Abstract—There has been significant recent interest in local electricity trading platforms, and particularly in the application of blockchain technology for distributed, or peer-to-peer energy trading in local energy communities. Several projects worldwide have demonstrated this concept on a small scale in Low Voltage (LV) distribution networks and microgrids. However, previous work in this area has not sufficiently addressed the potential impacts of peer-to-peer energy trading and other local electricity trading mechanisms on the control, operation and planning of the electricity distribution networks. Accordingly, this paper presents a methodology for the co-simulation of power distribution networks and local peer-to-peer energy trading platforms. The co-simulation approach uses the open-source distribution system simulator, OpenDSS for modelling the electricity distribution networks. The distribution system simulator is interfaced with a peer-to-peer energy trading simulator, which employs a blockchain-based distributed double auction trading mechanism. The presented co-simulation approach is demonstrated using a case study of typical European suburban distribution network.

I. INTRODUCTION

A number of alternative, local electrical energy trading mechanisms have been proposed in the literature. These energy trading mechanisms are designed to enable a more decentralized operation of the power system, better utilisation of grid assets, and improved integration of distributed energy resources via local energy balancing [1]–[5]. In particular, the application of distributed ledger or “blockchain” technology for peer-to-peer energy trading in microgrids and local energy communities has received significant attention [6]–[10]. Several projects worldwide have demonstrated the concept of blockchain-enabled peer-to-peer energy trading on a small-scale in Low Voltage (LV) distribution networks and microgrids [11]–[13].

However, it is currently unclear if such electricity local trading mechanisms are suitable for wide-scale implementation and what impacts these would have on the control, operation and planning of electricity distribution systems. This paper addresses this gap by presenting a methodology and software tool for the co-simulation of electricity distribution networks and blockchain-based peer-to-peer (P2P) energy trading platforms. This is achieved by detailed, three-phase modelling and simulation of typical European LV electricity distribution networks using the open-source electricity network simulator OpenDSS [14]. These distribution network models are integrated with the P2P energy trading platform. In our paper, the blockchain-assisted distributed double auction trading platform developed in [7], [8] is used to facilitate P2P trading between individual users of the LV network. This co-simulation approach provides a means of investigating the potential network impacts from various alternative trading mechanisms, including blockchain-based P2P energy trading platforms. The presented co-simulation approach is demonstrated using the IEEE European Low Voltage Test Feeder [15], which represents a typical European distribution network configuration.

The paper is structured as follows: Section II discusses the previous work on this topic. Section III provides an overview of the co-simulation approach used in this paper. Section IV describes the blockchain-based double auction approach used to simulate P2P energy trading. Section V contains the case study and results and Section VI concludes.

II. LITERATURE REVIEW

Peer-to-peer (P2P) local energy trading has been proposed as a means of efficiently coordinating large numbers of highly-distributed energy resources in power systems [16], [17]. Several authors have proposed market designs for P2P energy trading between small-scale electricity producers and consumers in distribution networks [18], [19] and in microgrids [20]. The security and privacy implications of such local electricity markets are discussed in [3] and [4].

The participation of large numbers of distributed users with flexible demands in the electricity market is a related concept, which is discussed in [5], [21], [22]. Generally, time-of-use electricity pricing has been used as a means of incentivising demand response in an efficient manner [23]. One of the issues associated with this is the possibility of reducing the load diversity factor and creating new demand peaks if all users take advantage of the same low price period [21]. Alternative electricity pricing schemes designed to mitigate against this problem and improve distribution network utilisation have been investigated in [5]. The transactive energy approach outlined in [1], [2] aims to provide a network environment for distributed energy nodes as opposed to the traditional hierarchical grid structure, and recent years have seen significant efforts towards standardisation of these techniques and ensuring wide-scale interoperability.
An approach for carrying out P2P energy trades between buyer and seller agents using a double auction mechanism is proposed in [24] and implemented using blockchain algorithms in [7]. A localised P2P energy trading model for carrying out electricity trading between Electric Vehicles (EVs) is proposed in [9]. An industrial application, with machine-to-machine based implementation of blockchain energy trading between chemical plants is discussed in [10]. A number of P2P energy trading trials and demonstration projects have also been carried out [11]–[13]. However, the scope of these projects is typically limited by regional and national electricity grid and market regulations. In all cases studied, the aim has been to develop scalable solutions, suitable for large-scale implementation [7]–[13]. However, the impacts of large-scale adoption of P2P energy trading on distribution network operation and planning are very unclear.

To the authors’ knowledge, the co-simulation of local P2P energy trading markets and electricity distribution networks has not been investigated in detail in the literature to date.

III. METHODOLOGY

In order for P2P energy trading to gain acceptance on a larger scale, it will be necessary for network operators to have the capability to model its impacts on the distribution networks, and the potential effects on network performance and reliability. The OpenDSS distribution network simulator is selected for this purpose since it is an open-source tool designed for modelling three-phase LV networks in detail and also since it is capable of interacting with the Python or MatLab software packages via an in-built Component Object Model (COM) interface. Python or MatLab can then be used to manage data input/output and automate electricity network simulation runs. An overview of the co-simulation approach used in this paper is provided in Figure 1.

The input data includes “User data”, which comprises of the demand profiles of each user in the LV network, along with EV demand profiles and/or photovoltaic (PV) generation profiles, as appropriate. The “DN data” provides the OpenDSS simulator with the necessary information of the physical structure of the distribution network, including the network layout and the characteristics of power lines, transformers, and network control elements, such as voltage regulators. The “P2P energy trading simulator” implements the distributed double auction trading mechanism described in Section IV of this paper. The “DN simulator” carries out 3-phase time series simulations of the electricity distribution network (DN) using OpenDSS [14]. Data is exchanged between each of these elements using comma-separated value (.csv) files. Finally, Python or MatLab may be used to manage data input/output and provide the post-processing and visualisation of the outputs from the network simulations. In this paper, MatLab was used to produce the results graphs shown in Section V. This co-simulation approach enables full end-to-end simulation of P2P energy trading in LV distribution networks, considering all relevant electrical network constraints (voltages, network branch loading limits, reliability and power quality requirements, and fault levels).
A double auction [8], [24] is used as a trade model for peer to peer energy trade in this paper. In double auction, buyers (who need energy) and sellers (who have excess energy) submit their reservation price (and amount of energy to buy or sell) to an auctioneer. A buyer’s reservation price is the maximum price it will pay for energy and a seller’s reservation price is the minimum price at which the seller will sell its energy. The auctioneer decides on the price for energy exchange and subsets of the buyers and sellers who will trade. McAfee’s mechanism [25] is used to determine the winner (who trades energy and at what price) of a double auction. There are several problems with a centralized double auction for peer to peer energy trade as follows:

- **Robustness**: Centralized auction is not robust as failure of the auctioneer would fail the entire trade operation.
- **Trust on the auctioneer**: The auctioneer may collude with a few peers to alter the result of the auction. Hence peers must evaluate their trust on the auctioneer.
- **Local Price**: Price for energy exchange may be determined by peers who are long distance apart from other peers. The approach in [25] is used to determine winner of the double auction. According to this mechanism the price for energy trade is determined by bids of a buyer and seller pair such that (a) buyer’s bid more or equal to the seller’s bid and (b) there is no other buyer-seller pair who satisfies the first condition. In a large network, it may happen that such a pair of buyer-seller peers are situated at distant locations from other peers. Due to long distance from other peers they may not engage in energy trade. Hence such price should not be used for energy transfer for the entire peer network.
- **Local exchange**: Peers who are located at distant locations from each other may trade energy and it will cause energy loss due to long transmission distances.
- **Security**: It is difficult to ensure security of information shared in peer to peer energy trade. Also, such a trade platform is vulnerable to cyber attacks.

The blockchain-based distributed double auction for P2P energy trade proposed in [7] and [8] is used to mitigate these problems. The blockchain mechanism [26] allows us to securely store transaction records between two peers in a peer to peer network. Security of blockchain maintained transaction record is guaranteed by encryption and distributed consensus protocol. The blockchain mechanism eliminates the requirement of a trusted third party to verify a transaction between two parties. In the proposed distributed double auction, any peer may act as the auctioneer and the blockchain mechanism ensures that each peer acts lawfully while it acts as an auctioneer.

Figure 2 shows an overview of the proposed method for P2P energy trading. It is summarised below as follows:

1) Houses equipped with energy generators form a blockchain peer to peer network for energy trade. Houses in close proximity (w.r.t the energy distribution lines) with each other become neighbours in this peer to peer network.

2) Energy surplus or deficiency information are encoded as blockchain transactions and a peer (a house) sends such a transaction to a neighbour to express its energy need. For example N1 sends the transaction T1 to N2 to express that it has energy surplus and N3 sends the transaction T3 to N2 to express its energy deficiency.

3) Upon receiving enough energy requirement information from its neighbours a peer executes the double auction winner determination algorithm. For example, N2 executes such algorithm with input transactions T1, T3, T5.

4) If a peer finds winner of such an auction then it creates appropriate transactions to reflect such winner. For example, N2 finds that N3 and N5 should consume energy and N1 should sell its excess energy. It makes transactions T1′, T3′1 and T3′3 to reflect this result.

5) If a peer fails to determine the winner of a double auction then it forwards its unspent transactions to another peer. For example, N4 received the energy deficiency information from N5 as the transaction T5 but it could not solve the double auction. Hence N4 forwards such information to N3 as the transaction T3, who solves the double auction.

For a detailed description of the double auction method, the reader is referred to [7] and [8]. Note that the outcome of an auction only indicates how much energy a peer should consume or contribute. But the actual energy consumption may be different and it will be recorded as transaction with Requirement field 0. We propose to create smart contract for payments. Given the result of each auction, the peers can form a smart contract among them. For example if the result of the auction states that peer mi should sell x units of energy at
price \( y \) between time \([t_1, t_2]\) and \( m_j \) should buy \( x \) units of energy at price \( y \) between time \([t_1, t_2]\) then, the smart contract will involve two parties \( m_i \) and \( m_j \), it will be funded by \( m_j \) with crypto-currency of value \( x \times y \). This smart contract will be triggered by energy consumption information from \( m_i \) and \( m_j \) and such information will decide the actual payment. For example, say \( m_i \) only contributes \( x_1 < x \) units of energy. Hence it will be paid \( x_1 \times y \) tokens and \((x - x_1) \times y \) tokens will be sent back to \( m_j \). Such a crypto-currency can be part of the blockchain infrastructure for energy trade and peers must buy these tokens with any other currency (i.e. € or $). However, the tokens used for energy trade information and auction are free as each peer is endowed with fixed number of tokens to express their future energy needs and actual energy consumption every day at a fixed time. Sidechains [27] can be used to implement this form of payment for peer to peer energy trade. Finally, each peer calculates its own energy requirement using weather and historical energy supply demand information. Intentional mismatch between the announced energy requirement and the actual energy consumption may affect the performance of any peer to peer energy trade. The blockchain keeps secure records of such information and any such malicious behaviour can be identified. Hence the proposed solution is a deterrent of such malicious behaviour.

V. CASE STUDY AND RESULTS

A. Case Study and Distribution Network Simulation Input Data

The distribution network impacts of local P2P energy trading schemes are investigated using a case study carried on the IEEE European Low Voltage Test Feeder [15]. This test network represents a typical three-phase European LV suburban residential system, and includes residential demand data based on actual measurements from residential LV customers in the Distribution Network. The DN layout and a sample of the demand data for each residential user connected to the network are shown in Figure 3.

![Fig. 3. Distribution network test case: (a) Layout of IEEE LV test system; (b) Load profiles for 55 individual users.](image)

In order to examine a future network scenario with a very high penetration of distributed energy resources, and to create opportunities for P2P trading, PV generation and EV charging demands were added to the IEEE European LV test network. Residential PV units are modelled as active power injections at each load point in the PV network. The PV production data is based on actual measurements of rooftop PV outputs at residential homes recorded by domestic smart meters in the SmartHG project [28]. The PV units use maximum power point tracking and operate at fixed unity power factor. The EV charging data used in this paper is taken from actual vehicle charging data from the Test-an-EV project [29]. Figure 4 shows a sample of the PV injections and EV charging demands taken from [28] and [29].

![Fig. 4. Samples of input data: (a) PV injections; (b) EV charging demands.](image)

In the DN simulation, a five minute time step was used in order to allow analysis of the changes in network power flows and voltages over the course of one day. Two cases are analysed below:

- **Base Case**: DN simulation is carried out at using the demand profiles, EV charging demands and PV generation outputs described in Figures 3 and 4, with no P2P energy trading.

- **P2P Case**: DN simulation is carried out at using the same input data, and applying the P2P energy trading based on the double auction mechanism described in Section IV.

The results presented in Section V-B below provide an analysis of the impacts on the LV test network over the course of one entire day, using the demand profiles in Figure 3b, the PV generation profiles in Figure 4a and the EV charging demands in Figure 4b. The co-simulation approach outlined in Figure 1 and Section III is used for both Base Case and P2P Case described above.

B. Distribution Network Simulation Results

Figures 5 and 6 show the active and reactive power import/export recorded at the MV/LV substation transformer in the OpenDSS network simulation. Since the case study has a very high PV penetration, there is a net export from the substation in the middle of the day, and hence kWh and kvarh values are negative during these time steps. The largest number of P2P energy trading transactions occur between the time steps 200 and 230 (see dashed lines in Figures 5 and 6), which approximately corresponds to the hours 17:00 to 20:00 in the day. It can be seen that the P2P energy trading has a significant impact on the kWh and kvarh flows in each phase during these times.

A summary of the results from the DN simulations is given in Table I. These results show that the net energy exported from the test DN is increased by approximately 19 kWh.
over the course of the day in the P2P case. The reactive power imported into the test DN is reduced by more than 13 kvarh. No significant change is observed in the maximum instantaneous kVA power demand (which occurs in the late evening and is driven by EV charging load), or in the network active power losses over the 24 hour period test as a result of the P2P energy trading.

The impact of P2P energy trading on DN voltages can also be measured using a voltage unbalance metric, which describes the differences between the magnitudes of the voltages in each phase of the three-phase LV distribution system. In this paper, the IEEE definition of voltage unbalance is applied. This is defined in [30] as the Phase Voltage Unbalance Rate (PVUR), the maximum voltage deviation from the average phase voltage as a percentage of the average phase voltage. PVUR is slightly reduced in the P2P Case (8.665%) as compared to the Base Case (8.866%), Table I.

<table>
<thead>
<tr>
<th>Simulation result [Units]</th>
<th>Base Case</th>
<th>P2P Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net energy exported [kWh]</td>
<td>-40.06</td>
<td>-59.12</td>
</tr>
<tr>
<td>Reactive power imported [kvarh]</td>
<td>41.07</td>
<td>34.85</td>
</tr>
<tr>
<td>Max complex power [kVA]</td>
<td>148.73</td>
<td>149.32</td>
</tr>
<tr>
<td>Active power losses [%]</td>
<td>3.33</td>
<td>3.40</td>
</tr>
<tr>
<td>Phase Voltage Unbalance Rate [%]</td>
<td>8.866</td>
<td>8.665</td>
</tr>
</tbody>
</table>

Figures 7 and 8 illustrate the voltage profiles for all 55 users connected to the network for the Base Case and P2P Case respectively. In order to simplify the voltage analysis and to enable direct comparison between the voltages in each case, a
fixed voltage of 1.0 per unit was assumed at the MV side of the MV/LV substation transformer. These results demonstrate that the proposed co-simulation approach allows us to analyse the impact of DN voltages of P2P trading. The user voltage profiles in the Base Case and P2P Case are similar during time steps where there are few P2P transactions. The most significant changes in voltage again occur during the time steps from 200 to 230 in Figures 7 and 8 (in the late afternoon/early evening between the hours of 17:00–20:00).

VI. CONCLUSIONS

P2P energy trading schemes are designed to allow network users to trade with their neighbours in order to balance energy surpluses and shortfalls locally. This is expected to improve distribution network asset utilisation and network integration of renewable energy sources. The co-simulation approach presented in this paper provides a means of assessing the feasibility of large-scale adoption of P2P energy trading schemes, analysing their impacts on the distribution network, and validating their potential benefits. The analysis presented in Section V demonstrates that this co-simulation approach can be used to analyse the impacts of P2P energy trading on network power flows and voltages.

In this paper, the distribution network analysis is carried out over the course of one 24 hour period and does not examine the sensitivity to day types and seasonal factors. Future work will address these issues, and provide a more complete analysis of the impacts of various P2P energy trading mechanisms on network asset utilisation, reliability and power quality. The overall aim of this work is to examine the medium to long-term effects of P2P trading on distribution system planning and operation, and compare this with traditional, centralised market arrangements.

VII. ACKNOWLEDGEMENTS

The authors acknowledge the support of the International Energy Research Centre (IERC) project “EnerPort: Peer to Peer Energy Trading in the Distributed Grid using Blockchain Technology”, funded by Enterprise Ireland (contract reference number TC-2013-0002B) and the contributions from the EnerPort industry partners Systemlink Technologies Ltd., mSemicon Teoranta, and Verbatim.

REFERENCES


