determine if market participants are better off in a P2P market or a traditional energy market, the profit of a market participant is derived. The profit of a P2P market participant, π^i_{P2P}, is the net energy exported during a settlement period, $E^{i,k}_{exp}$, multiplied by the price the energy is sold for in that period, λ^k_{P2P}, minus any imbalance charges incurred during that period, $C^{i,k}_{imb}$, summed for the set of settlement period in question, K.

$$\pi^i_{P2P} = \sum_{k\in K}(E^{i,k}_{exp}\lambda^k_{P2P} - C^{i,k}_{imb}) \tag{13}$$

The profit of a participant in a traditional electricity market, π^i_{trad}, is the net exported energy, $E^{i,k}_{exp}$, multiplied by the feed-in tariff, λ_{FIT}, if the net exported energy is positive. The profit is the net exported energy, $E^{i,k}_{exp}$, multiplied by the retail market price, λ_{trad}, if the net exported energy is negative (i.e. a net import of energy). The net exported energy, $E^{i,k}_{exp}$, is the energy generation minus demand during that settlement period.

$$\pi^i_{trad} = \begin{cases} E^{i,k}_{exp}\lambda_{FIT}, & \text{if } E^{i,k}_{exp} > 0 \\ E^{i,k}_{exp}\lambda_{trad}, & \text{if } E^{i,k}_{exp} < 0 \end{cases} \tag{14}$$

B. MALICIOUS BEHAVIOUR

The method of calculating imbalance charges in the British BSC (see Section II) allows market participants to intentionally adjust their energy market position to benefit from imbalance charges. These actions are not beneficial to the market participant under the proposed symmetric imbalance charge mechanism. This section introduces two types of malicious behaviour and shows that they are beneficial to the market participant under the current British imbalance charge mechanism, but not under the symmetric imbalance charge mechanism.

1) PURCHASING MORE ENERGY THAN REQUIRED

The imbalance price is normally above the P2P market price, $\lambda^k_{imb} > \lambda^k_{P2P}$, based on historic data [43]. When under the current British imbalance charge mechanism participants are paid the imbalance price for excess energy. Therefore, if the market participant intentionally creates a long position in the market by purchasing more energy than they predict they will need, or not selling energy they predict they will generate they will be paid the imbalance price for this energy during settlement. Since the imbalance price is normally above the market price they will, on average, financially benefit from this action.

Acting maliciously in this manner is low effort for the market participants. They do not need to make any predictions of the market prices in order to benefit from this strategy. However, if the market participants are able to predict the market price and imbalance price, then they can gain greater financial benefit by using this information.

The symmetric imbalance charge mechanism prevents market participants from acting maliciously in this manner. Under the symmetric imbalance charge mechanism participants are penalised irrespective of the direction of their imbalance. Therefore, participants will be penalised for a long market position.

2) ADJUSTING POSITION BASED ON IMBALANCE PRICE PREDICTION

If the imbalance price is below the market price during a settlement period, $\lambda^k_{imb} < \lambda^k_{P2P}$, market participants can benefit under the current British imbalance charge mechanism by creating a short position. Market participants could sell more energy than they anticipate generating, or buy less than they anticipate demanding in the P2P market. The market participant will be forced to purchase this deficit in energy at the imbalance price during settlement. However, if the imbalance price is below the market price, then they will be better off.

Acting maliciously in this manner is higher effort than the manner described in Section III-B1. The imbalance price is normally above the market price. Market participants must be able to predict the settlement periods in which the imbalance price will fall below the market price in order to profitably act on this strategy. If they can accurately predict the imbalance price, they could combine both strategies depending on the relative level of imbalance and market prices.

The symmetric imbalance charge prevents this behaviour by putting a lower bound on the imbalance price at the P2P market price. If the imbalance price never falls below the market price then acting maliciously in this manner is never financially beneficial.

IV. METHODS AND DATA

To demonstrate the symmetric imbalance charge mechanism we present a Monte Carlo simulation of households with PV acting in a P2P electricity market. We subject the households to the symmetric imbalance charge mechanism and for comparison also to the current British imbalance charge mechanism. In this section we present the datasets we have used, followed by the method of analysis and finally the key assumptions.

A. INPUT DATA

We have used three datasets in our modelling, covering household demand, rooftop PV generation and imbalance prices.

1) HOUSEHOLD DEMAND

The UK Power Networks' SmartMeter Energy Consumption Data in London Households dataset [45] contains demand data from 5,567 households in London, UK. The data was collected between November 2011 and February 2014. The length of data collection varies for each household. We extracted 1,192 year long datasets which do not contain any missing data points. The datasets contain the energy consumed during each half-hour settlement period for one year. The maximum demand of the households varied from 0.022 kW to 18.282 kW across the different datasets. During each model run one of the 1,192 demand datasets was randomly selected.

2) ROOFTOP PV GENERATION

The UK Power Networks' Photovoltaic (PV) Solar Panel Energy Generation dataset [46] contains data from six rooftop PV installation in South East England. The data was collected between July 2013 and November 2014. The data from June to November 2014 is provided in 10 minute intervals. The data prior to June 2014 is provided as hourly minima and maxima. We have created six year-long datasets with a half-hour temporal resolution. The datasets contain energy generated by the PV installation during each half-hour settlement period for one year. Where available we have summed the 10 minute resolution data into 30 minute periods. For the periods where 10 minute resolution data was not available we have used the hourly data. We have taken a random value from a uniform distribution bounded by the minimum and maximum recorded value for that hour. The installed capacity of the PV installations ranged from 0.444 kW to 3.965 kW.

We used the European Commission's PV-GIS system [47] to calculate the theoretical difference in generation between a PV installation in the most Northerly and Southerly location. The difference is less than 4%, much smaller than the difference due to the variation in installed capacity between the installations. The largest PV installation in the dataset is almost nine times the size of the smallest. Therefore, it is reasonable to use data from the different PV installation in the same P2P market in the model. During each model run one of the 6 generation datasets was randomly selected.

3) IMBALANCE PRICES

We have used imbalance prices from 2019 and 2020 in Great Britain. The data was collected from the Elexon Data Portal [43]. The two datasets contain the British imbalance price for each half hour settlement period in the year. During each model run one of the 2 imbalance price datasets was randomly selected. Imbalance prices from before 2019 were not used because the way the imbalance price was calculated in Great Britain changed at the end of 2018 [48].

4) PEER-TO-PEER MARKET PRICE

The P2P market price is bounded by the retail market price and the feed-in tariff. The mean standard variable tariff in Great Britain, 14.4 p/kWh [49], is the upper bound of the P2P market price. The highest feed-in tariff (Smart Export Guarantee) price, 5.6 p/kWh [50], is the lower bound of the P2P market price. These values have been chosen because they were the values published. During each model run either 14.4 p/kWh or 5.6 p/kWh is randomly selected as the P2P market price. Hence, the prices tested in this model are the maximum and minimum possible P2P market prices.

B. MODEL

We use a Monte Carlo simulation [51], [52] to examine the effect of imbalance charge design on the profitability of a household in a P2P electricity market. The model is of a single household with load and a rooftop PV installation trading in a P2P electricity market. The load and generation profiles are randomly allocated at the beginning of the model run. See Sections IV-A1 and IV-A2 for more details about the datasets. We assume that the household is responsible for their energy imbalances. Therefore, the household will be penalised for any energy imbalances they incur.

The aim of this model is to identify the range of imbalance charges and profits which are feasible under both the symmetric imbalance charge mechanism and the current British imbalance charge mechanism for comparison. The purpose of this model is to test the effectiveness of the symmetric imbalance charge mechanism in providing a financial incentive to minimise energy imbalances. This model does not optimise the behaviour of the market participants subject to the imbalance charges. Optimal scheduling of resources to minimise energy imbalances is the subject of other works [11], [22]–[34].

The household acts in a P2P market which is sufficiently large that it can accommodate all their supply and demand for energy during every settlement period. It is assumed that all excess supply from the household is sold at the market price and that all excess demand is purchased at the market price. The rest of the P2P market is not explicitly modelled. This assumption is discussed further in Section IV-C.

The model has a settlement period of 30 minutes and gate closure is one hour before the start of the settlement period. The length of settlement period and gate closure are those currently used in Great Britain. At gate closure the household estimates their supply or demand of energy for the settlement period. The P2P market is an hour ahead futures market to conform with the gate closure requirement. The household's estimated supply or demand of energy is bought or sold in the P2P market. Any difference between the estimated supply or demand and the actual supply or demand for energy during the settlement period is an energy imbalance. The household is penalised for energy imbalances according to the imbalance charge mechanism.

The household estimates their supply and demand for energy using a simple moving average with a backward window of one. A simple moving average is a computationally simple estimation method that would be easy to implement. It is likely that more sophisticated and accurate estimation methods would be used in a real P2P market. The aim of using a simple moving average in this model is that it is the worst estimate of supply and demand that a household could credibly make.

Simple moving average backward windows of one, 2, 3, 4, 5, 7 and 10 were tested. The backward window determines how many previous periods the simple moving average averages over. A backward window of one gives the best estimate of energy supply and demand using a simple moving average.

The μ_{pred} parameter replicates improvements in the prediction of energy supply and demand. We test a uniform distribution of μ_{pred} between zero and 1 in steps of 0.1. A μ_{pred} value of one is equivalent to the simple moving average estimate. Smaller values of μ_{pred} reduce energy imbalances, mimicking installation of storage or flexible load which can dynamically adjust its demand or supply to meet the prediction, or trading within the P2P market to net-off imbalances.

The household is subject to one of two imbalance charge mechanisms: either the symmetric imbalance charge mechanism (Equation 6), or the current British imbalance charge mechanism (Equation 3). When subject to the symmetric imbalance charge mechanism, the imbalance price coefficient, μ_{imb}, is selected from a uniform distribution between zero and 1 in steps of 0.1. The imbalance price coefficient reduces the imbalance price from today's level, mimicking a reduction to maintain the system operators revenue (see Equation 12). The imbalance charge mechanism and imbalance price coefficient are constant during each model run.

The household can either act honestly or maliciously in the model (see Section III-B). If the household acts honestly, they buy or sell their estimated supply or demand for energy in the futures market. If the household acts maliciously, they adjust their futures market position in an attempt to financially benefit from the imbalance charge. Two types of malicious behaviour are modelled.

Under the first type of malicious behaviour (Section III-B1), a household reduces their estimated export of energy by 50% if it is positive, and increase it by 50% if it is negative. These changes to the final notification volume make households acting maliciously more likely to have a negative energy imbalance.

Under the second type of malicious behaviour (Section III-B2), the household predicts the relative levels of market price and imbalance price. If the imbalance price is above the market price the household reduces their estimated export of energy by 50% if it is positive, and increases it by 50% if it is negative. If the imbalance price is below the market price the household increases their estimated export of energy by 50% if it is positive, and reduces it by 50% if it is negative. In the model there is a 60% chance a household will decide to act honestly, and a 20% chance they will choose each of the malicious behaviours.

The choice to change final notification volumes by 50% in these models of malicious behaviour has been selected by the authors for illustrative purposes and does not constitute a threshold value. The same effect can be observed to a greater or lesser extent at any percentage change. When designing this model a variety of percentage changes were tried and the value of 50% has been presented in this paper because the effect is visible on small graphs. The actual percentage changes used by market participants acting maliciously in reality would be a trade-off between maximising their gain while trying to avoid detection.

For this Monte Carlo simulation, 10,000 model runs were performed. Each run was 10,000 settlement periods long, equivalent to 208.3 days. Algorithm 1 shows pseudo-code of the model.

C. ASSUMPTIONS

In the course of building the model, four important assumptions have been made.

1) EACH HOUSEHOLD IS LIABLE FOR THEIR ENERGY IMBALANCES

This means that each household must notify the system operator of their supply or demand for energy an hour before the settlement period. They must accept any imbalance charges due to deviation from that final notification volume. In traditional energy markets, energy suppliers are responsible for energy imbalances on behalf of households.

There are two ways individual households might become liable for their energy imbalances in P2P markets. Firstly, every household in a P2P market could become a BSC party. This would be a significant change from the current system, but has been suggested in some literature [38], [53]. Secondly, a market operator could act as the BSC party for the whole P2P market, but directly pass the imbalance charges onto the market participants. This arrangement may be possible under the Virtual Power Plant provision in the BSC [3]. The results of this model are not affected by the method in which imbalance charges are passed to households.

Algorithm 1 Imbalance Charge Model Pseudo Code

Initialise model
  select randomly
    Demand profile $\in$ *set of* 1192
    Generation profile $\in$ *set of* 6
    Imbalance price profile $\in$ *set of* 2
    $\lambda_{P2P} \in \{5.6, 14.4\}\ p/kWh$
    $\mu_{pred} \in 0 \leq \mu_{pred} \leq 1, \quad step\ 0.1$
    $\mu_{imb} \in 0 \leq \mu_{imb} \leq 1.1, \quad step\ 0.1$
    $\mu_{mal} \in \{1, 1, 1, 2, 3\}$
Run model
  for $k = 1$ **to** 10000
    Calculate exported energy.
    $E^k_{exp} = E^k_{gen} - E^k_{dem}$
    Calculate futures market position. The predicted energy export is the energy exported in the settlement period immediately prior to gate closure with the error reduced depending on μ_{pred}.
    $E^k_{pred} = E^k_{exp} + \mu_{pred}(E^{k-3}_{exp} - E^k_{exp})$
    if $\mu_{mal} = 1$
      If the household is acting honestly then they will trade their predicted export in the P2P market.
      $E^k_{P2P} = E^k_{pred}$
    else if $\mu_{mal} = 2$
      If the household is acting maliciously by just increasing their predicted export then:
      if $E^k_{pred} > 0$
        $E^k_{P2P} = E^k_{pred} \cdot 1.5$
      else
        $E^k_{P2P} = E^k_{pred} \cdot 0.5$
    else
      If the household is acting maliciously by adjusting the market position based on a prediction of the relative levels of the market and imbalance prices then:
      if $\lambda^k_{imb} > \lambda^k_{P2P}\ \&\ E^k_{pred} > 0$
        $E^k_{P2P} = E^k_{pred} \cdot 1.5$
      else if $\lambda^k_{imb} > \lambda^k_{P2P}\ \&\ E^k_{pred} < 0$
        $E^k_{P2P} = E^k_{pred} \cdot 0.5$
      else if $\lambda^k_{imb} < \lambda^k_{P2P}\ \&\ E^k_{pred} > 0$
        $E^k_{P2P} = E^k_{pred} \cdot 0.5$
      else if $\lambda^k_{imb} < \lambda^k_{P2P}\ \&\ E^k_{pred} < 0$
        $E^k_{P2P} = E^k_{pred} \cdot 1.5$
      else
        $E^k_{P2P} = E^k_{pred}$
    Calculate the profit from the traditional market.
    if $E^k_{exp} > 0$
      $\pi^k_{trad} = E^k_{exp}\, \lambda_{FIT}$
    else
      $\pi^k_{trad} = E^k_{exp}\, \lambda_{trad}$
    Calculate the energy imbalance.
    $E^k_{imb} = E^k_{P2P} - E^k_{exp}$
    If $\mu_{imb} = 1.1$ the current British imbalance charge mechanism is used. If $0 \leqslant \mu_{imb} \leqslant 1$ the symmetric imbalance charge mechanism is used.
    if $\mu_{imb} = 1.1$
      $C^k_{imb} = E^k_{imb}\, \lambda^k_{imb}$
    else
      if $\lambda^k_{imb} < \lambda_{P2P}$
        If the imbalance price is lower than the P2P market price the imbalance price will be set at the market price.
        $\lambda^k_{imb} = \lambda_{P2P}$
      $C^k_{imb} = |E^k_{imb}|\, \lambda^k_{imb}\, \mu_{imb}$
    Calculate the additional profit from the P2P market.
    $R^k_{P2P} = E^k_{P2P}\, \lambda_{P2P}$
    $\pi^k_{P2P} = R^k_{P2P} - C^k_{imb}$
    $P2P\ market\ additional\ profit = \pi^k_{P2P} - \pi^k_{trad}$

2) THE HOUSEHOLD CAN BUY OR SELL ALL THEIR EXCESS ENERGY IN THE P2P MARKET

The model assumes that there is sufficient demand in the P2P market to purchase all excess energy the household has, and there is sufficient supply to meet all the demand the household has. This means that the household can always sell all their excess energy and they can always buy all the energy they need to meet a deficit. In a real P2P market it is unlikely that supply and demand for energy would perfectly balance during every settlement period as assumed in this model.

In the current literature, some P2P market models aim to perfectly balance energy supply and demand within the market [11], [54], [55], as assumed in this paper, but many assume that the traditional energy market acts as a supplier of last resort [13]–[16]. In the case that the household purchases energy from the retail market, they are likely to pay the retail market price, which is higher than the P2P market price. In the case that the household cannot sell their energy in the P2P market, they may be able to sell it at the feed-in tariff which is lower than the P2P market price, or they may not be able to sell it at all. It is therefore possible that the revenue of a household in a real P2P market will be lower than in the model in this paper.

3) THE ENERGY IMBALANCE OF THE P2P MARKET DOES NOT AFFECT THE IMBALANCE PRICE

The model assumes there is no correlation between the household's energy imbalance and the imbalance price. If P2P markets form only a small proportion of the total supply and demand in the electricity system, there will be little or no correlation between the energy imbalance of the household in the P2P market and the imbalance price. If the network energy imbalance is correlated with the P2P market energy imbalance, the imbalance charge will become correlated with the energy imbalance of the household.

Errors in widely used forecasts could also lead to energy imbalances correlating with the imbalance price. If a large proportion of a country's energy market participants are relying on the same weather forecast, which is inaccurate, then they are likely to have energy imbalances in the same direction. This error could lead to a correlation between a national imbalance price and energy imbalance in a small P2P market. We do not consider this correlation in this paper.

4) THE P2P MARKET PRICE IS NOT ADJUSTED FOR NON-ENERGY COSTS

The P2P market price in the model is based on the current electricity market prices in Great Britain. These prices include system operator and network operator fees, including the imbalance charge. In Britain network charges account for 22% of an average customer bill, and operating costs account for 17% [56]. Operating costs include imbalance charges and non-energy balancing costs such as the cost of reserve and geographical balancing. In reality the lower bound of the P2P market price may be slightly higher and the upper bound may be slightly lower. This is because the imbalance charges are calculated separately in the P2P market.

V. RESULTS AND ANALYSIS

The results show that household revenue is mostly higher in the P2P market than the traditional market. Only 0.3% of households not acting maliciously (18 of 5,928) had a higher revenue in the traditional market. However, the imbalance charges experienced by households can dramatically affect the profits households make in the P2P market. Even though 99.7% of households not acting maliciously (5,910 of 5,928) had a higher revenue in the P2P market, only 51.6% of households (3,059 of 5,928) had a higher profit.

In this section the results from the Monte Carlo simulation are analysed to explain why imbalance charges have such a significant effect on the profits in P2P markets. Section V-A analyses the revenues of households. Section V-B analyses the energy imbalances of the households. Section V-C analyses the imbalance charges of households subject to the symmetric imbalance charge mechanism and Section V-D analyses the profits. Sections V-E and V-F analyse the imbalances charges and profits of households subject to the current British imbalance charge mechanism. Sections V-B - V-F discuss the results of households which act honestly in the market. Section V-G analyses whether households can adjust their supply and demand predictions to improve their profits. Section V-H discusses the economic efficiency of the symmetric imbalance charge mechanism. Section V-I discusses how the symmetric imbalance charge mechanism might be implemented. Finally, Section V-J discusses methods by which P2P market participants might reduce their energy imbalances in response to the imbalance charge.

A. HOUSEHOLD REVENUES

The total revenue of households in the P2P market at the end of the model run forms a bi-modal distribution with a large negative skew. The highest peak of the distributions is at a revenue of 118.37 GBP/year and the secondary peak is at −57.87 GBP/year. The maximum and minimum revenues at the end of the model runs were 717.96 GBP/year and −5,028.32 GBP/year respectively. The shape of the revenue distribution is determined by the generation and demand of the household.

The bi-modal nature of the distribution is caused by the generation datasets. Of the six PV generation datasets used in the model, four have a mean generation between 0.211 kWh and 0.287 kWh per settlement period, while the other two have mean generations of 0.025 kWh and 0.050 kWh per settlement period. Households which used one of the higher generation profiles are more likely to have higher net energy exports, and therefore high revenues. These households with higher generations profiles form the peak at a revenue of 118.37 GBP/year. The households using one of the lower two generation profiles had lower net energy exports and so formed the lower peak at a revenue of −57.87 GBP/year. The bi-modal nature of the distribution would not exist in reality but is caused by the small number of PV generation profiles used in the model.

The large negative skew of the revenue distribution is caused by the demand datasets. The mean of the distribution of mean energy demand was 0.224 kWh per settlement period. However, the distribution has a large positive skew. The minimum mean energy demand is 0.001 kWh per settlement period. The maximum mean energy demand is 2.043 kWh per settlement period. This large positive skew is caused by a small number of demand datasets which have very large energy demands compared to the rest. Only two of the 1,192 demand datasets have a mean energy demand of over 1.5 kWh per settlement period, only 7 have a mean energy demand of over 1 kWh per settlement period. Households with the large demand datasets have low net exports and therefore low revenues compared to other households.

However, the absolute revenue of the households in the P2P market matters less than relative revenue compared to the traditional market. Of the households not acting maliciously by intentionally adjusting their energy prediction, only 18 of 5,928 households had a lower revenue in the P2P market than the traditional market. The reason most households have a higher revenue in the P2P market is that there is no spread between buy and sell prices in the market. Households in the P2P market are either paid more for exporting electricity, or pay less to import electricity than in the traditional market. The reason a small number households were better off in the traditional market is that their actual energy export was significantly greater than their predicted energy export.

The revenue of households in the P2P market does not take account of imbalance charges caused by their energy imbalances. The energy imbalances have a significant effect on the relative benefit of participating in P2P markets. Section V-B discusses the energy imbalances which households experience.

B. HOUSEHOLD ENERGY IMBALANCES

During individual settlement periods households can experience very high energy imbalances. The energy imbalance in a settlement period can be a significant proportion of, or even higher than the demand and generation. The largest energy imbalance in a settlement period, 6.713 kWh, is slightly less than the highest demand, 8.204 kWh, and much greater than the highest generation, 1.942 kWh.

However, these high energy imbalances are the extremities of a distribution with a very low mean. These large outlying values are reflected in the high kurtosis of the distributions, a measure of the size of the distribution's tails. The highest absolute mean energy imbalance of any household was only 0.0011 kWh.

Households have fairly equal energy imbalances in both the positive and negative direction. The energy imbalance distributions have a low skewness, a measure of the asymmetry of a distribution. Figure 2 shows the energy imbalance distribution of a typical household. This low skewness combined with the low mean causes the energy imbalances in the positive and negative direction to cancel out. Therefore, households have a low cumulative energy imbalance at the end of the run. The highest cumulative energy imbalance at the end of 10,000 settlement periods was 10.557 kWh, only 157% of the highest energy imbalance in a single settlement period.

Households which are making more accurate predictions of their energy supply and demand, experience lower energy imbalances. As the prediction accuracy of households improves (μ_{pred} decreases), the mean, highest and cumulative energy imbalances all decrease. This means that investing in technologies like energy storage which can reduce prediction errors will reduce energy imbalances of households. However, the shape of the energy imbalance distribution does not significantly change. The skewness and kurtosis of the energy imbalance distribution is not correlated with the prediction accuracy coefficient (μ_{pred}). Table 1 shows a summary of the energy imbalance distributions for different values of the prediction accuracy coefficient (μ_{pred}).

The closest mathematical approximation of the distribution observed in the results is Johnson's S_U distribution [57], [58]. Previous papers which have considered energy imbalances in P2P markets have assumed the imbalances follow a Gaussian distribution [38]. However, a Gaussian distribution is a relatively poor approximation of energy imbalances in the model presented in this paper. Table 2 in Appendix A gives the parameters for Johnson's S_U distribution which best represent the energy imbalances in the model for different values of prediction accuracy (μ_{pred}).

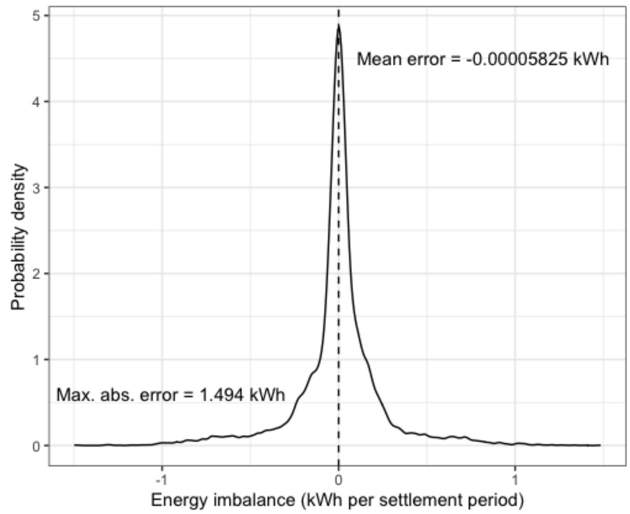

FIGURE 2. Probability density function of energy imbalance for a representative household acting under the current British imbalance charge mechanism ($\mu_{mal} = 1$, $\mu_{pred} = 1$).

C. IMBALANCE CHARGES UNDER THE SYMMETRIC IMBALANCE CHARGE MECHANISM

Households subject to the symmetric imbalance charge mechanism incur positive imbalance charges which grow over time. Households are charged the imbalance price irrespective of the direction of their imbalance. Households subject to the symmetric imbalance mechanism at today's imbalance prices ($\mu_{imb} = 1$) and who do not take action to reduce their energy imbalance ($\mu_{pred} = 1$) have a distribution of imbalance charges with a large positive skew. The mean imbalance charge of these households was 0.08 GBP, with a minimum of -1.76 GBP and a maximum of 15.34 GBP. The reason it is possible for households to experience negative imbalance charges under the symmetric imbalance charge mechanism is that the imbalance price is occasionally negative.

The ratio of net to gross energy imbalance in the model is $\alpha = 0.4$ (see Equation 6). This means that reducing imbalance prices to 40% of today's level will keep the system operator's revenue constant. The value of $\alpha = 0.4$ is specific to the data used in this model. The system operator's revenue must be maintained to allow them to pay for the required balancing actions. Reducing the imbalance prices to 40% of today's level ($\mu_{imb} = 0.4$) reduces the imbalance charges households experience. The shape of the distribution does not change but the mean imbalance charge reduces to 0.03 GBP, and the maximum and minimum imbalance charges reduce to 16.80 GBP and -0.99 GBP respectively.

TABLE 1. Energy imbalance distribution summary data for all households.

	Prediction Accuracy Coefficient (μ_{pred})	Highest Absolute Mean Energy Imbalance (kWh)	Highest Absolute Energy Imbalance (kWh)	Highest Absolute Cumulative Energy Imbalance (kWh)	Range of Energy Imbalance Standard Deviation	Range of Energy Imbalance Skewness	Range of Energy Imbalance Kurtosis
Decreasing energy imbalance ↓	1.0	0.0011	7.244	10.557	0.034 - 1.282	-2.130 - 0.584	3.9 - 80.4
	0.9	0.0007	5.603	6.702	0.050 - 1.031	-3.545 - 0.583	3.8 - 148.1
	0.8	0.0008	5.734	8.446	0.031 - 0.884	-1.994 - 0.923	3.8 - 89.7
	0.7	0.0007	4.607	6.511	0.038 - 0.912	-2.248 - 0.820	3.8 - 87.3
	0.6	0.0006	3.820	6.281	0.031 - 0.682	-1.671 - 1.201	3.8 - 113.8
	0.5	0.0003	3.099	3.269	0.016 - 0.573	-1.994 - 0.674	4.1 - 122.9
	0.4	0.0003	2.685	2.801	0.016 - 0.458	-1.994 - 0.781	3.8 - 47.6
	0.3	0.0002	1.974	2.512	0.015 - 0.395	-1.969 - 0.918	3.9 - 105.3
	0.2	0.0002	1.316	2.279	0.011 - 0.256	-2.130 - 0.986	3.8 - 80.4
	0.1	0.0001	0.623	0.919	0.003 - 0.108	-1.916 - 0.583	4.3 - 113.8

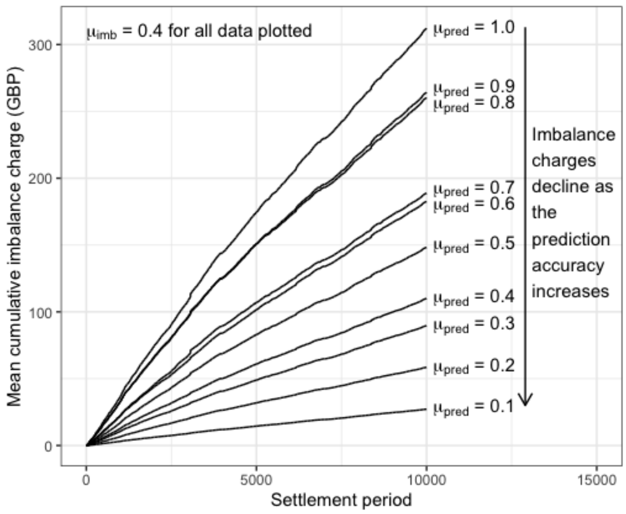

FIGURE 3. Cumulative imbalance charge over duration of the simulation for different values of imbalance price.

Under the symmetric imbalance charge mechanism, increasing the prediction accuracy (lowering energy imbalances) reduces the cumulative imbalance charges experiences by households over the duration of the simulation. Figure 3 shows how the cumulative imbalance charge develops over the duration of the simulation for the symmetric imbalance charge mechanism and an imbalance price multiplier $\mu_{pred} = 0.4$. The imbalance charge linearly increases over the duration of the model for the symmetric imbalance charge mechanism. As the prediction accuracy increases, the cumulative imbalance charge increases at a slower rate. This means that households have a financial incentive to invest in technologies such as storage which can reduce their energy imbalances.

D. HOUSEHOLD PROFITS UNDER THE SYMMETRIC IMBALANCE CHARGE MECHANISM

At today's imbalance price level ($\mu_{imb} = 1$), household energy imbalances must significantly decrease to allow P2P markets to function. When households are subject to the symmetric imbalance charge mechanism, current imbalance prices ($\mu_{imb} = 1$), and do not take action to reduce their energy imbalances ($\mu_{pred} = 1$), all households are worse off in the P2P market than the traditional market. This would cause households to switch out of the P2P market back to the traditional market. Reducing energy imbalances to 10% of their level when no action is taken ($\mu_{imb} = 0.1$) still means that 27.66% are worse off in the P2P market compared to the traditional market. Therefore, most households would have to significantly reduce their energy imbalance before being more profitable in a P2P market than a traditional market.

For a P2P market to function using the symmetric imbalance charge mechanism, the imbalance prices must be lower than they currently are in Great Britain. For this market, reducing imbalance prices to 40% of their current level ($\alpha = 0.4$) maintains the system operator's revenue at its current level. At $\mu_{imb} = 0.4$, 7.7% of households are better off in the P2P market when they do not take action to reduce their energy imbalances ($\mu_{pred} = 1$). If energy imbalances are reduced to 10% of their level when no action is taken ($\mu_{pred} = 0.1$), 90.2% of households are better off in the P2P market.

Figures 4 and 5 show box plots of the difference in profit between acting in a P2P and traditional market for imbalance price multipliers of $\mu_{imb} = 1$ and $\mu_{imb} = 0.4$ respectively. The plot for imbalance price multiplier of $\mu_{imb} = 1$ (Figure 4) shows that the prediction accuracy must be reduced to around 20% of its level when no action is taken before over 50% of households are better off in the P2P market. With an imbalance price multiplier of $\mu_{imb} = 0.4$, Figure 5 shows that a household only needs to reduce their prediction accuracy to 40% of the level when no action is taken before over 50% of households are better off in a P2P market. Table 3 in Appendix A shows the proportion of households which have a higher profit in the P2P market for different values of prediction accuracy and imbalance multiplier. Table 4 in Appendix A shows the mean additional profit when acting in the P2P market.

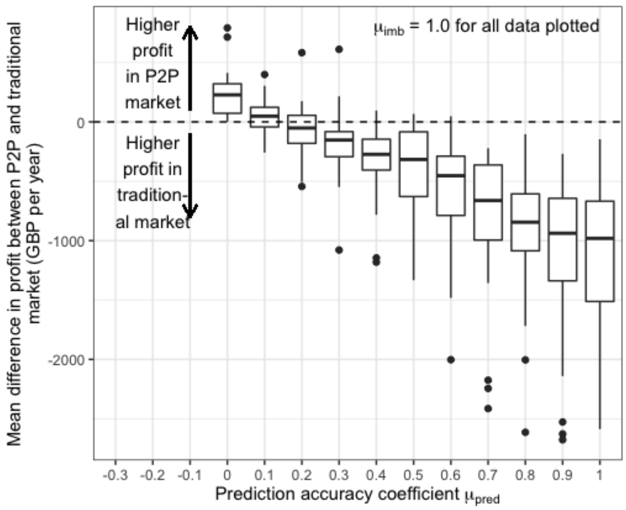

FIGURE 4. Box plot showing the difference in profit between the P2P market and the traditional market at the end of the simulation for imbalance price coefficient $\mu_{imb} = 1.0$.

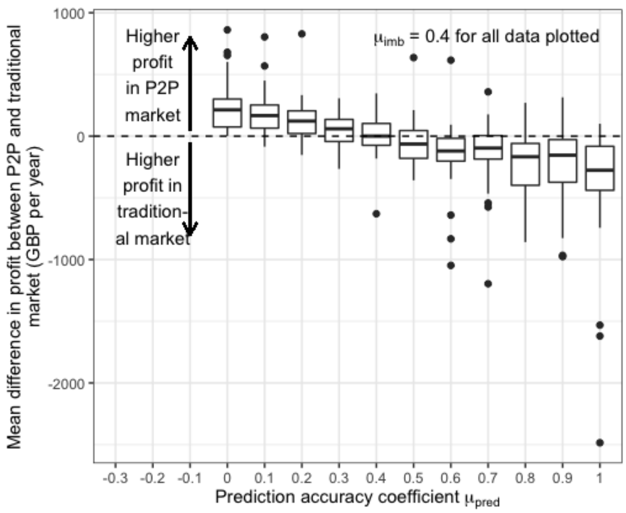

FIGURE 5. Box plot showing the difference in profit between the P2P market and the traditional market at the end of the simulation for imbalance price coefficient $\mu_{imb} = 0.4$.

The imbalance price in Great Britain is currently the marginal cost of the balancing actions taken by the system operator. The reason the imbalance price is based on the marginal cost is that it incentivises BSC parties to continue to take action to balance their own supply and demand of energy until those actions become more costly than the same action taken by the system operator. This idea that the parties who can take balancing actions at the lowest cost should take those actions is based on minimising the overall system cost and therefore consumers bills. Reducing the imbalance price to 40% of its current level will leave a significant gap between the price of balancing actions which P2P market participants will take, and the cost of the system operator taking those same actions. This will raise the overall system cost. Therefore, there is a trade off when setting the imbalance price between minimising imbalance charges for the P2P market participants and creating the correct incentives to reduce energy imbalances. Section V-H discusses the economic efficiency of the symmetric imbalance charge further.

Sections V-E and V-F will show that under the current British imbalance charge mechanism, P2P market participants are not incentivised to take any balancing actions. Since the imbalance prices in the positive and negative direction cancel out over time, imbalance charges are simply a cash flow issue for P2P market participants. The households may have to pay relatively large imbalance charges during a particular settlement period, however over time these large charges will be cancelled out by charges paid to the households by the system operator. Therefore, the current imbalance charge mechanism does not incentivise market participants to take balancing actions. Although the symmetric imbalance charge mechanism leaves a gap between the imbalance price and the system operator's marginal balancing action cost, it provides a greater incentive for P2P market participants to balance their supply and demand for energy than the current British imbalance charge mechanism does.

For any combination of μ_{imb} and μ_{pred} there is a range of results for household profit. This range affects whether or not households are better off in the P2P or traditional market. Some of this variability is explained by the ratio of installed demand capacity to installed generation capacity of the household, and by the market price. Households with a relatively high proportion of generation have higher profits at higher P2P market prices. Households with relatively high proportions of demand have higher profits at lower P2P market prices.

The proportion of generation to demand and the market price does not explain all the variance in profit. There is an element of randomness to the outcome of a household in the model because imbalance prices are not correlated to the energy imbalance in the model. Therefore two households with identical energy imbalances could end up with significantly different levels of profit under the symmetric imbalance charge mechanism. One household might happen to have high energy imbalances during settlement periods with low imbalance prices, leading to a lower imbalance charge. Another household might have high energy imbalance during settlement periods with high imbalances prices, leading to higher imbalance charges.

E. IMBALANCE CHARGES UNDER THE CURRENT BRITISH IMBALANCE CHARGE MECHANISM

The imbalance charges households experience when subject to the current British imbalance charge mechanism follow the same pattern as their energy imbalances. In individual settlement periods households can experience high imbalance charges. The highest imbalance charge during a settlement period for a household which did not take any action to reduce their energy imbalance ($\mu_{pred} = 1$) was 10.18 GBP.

By comparison the highest revenue during a settlement period in the same group of households was 0.27 GBP. However, the distribution of imbalance charges has a low mean and skewness. The highest mean imbalance charge of any household under the current British imbalance charge mechanism was 0.006 GBP. Figure 6 shows the probability density function for the imbalance charges of a representative household acting under the current British imbalance charge mechanism.

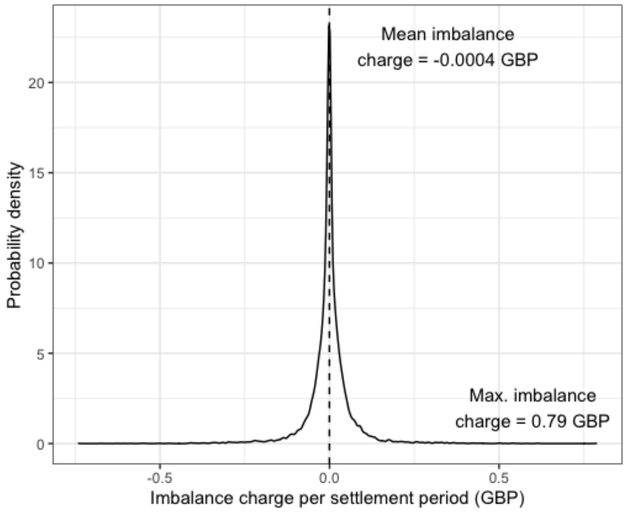

FIGURE 6. Probability density function of imbalance charges for a representative household acting under the current British imbalance charge mechanism ($\mu_{mal} = 1,\ \mu_{pred} = 1$).

Over the course of the model run, the cumulative imbalance charge is low. Figure 7 shows the cumulative imbalance charge of the same representative household as Figure 6, developing over the course of the model run. These graphs show that the highest imbalance charge for this household during a single settlement period was 0.79 GBP. However, the cumulative imbalance charge at the end of 10,000 settlement period was -3.50 GBP (paid by the system operator to the household). The reason for this low cumulative imbalance charge is that the imbalance charges during individual settlement periods cancel out.

The reason the imbalance charges follow the same pattern as energy imbalances is that there is little correlation between energy imbalances and imbalance prices (Pearson coefficient $\rho = .01$). The reason for the poor correlation between energy imbalance and imbalance price is that there are currently no BSC parties who act like the households modelled in this paper. If the types of P2P markets modelled in this paper form a small part of the British electricity market, and therefore cause only a small proportion of the energy imbalances, this disconnect between energy imbalances in P2P markets and imbalance price is likely to remain. However, if P2P markets formed a substantial part of the electricity market, the system energy imbalance is likely to become correlated with the P2P market energy imbalance.

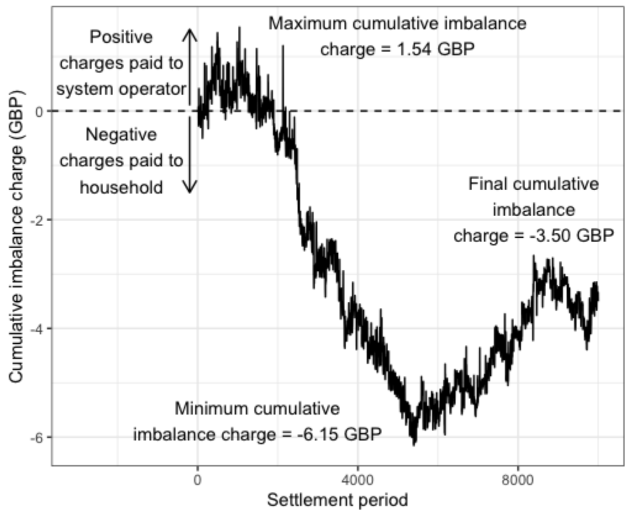

FIGURE 7. Graph of cumulative imbalance charges for a representative household acting under the current British imbalance charge mechanism ($\mu_{mal} = 1,\ \mu_{pred} = 1$).

A higher correlation between energy imbalance and imbalance price could lead to higher cumulative imbalance charges. It would become more likely that the energy imbalance of the household would be in the same direction as the system imbalance. When a household's energy imbalance is in the same direction as the system imbalance they are penalised. Therefore, the mean energy imbalance of a household would increase, leading to a higher cumulative imbalance charge over time. The extent to which higher correlations between energy imbalance and imbalance price would affect the imbalance charge is not considered in this paper.

F. HOUSEHOLD PROFIT UNDER THE CURRENT BRITISH IMBALANCE CHARGE MECHANISM

Under the current British imbalance charge mechanism, 98.6% of households (491 of 498) which do not act maliciously have a higher profit in the P2P market than the traditional market. This level of profitability is caused by the fact that households have higher revenues in the P2P market and experience low imbalance charges, see Sections V-A and V-E respectively. Although this level of profitability in P2P markets is beneficial to the households, it is indicative of the fact that the current British imbalance charge mechanism does not provide an incentive for households to reduce their energy imbalances.

The level of energy imbalance does not affect the profitability of households. Changing the prediction accuracy, μ_{pred}, has little effect on the profitability of households. For high values of μ_{pred} households experience higher imbalance charges in any given settlement period. At $\mu_{pred} = 1$ the average absolute imbalance charge is 0.08 GBP, compared to 0.01 GBP when $\mu_{pred} = 0.1$. However, the imbalance charges are equal in opposite directions. Over enough settlement periods the imbalance charges average out to low values irrespective of the value of μ_{pred}. For example at $\mu_{pred} = 1$, the average total imbalance charge at the end of the model run was -14.33 GBP, compared to -2.19 GBP for $\mu_{pred} = 0.1$.

Figure 8 shows a box plot of the difference in profit between the P2P market and the traditional market at the end of the simulation. Almost all households have a higher average profit in the P2P market. The prediction accuracy coefficient does not affect the household profit.

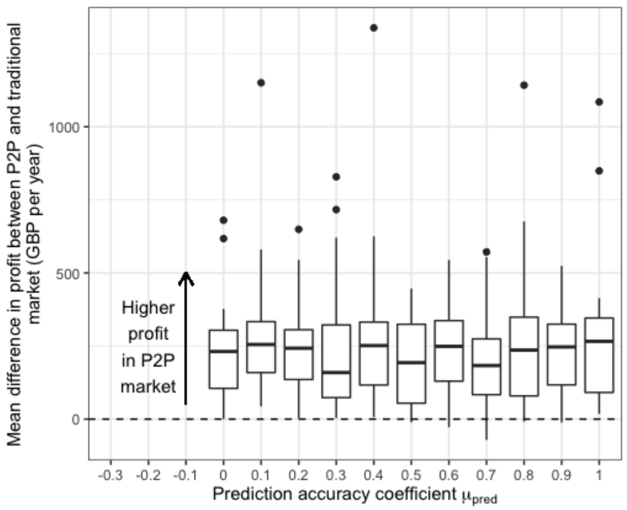

FIGURE 8. Box plot showing the difference in profit between the peer-to-peer market and the traditional market at the end of the simulation.

Not addressing the high potential energy imbalances in P2P electricity markets could create a problem for the whole electricity network, and for P2P markets internally. The system operator must remedy any energy imbalances to ensure there is sufficient energy to meet the network demand. The imbalance price is calculated using the marginal cost of balancing actions during each settlement period. Therefore, higher total system energy imbalances will lead to higher imbalance prices, which in turn will be passed onto the consumers, both inside and outside the P2P market, as higher energy prices. The mean ratio of energy imbalance to demand in the model is 1.007. In the current British electricity network, the mean energy imbalance to demand ratio in 2020 was 0.010 [43]. It is not possible to directly compare these two figures because the imbalances at a national level will net-off. However, they do show that imbalances in P2P market are likely to be very high relative to the market demand.

High imbalances within P2P markets might cause a problem for the internal functioning of those markets. Many P2P market designs consist of an optimisation problem in a futures market. Deviation from the futures market position, an energy imbalance, will reduce the efficiency of these markets. Sections V-C and V-D present the results of the symmetric imbalance charge mechanism and shows how it can alleviate this problem.

G. MALICIOUS BEHAVIOUR

A secondary advantage of the symmetric imbalance charge mechanism is it prevents households from manipulating their final notification volume, E_{fnv}, to increase their profit. Two types of malicious behaviour have been modelled. They are described in Section III-B. The results presented in this section demonstrate that under the current British imbalance charge mechanism, households can manipulate their final notification volume to increase their own profit to the detriment of the electricity system. The results also show that under the symmetric imbalance charge mechanism households cannot increase their profit by manipulating their final notification volume.

1) PURCHASING MORE ENERGY THAN REQUIRED

In the model, 2,004 of the 10,000 households acted maliciously by decreasing their final notification volume, E_{fnv}, by 50%. Of the households acting maliciously in that manner, 165 were subjected to the current British imbalance charge mechanism. The mean profit of these 165 household was 189.58 GBP/year. By contrast, the mean profit was -44.59 GBP/year for households which did not manipulate their final notification volume. This additional profit gives households a significant incentive to act dishonestly in the market.

The reason the household's profit is increased by reducing the final notification volume is that it increases the likelihood the household will export more energy than the final notification volume. This increases the likelihood the household will be paid the imbalance charge. The mean imbalance charge for households not acting maliciously was -12.98 GBP/year. However, for households acting maliciously the mean imbalance charge was -518.61 GBP/year, where a negative charge is paid to the household by the system operator. This significant increase in the imbalance charge paid to the household dramatically increases their profit.

Acting maliciously actually reduces the revenue of the household in the P2P market. The mean revenue of households not acting maliciously was -57.57 GBP/year, compared to -329.02 GBP/year for households acting maliciously. However, the reduction in revenue was more than offset by the additional imbalance charge paid to the household, leading to a higher profit.

The reason it is undesirable for households to adjust their final notification volume is that it dramatically increases the energy imbalance in the market. The mean energy imbalance of households not acting maliciously was 0.00002 kWh. By contrast, households acting maliciously by decreasing their final notification volume had a mean energy imbalance of 0.07 kWh. The high energy imbalances of one market participant are detrimental to all other energy market participants, as discussed in Section V-C. The symmetric imbalance charge mechanism removes this incentive for households to artificially increase their energy imbalance.

The symmetric imbalance charge eliminates the benefit of manipulating the final notification volume. Under the symmetric imbalance charge mechanism, the mean profit of households ($\mu_{imb} = 1$) acting maliciously was −1,220.40 GBP/year, compared to −766.41 GBP/year for households acting honestly. Acting maliciously leaves households considerably worse off than acting honestly. Acting maliciously does not have the same impact on the imbalance charges households incur under the symmetric imbalance charge mechanism. The mean imbalance charge for households acting honestly under the symmetric imbalance charge regime ($\mu_{imb} = 1$) was 682.42 GBP/year, compared to 911.11 GBP/year for households acting maliciously. Therefore, the symmetric imbalance charge mechanism incentivises households to accurately report their final notification volumes, decreasing the total system energy imbalance.

This section has shown that the symmetric imbalance charge mechanism eliminates the possibility of households increasing their profit by decreasing their final notification volume. The next section will show that the symmetric imbalance charge mechanism also removes the benefit of the more sophisticated form of malicious behaviour based on predicting imbalance prices.

2) ADJUSTING POSITION BASED ON IMBALANCE PRICE PREDICTION

If a household is able to predict whether the market price or imbalance price will be higher, they can increase their profits under the current British imbalance charge mechanism by adjusting their final notification volume, E_{fnv}. A full description of the method of malicious behaviour is presented in Section III-B2. In the model 2,068 of 10,000 households acted maliciously in this manner. Of those 2,068 households, 167 were subject to the current British imbalance charge mechanism. The mean profit of those 167 households was 244.17 GBP/year. This profit is higher than the mean profit of households acting in the less sophisticated malicious manner described in Section V-G1 (189.58 GBP/year), and significantly higher than households not acting maliciously (−44.59 GBP/year).

The imbalance charge of households acting maliciously by predicting the market and imbalance prices is much lower (more money paid to the household) than those which are not under the current British imbalance charge mechanism. The mean imbalance charge was −12.98 GBP/year for households not acting maliciously, compared to −507.60 GBP/year for those predicting the market and imbalance prices. Revenues are lower for households which adjust their final notification volumes, −263.43 GBP/year as opposed to −57.57 GBP/year for those which do not, but that is not sufficient to offset the gains made from imbalance charges.

As with the previous method of malicious action, the symmetric imbalance charge mechanism eliminates the benefit of acting maliciously in this manner. The profit of households acting maliciously by predicting the market and imbalance prices under the symmetric imbalance charge ($\mu_{imb} = 1$) was −1106.99 GBP/year, compared to −766.41 GBP/year for those not acting maliciously. This significantly lower profit will disincentivise households from acting maliciously. This decrease in profit for households acting maliciously under the symmetric imbalance charge is caused by a higher imbalance charge (836.01 GBP/year for households acting maliciously compared to 682.42 GBP/year for those not), combined with a lower revenue (−270.98 GBP/year for households acting maliciously compared to −84.00 GBP/year for those not).

The results presented in this section have shown that the symmetric imbalance charge produces a financial penalty if households choose to adjust their final notification volume from their best prediction of energy supply and demand, artificially creating an energy imbalance. This contrasts with the current British imbalance charge mechanism, under which households can financially gain by adjusting their final notification volume, giving them an incentive to artificially increase their energy imbalances.

H. ECONOMIC EFFICIENCY OF THE SYMMETRIC IMBALANCE CHARGE MECHANISM

The current British imbalance price is set at the marginal cost of the balancing mechanism during each settlement period. Setting the imbalance price at the marginal cost of the balancing mechanism should incentivise market participants who can take balancing actions more cheaply than the system operator. Under the symmetric imbalance charge we have suggested it is possible, but not necessary for the imbalance price to be lowered. See Sections II and III for more details on the imbalance price in Britain now and under the symmetric imbalance charge mechanism.

Reducing the imbalance price below the marginal cost of the balancing mechanism creates the possibility of economic inefficiency. The system operator might be forced to take a balancing action which a market participant could have taken more cheaply. However, because the price of that balancing action was above the imbalance price, the market participant would have been worse off by taking it. However, this economic efficiency makes two assumptions which may not be correct in P2P markets.

Firstly, the economic efficiency argument assumes that market participants know what the imbalance price will be. In Britain the imbalance price is only published after the settlement period [43]. For market participants to act on the imbalance price they must make a prediction of what it is likely to be. Households are less likely to be able to make such predictions than sophisticated traders in traditional markets.

The second important assumption made by the economic efficiency argument is that market participants will be able to respond to the imbalance price. The main thing which determines the ability of P2P market participants to respond to the imbalance price is the level of storage and flexible load in the market. Storage and flexible loads have low operating costs but high capital costs. The imbalance charge in a single settlement period, which will determine how storage and flexible loads are operated, is therefore less important than the cumulative imbalance charge over time, which will determine the investment in storage and flexible loads.

The results presented in Section V-E show that the cumulative imbalance charge of a household subjected to the current British imbalance charge mechanism will be very low. This low cumulative imbalance charge provides no incentive for them to invest in storage or flexible loads. Therefore, they will be unable to respond to high imbalance prices during any particular settlement period.

In contrast, the results presented in Section V-C show that the cumulative imbalance charge of a household subjected to the symmetric imbalance charge mechanism consistently grows over time. This cumulative imbalance charge growth provides a strong incentive for investment in storage and flexible loads. It is therefore likely that although households have a less economically efficient incentive to adjust their energy imbalances during a settlement period, they will have a more effective incentive to reduce their energy imbalances over time.

I. IMPLEMENTATION OF THE SYMMETRIC IMBALANCE CHARGE MECHANISM

There are two ways the symmetric imbalance charge mechanism could be implemented. Firstly, the codes which govern imbalance charges (the BSC in Great Britain) could be amended so that all market participants, both inside and outside the P2P market, are subject to the symmetric imbalance charge mechanism. Secondly, a P2P market operator could impose the symmetric imbalance charge mechanism only within a P2P market.

Subjecting the whole electricity market to the symmetric imbalance charge mechanism could have significant consequences for traditional market participants. The business models and trading arrangements of current physical and non-physical traders are designed around the current system. A significant change, as proposed in this paper, would have ramifications for them which would need to be assessed. Further evidence of the impact of these changes on current BSC parties would need to be gathered before a change to the whole system could be considered. In Great Britain, Ofgem has a significant code review process which allows them to assess the effect of changes on BSC parties.

Only subjecting a P2P market to the symmetric imbalance charge mechanism would require minimal to no changes to codes, and would not have any impact on traditional market participants. A P2P market operator could act as the conduit to the traditional market (BSC party in Great Britain) for the whole P2P market. The market operator would be subject to the imbalance charges for all P2P market participants under the current imbalance charge mechanism. The market operator can then impose the symmetric imbalance charge mechanism on the P2P market participants. This paper has shown how the revenue of the two imbalance price mechanisms can be made equal. Therefore, the market operator will receive the same revenue from the P2P market participant as they must pay in imbalance changes to the system operator. In this way the P2P market participants are being effectively subjected to the symmetric imbalance charge mechanism with minimal effect to the rest of the electricity market. In Great Britain the P2P market operator may be able to act as a BSC party under the Virtual Power Plant provision in the current BSC [3].

In the event the symmetric imbalance charge is only implemented inside a P2P market, the market operator must choose to impose it upon the P2P market. The most likely reason the system operator would choose to implement an imbalance charge system that incentivises reduced imbalances is that imbalances make the P2P market less efficient. Many P2P market designs are based around an optimisation function in a futures market. Energy imbalances are not accounted for in the optimisations and therefore make the P2P market less efficient.

J. METHODS OF REDUCING ENERGY IMBALANCES IN PEER-TO-PEER MARKETS

The results presented in Section V-D show that the symmetric imbalance charge mechanism gives P2P market participants a clear financial incentive to reduce their energy imbalances. This section briefly discussed the methods which P2P market participants could employ to reduce their energy imbalances. These methods fall into three broad categories: improving energy supply and demand predictions; increasing flexibility of energy supply and demand; and netting-off energy imbalances within a P2P market.

Energy imbalances of P2P market participants who are not acting maliciously are caused by errors in energy supply and demand forecasting. Improving the accuracy of the forecasts used, e.g. through improved weather forecasting, will reduce the level of energy imbalance.

Installing sources of flexibility, such as energy storage or flexible loads, will allow P2P market participants to adjust their supply or demand for energy during a settlement period. These supply and demand adjustments can be used to reduce energy imbalances. In the circumstance where a whole P2P market is a single BSC party, real-time trading can be used to take advantage of all the storage and flexible load in the market. If one market participant is experiencing an energy imbalance during a settlement period, they can sell or purchase energy from other participants using storage or flexible load to adjust their own supply or demand. To the system operator this will just appear to be a reduction in energy imbalance.

If the whole P2P market is a single BSC party and two market participants have energy imbalances in opposite directions, those participants can trade to eliminate both their energy imbalances. This possibility of P2P trading as a means of reducing imbalances has been discussed in other works [28], [29]. This is possible because all imbalances within the market are netted-off from the system operator's point of view as the whole market acts as a single BSC party.

VI. CONCLUSION

This paper has proposed a symmetric imbalance charge mechanism which provides a financial incentive for P2P electricity market participants to reduce their energy imbalances. Having a financial incentive is important because the measures a market participant might take to reduce their energy imbalances are expensive. These measures include installing energy storage or demand response, or trading with other market participants who have storage or demand response. The symmetric imbalance charge would therefore complement P2P market designs which use such devices with the aim of minimising energy imbalances, by providing an external financial incentive. The symmetric imbalance charge mechanism also prevents P2P market participants from adjusting their final notification volumes to benefit from the imbalance charge mechanism at the expense of other electricity market participants.

To show the advantages of the symmetric imbalance charge mechanism, this paper has shown that the current British imbalance charge mechanism does not provide an effective incentive for P2P market participants to reduce their energy imbalances. The energy imbalances of households who might participate in P2P markets are much higher, as a proportion of demand, than the energy imbalances currently experienced in Great Britain. Therefore, the introduction of P2P electricity markets without an incentive for participants to reduce their energy imbalances might significantly increase the total energy imbalance, and therefore overall electricity system cost.

Finally, this paper has addressed some of the issues involved with implementing the symmetric imbalance charge mechanism. The imbalance price can be reduced while maintaining the system operator's revenue. The symmetric imbalance charge mechanism could either be implemented as a change to the British BSC, or it could be implemented only within the boundaries of a P2P electricity market.

The work in this paper has shown that when P2P market participants are subject to appropriate imbalance charges, the charges are not negligible. Therefore, P2P market trading strategies should consider imbalance charges. Most current literature proposing P2P trading strategies neglects imbalance charges. Future work should consider what effect these imbalance charges have on optimal trading strategies in P2P markets, and on P2P market design.

This work has also shown that P2P markets could have a significant effect on the energy imbalance of the electricity network. Therefore, the system operator and regulators should ensure that codes and standards effectively incentivise P2P markets to minimise their imbalances. The introduction of P2P markets is likely to require an amendment to the British BSC and other similar codes in different countries. Future work should consider the design of this amendment, and the effect of this amendment on traditional electricity market participants such as energy suppliers.

In this paper we have made several key assumptions, including that the household can buy and sell all the energy they require in the P2P market, and that the P2P market energy imbalances do not affect the imbalance price. These assumptions limit how broadly the results of this paper can be applied. Future work could usefully examine the effect of these assumptions by applying imbalance charges to P2P market models with a finite supply and demand for energy, and by examining the size of P2P markets that would begin to affect imbalance charges.

The work presented in this paper demonstrates that, for peer-to-peer markets to function, the design of imbalance charge must be carefully considered. The regulatory challenges associated with energy imbalances in P2P markets are surmountable. They should not stand in the way of the environmental benefits large scale adoption of distributed renewable generators can bring. We have demonstrated a simple alternative imbalance charge design which provides peer-to-peer market participants with corrective incentives to reduce their energy imbalances.

DATA AVAILABILITY

This study is an analysis of three existing publicly available datasets which are openly available from the Elexon Portal at https://www.elexonportal.co.uk, and the London Datastore at https://data.london.gov.uk/dataset/smartmeter-energy-use-data-in-london-households and https://data.london.gov.uk/dataset/photovoltaic–pv–solar-panel-energy-generation-data, reference numbers [43], [45], [46]. The code for the model developed in this study is openly available in Figshare at https://doi.org/10.48420/14681502, reference number [59].

APPENDIX A
SUPPORTING DATA

This appendix contains supporting numerical results. In addition to the supporting data in this section, the location of the datasets and code used in this paper can be found in Section VI.

TABLE 2. Johnson's S_U distribution parameters for energy imbalances.

	Prediction Accuracy Coefficient (μ_{pred})	Johnson's S_U Distribution Parameters γ	δ	ξ	λ
Decreasing energy imbalance ↓	1.0	0.01036806	0.5625183	0.004420315	0.06183279
	0.9	0.009466865	0.547397	0.003673008	0.0499467
	0.8	0.008295291	0.5533258	0.003397922	0.04700802
	0.7	0.008781784	0.5586379	0.002746877	0.04178138
	0.6	0.01073683	0.5601633	0.002548438	0.03611655
	0.5	0.009438837	0.5476537	0.001941413	0.02788683
	0.4	0.009319987	0.5656411	0.001584124	0.02520433
	0.3	0.008683168	0.5609285	0.001211573	0.0184287
	0.2	0.01094719	0.554656	0.0008810541	0.01131903
	0.1	0.009949628	0.5509336	0.0004090998	0.005739197

Table 2 shows the Johnson's S_U distribution parameters for different values of the prediction accuracy coefficient (μ_{pred}). These parameters have been calculated to give the best fit for

TABLE 3. Decimal proportion of households with higher profits in the P2P market.

	Prediction Accuracy Coefficient (μ_{pred}) Increasing energy imbalance →										
Imbalance Coefficient (μ_{imb}) Increasing prices ↓	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
0.0	1.00	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	1.00	0.98
0.1	1.00	0.93	0.89	0.87	0.89	0.84	0.81	0.77	0.74	0.74	0.72
0.2	1.00	0.83	0.89	0.83	0.79	0.71	0.59	0.52	0.47	0.50	0.41
0.3	1.00	0.81	0.77	0.79	0.65	0.59	0.44	0.37	0.31	0.23	0.13
0.4	1.00	0.95	0.77	0.58	0.51	0.36	0.17	0.26	0.14	0.18	0.08
0.5	1.00	0.87	0.60	0.51	0.30	0.26	0.20	0.13	0.03	0.08	0.02
0.6	1.00	0.82	0.71	0.39	0.22	0.17	0.07	0.00	0.03	0.00	0.00
0.7	1.00	0.85	0.53	0.24	0.21	0.09	0.10	0.07	0.00	0.02	0.00
0.8	0.98	0.78	0.55	0.16	0.14	0.10	0.02	0.02	0.00	0.00	0.00
0.9	1.00	0.81	0.44	0.15	0.14	0.05	0.00	0.00	0.00	0.00	0.00
1.0	1.00	0.57	0.38	0.12	0.07	0.03	0.02	0.00	0.00	0.00	0.00

TABLE 4. Additional profit of households in the P2P market (GBP per year, positive is additional profit in P2P market).

	Prediction Accuracy Coefficient (μ_{pred}) Increasing energy imbalance →										
Imbalance Coefficient (μ_{imb}) Increasing prices ↓	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
0.0	291.99	317.32	180.75	293.57	269.56	192.78	238.69	253.22	255.34	180.23	215.68
0.1	251.99	205.08	256.86	233.70	193.74	222.45	164.23	173.37	126.68	97.54	89.45
0.2	265.72	153.45	192.94	167.14	125.57	51.00	53.03	52.84	-12.56	21.53	-19.53
0.3	261.70	168.98	118.25	174.78	79.91	85.96	-18.99	-63.06	-96.89	-127.13	-149.20
0.4	230.55	176.87	119.89	48.73	14.88	-42.13	-141.44	-120.64	-228.71	-220.65	-359.79
0.5	207.97	156.14	66.28	0.60	-74.38	-94.82	-195.08	-240.52	-417.63	-475.41	-537.14
0.6	222.47	149.24	81.56	-36.61	-119.44	-200.36	-280.89	-336.75	-465.42	-399.94	-658.66
0.7	179.48	150.67	25.21	-58.02	-96.33	-268.21	-325.96	-385.24	-530.33	-596.20	-705.30
0.8	268.15	105.94	36.51	-138.44	-191.56	-330.71	-411.16	-630.76	-500.03	-739.21	-944.35
0.9	238.09	136.41	-8.32	-148.76	-269.70	-335.25	-570.25	-617.40	-729.28	-729.31	-1060.22
1.0	222.13	42.65	-82.79	-183.44	-319.02	-372.06	-550.64	-752.19	-903.39	-1079.69	-1109.78

the total distribution of energy imbalances for all households with each value of μ_{pred} who are not acting maliciously.

Table 3 shows the decimal proportion of households who have a higher profit in a P2P market compared to a traditional market for different values of prediction accuracy coefficient (μ_{pred}) and imbalance charge coefficient (μ_{imb}). The prediction accuracy coefficient (μ_{pred}) is multiplied by the energy imbalance, meaning low values of μ_{pred} are associated with lower energy imbalances and higher values with higher energy imbalances. Likewise, the imbalance charge coefficient (μ_{imb}) is multiplied by the imbalance price, so low values of μ_{imb} are associated with lower imbalance prices and higher values with higher imbalance prices.

Table 4 shows the average difference in profit between the P2P and traditional markets (values in pence). A positive value means the profit was higher in the P2P market, a negative value means the profit was higher in the traditional market.

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