ISSN 2004-2965 Energy Proceedings, Vol. 22, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, in Thailand/Virtual
Paper ID: 572

Impact of Local Electricity Market in the Low Voltage Distribution Network

A. U. N. Ibn Saif[1,2*], Shafi K Khadem[1], Michael Conlon[1] and Brian Norton[1,2]

1 International Energy Research Centre, Tyndall National Institute, Cork, Ireland

2 Technological University Dublin, Dublin, Ireland

ABSTRACT

This paper explores the impact of the local electricity market (LEM) in a low-voltage distribution network. At first, a LEM model is established in parallel to the retail electricity market (REM), which enables the customers to engage in trading without considering the network constraints. The motivation of the proposed LEM is to minimise the financial transactions associated with the energy exchange with the electricity retailer by boosting local trading. Subsequently, the LEM model is superimposed to the low voltage distribution network (LVDN) model to understand the impact of the local electricity trading on the LVDN operational performances. The proposed LEM reveals a decline of grid supply by 7.32% and thus increase clean energy local consumption. On the contrary, voltage profiles at certain nodes deteriorate as a result of the LEM. Real-life measured data from an energy community in Ireland is considered for the study where all the participating customers are equipped with energy storage and part of them have PV.

Keywords: local electricity market, peer-to-peer transactions, low voltage grid, network impact

1. INTRODUCTION

The rapid share of distributed energy resources (DERs) connected to low-voltage (LV) and medium-voltage (MV) distribution networks (DN) are pushing the transformation of existing energy systems towards a decentralised, decarbonised and digitalised one. A significant portion of DERs is located at or near the end-users. To facilitate the integration of DERs, a consumer-centric approach is stressed in the EU SET-Plan where consumers are placed at the centre of the energy transition [1]. This has led to a significant interest in a consumer-centric market for electricity customers, especially small-scale residential customers. Currently, residential customers have only engagement in REM where consumers have a long-term contract with electricity retailer [2]. This type of contract specifies the electricity price as fixed-rate or time-of-use prices [3]. The existing REM structure offers very little opportunity to its customers with active participation in the energy transition. The LEM is an emerging and consumer-centric market approach that enables electricity customers to trade electricity among consumers, producers and prosumers within the regulatory boundary of the energy community. Apart from the empowerment of electricity customers with more active participation, LEM also comes up with multi-benefits, e.g. efficient utilisation of DERs, local consumption of locally generated, mostly green electricity, economic savings for local market participants etc. [4]. However, traded electricity in LEM is transported through the physical electrical networks and therefore requires to respect network constraints. It is of paramount importance to investigate the impact of local electricity trading on network operational performance.

Over the past years, several studies have been conducted on the coordination of modelling of LEM and distribution network constraints [5]. The most prominent method is AC optimal power flow (OPF) where network constraints are formulated as AC branch flow equations in the local market clearing problem [6]. Due to the non-convexity and computational burden, approximation and convex relaxation have been applied on AC OPF. Linearised DC approximation is one such representation where line loss and reactive power flow are neglected. The authors in [7] have proposed their studies based on DC optimal power flow. However, such market design has challenges in implementation as it requires an entity aware of both market participants and grid topology.

In [8], authors consider only power losses in the power lines as network constraints and include these in the LEM formulation. [9] present network constraints in terms of sensitivity factors and additional costs, calculated based on sensitivity factors, are assigned in the peer-to-peer (P2P) transactions to avoid network constraints. An alternative approach lies where power flow is performed separately and subsequently after LEM is cleared and power flow is performed to assess network operational performance. [10] demonstrates the impact of local market trading, based on distributed double auction mechanism, on the network operational performance. [11] investigates LEM model alleviating network congestion for DSO using prosumers' flexibility.

This study is inspired by [12] but considers a real-life local energy community located in Ireland where all the LEM participants are equipped with ES. Network performance has been analysed on IEEE low-voltage European distribution test feeder. The proposed LEM has been considered to operate under the existing REM and pricing in Ireland to achieve realistic results. All the participants in the community have residential energy storage (ES) in their premises with half of the participants also having roof-top PV systems. It has allowed a comprehensive analysis of the role of different DER assets, such as PV and ES in combined and separate operating modes, on the LEM trading and consecutively on the LVDN.

The rest of the paper is organized as follows: Market architecture and modelling approaches have been presented in Section 2. Section 3 presents descriptions of the test scenario followed by the simulation results and analysis. Finally, conclusions are drawn in Section 4.

2. METHODOLOGY

2.1 Market Architecture

The LEM envisioned in the paper is focused on the residential electricity customers, typically under the REM. The proposed LEM provides an alternative for customers to engage in P2P transactions among themselves to reduce dependency on electricity purchases from the REM. The study also investigates how the flexibility emanating from residential battery ES stimulates the local trading of electricity and how it impacts the network.

It is logical that LEM participants collectively will not have self-sufficiency across all market periods in the operational time horizon. This necessitates an arrangement to provide excess/deficit energy from the central electricity market to maintain the security of supply. To clarify the case, the deficit/excess energy mentioned above refers to the amount of energy in deficit or excess respectively on customers' level after local P2P transactions are settled. This work considers that electricity retailer is responsible to meet the surplus/deficit energy of market participants in business as usual way. The other key actors are: local electricity market operator (LEMO), distribution system operator (DSO). The role of LEMO involves managing the P2P transactions among the market participants to reach the goal of the LEM. Market participants in the LEM are the electricity customers: producers, prosumers and consumers. DSO ensures the P2P transactions in the local market operation is adhering to the technical constraints of the network. Fig. 1 illustrates a schematic diagram of the LEM considered in the study.

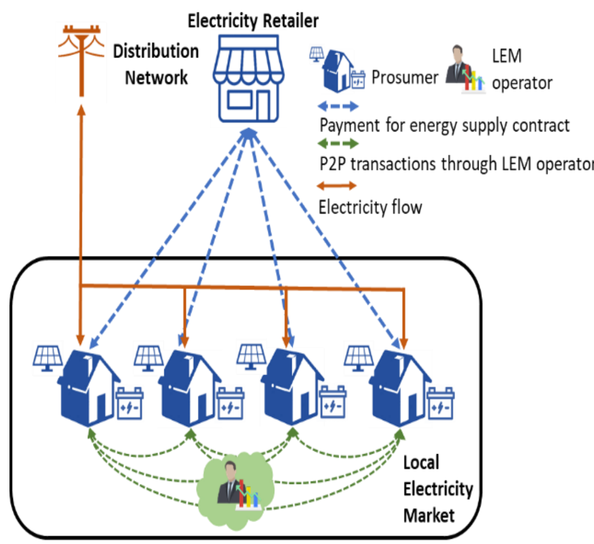

Fig. 1. Local Electricity Market architecture

The LEMO controls the P2P transactions based on the forecasted generation and consumption profiles along with status and characteristics of DER assets, e.g. state-of-charge of batteries, maximum charging/discharging limits etc. LEM is considered to have interaction with REM only and no direct involvement with the wholesale electricity market (WEM).

2.2 Modelling approach

To study the LEM and its impact on LVDN performance, the LEM model has been superimposed on the LVDN model. The LEM model has been created to minimise the cost of procuring electricity and maximise the revenue from exporting energy to the grid under the REM. A linear multi-period optimisation model has been formulated for a set of market participants, $P =$

$\{1,2,\ldots\ldots,N_p\}$ across a market horizon, T with trading period denoted by t having market time duration ΔT to describe the LEM framework. The objective function of the problem is given by equation (1),

$$\operatorname*{Min}_{P_{p,t}^{Im},P_{p,t}^{Ex}} \sum_t \left(\sum_p \lambda_t^{Im} P_{p,t}^{Im} - \sum_p \lambda_t^{Ex} P_{p,t}^{Ex} \right) \Delta T \qquad (1)$$

where, λ_t^{Im} is the time-of-use retail electricity price, λ_t^{Ex} is the grid feed-in tariff, $P_{p,t}^{Im}$ represents the amount of electricity procured from the grid and $P_{p,t}^{Ex}$ represents electricity sold to the grid. The first term of the objective function represents the cost function related to buying electricity from REM under time-of – use tariff scheme. The second term refers to the revenue function denoting electricity exported to the grid at a feed-in-tariff rate.

The objective function is subjected to several constraints. Power balance constraints for each market participant needs to be respected for each trading period, t. This constraint ensures that the summation of injected power in terms of grid import $P_{p,t}^{Im}$, purchased electricity through P2P transactions from other market participants $\sum_{q\neq p} P_{q\to p,t}^{P2P\ buy}$, battery discharge $P_{p,t}^{dis}$ and self-generated power $P_{p,t}^{gen}$ (if available) must satisfy the load $P_{p,t}^{dem}$, battery ES charging $P_{p,t}^{ch}$, sold electricity in P2P transactions to others $\sum_{q\neq p} P_{p\to q,t}^{P2P\ sell}$ and grid export $P_{p,t}^{Ex}$.

$$P_{p,t}^{Im} + \sum_{q\neq p} P_{q\to p,t}^{P2P\ buy} + P_{p,t}^{dis} + P_{p,t}^{gen} = P_{p,t}^{Ex} + \sum_{q\neq p} P_{p\to q,t}^{P2P\ sell} + P_{p,t}^{ch} + P_{p,t}^{dem} \qquad (2)$$

The latter constraint is more focused on the balance constraint on P2P transactions inside LEM. This constraint guarantees that total electricity purchased through P2P transactions should be equal to electricity sold in P2P transactions at each trading period t.

$$\sum_p \sum_{q\neq p} P_{q\to p,t}^{P2P\ buy} = \sum_p \sum_{q\neq p} P_{p\to q,t}^{P2P\ sell} \qquad (3)$$

where, $P_{q\to p,t}^{P2P\ buy}$ corresponds to the electricity purchased by house p from peer q in the local market and $P_{p\to q,t}^{P2P\ sell}$ corresponds vice-versa.

Battery ES is one of such key DER assets and is considered her to study their impact on market outcome. The charging power $P_{p,t}^{ch}$ and the discharging power $P_{p,t}^{dis}$ of the battery ES is limited by the inverter size. The upper and lower limit of state-of-energy $E_{p,t}$ is bounded by battery capacity.

$$P_{p,t}^{ch} \leq P_p^{ch,max} \;\; ; \;\; P_{p,t}^{dis} \leq P_p^{dis,max} \qquad (4)$$

$$\underline{E_p} \leq E_{p,t} \leq \overline{E_p} \qquad (5)$$

where, $P_p^{ch,max}$ and $P_p^{dis,max}$ are maximum charging and discharging power respectively. $\overline{E_p}$ and $\underline{E_p}$ represent upper and lower limits of the battery capacity. A simplified linear formulation is used to model battery storage. It is assumed that the charging/ discharging power is constant during the trading period and the state of energy of the battery $E_{p,t}$ is governed by,

$$E_{p,t} = E_{p,t-1} + \eta_p^{ch} P_{p,t}^{ch} \Delta T - P_{p,t}^{dis} \left(\frac{1}{\eta_p^{dis}} \right) \Delta T \qquad (6)$$

where, η_p^{ch} and η_p^{dis} are the charging and discharging efficiency of battery storage.

Modelling of LVDN is required to conduct power flow simulation on each trading period of the market outcome horizon. Power flow simulation examines the feasibility of LEM trading from the network operational perspective. The electricity customers may be LEM participants or non-market participants. For market participants, the load node profiles are created from net injection profiles, $P_{p,t}^{inj}$ calculated by,

$$P_{p,t}^{inj} = P_{p,t}^{Im} + \sum_{q\neq p} P_{q\to p,t}^{P2P\ buy} - P_{p,t}^{Ex} - \sum_{q\neq p} P_{p\to q,t}^{P2P\ sell} \qquad (7)$$

Hence, the load node profile is the net profile calculated from the difference of the sum of the active power imported to the node and the sum of the active power exported from the node. The operation of the battery ES is considered taking place behind the meter and therefore not included in equation (7). The rest of the load node profiles connecting non-market participants are typical consumption profiles. The power flow model requires not only active power profiles but the reactive power profiles as well, though the LEM model only deals with active power profiles. The reactive power profile is obtained from the active power profile considering a constant power factor.

3. CASE STUDY

3.1 Test scenario descriptions

The data set used for LEM in the case study, are real-life measurements from twenty smart homes located in the Dingle area in Ireland [13]. All of those smart homes are equipped with 10kWh/3.3 kW peak lithium-ion batteries. The efficiency of the battery ES is assumed to be independent of state-of-charge level and constant throughout the charging and discharging cycle. Both charging and discharging efficiency are 95%. 9 out of the 20 smart homes have roof-top PV with a capacity of 2.1 kW. The measurements used in the study encompasses the entire month of June 2020. All those 20 houses have been considered as market participants of the LEM and market simulation is performed based on the real-life measurement data set. ES operation is based on the market optimisation algorithm.

As discussed in 2.1, the proposed LEM depends upon the existing REM pricing scheme in Ireland. The day-night retail pricing comprises wholesale energy cost, supplier's cost, grid tariff and government taxes, levies [14]. In 2020, domestic consumers in Ireland with day-night pricing were charged as 20.07 cEUR/kWh and 9.91 cEUR/kWh respectively. Exporting of the electricity to the grid is assumed on the fixed tariff of 9 cEUR/kWh. The study considers trading happens in hourly resolution in the LEM model.

The IEEE European low voltage test feeder is taken as a test network, which is a radial, 3-phase distribution feeder [15] and is supplied by an 11 KV/0.416 KV substation having a capacity of 0.8 MVA and delta/grounded-wye connection. The test feeder consists of 906 buses and 55 connection points (load nodes) for single-phase residential customers. Twenty LEM participants are allocated at different connection points and the rest of the connection points are connected with non-LEM participants: pure consumers having no DER assets. In alignment with the temporal resolution of the LEM model, the power flow simulation is also conducted on hourly resolution.

3.2 Simulation results

There are two test cases considered in this paper: 1) Base case: This is the business-as-usual scenario where no local market exists. The ES and PV are utilised by the home EMS to minimise the cost of buying electricity from the grid. 2) Local market case: the customers are engaged in the trading of electricity based on the LEM approach described in Section 2.2. LEM model is implemented in MATLAB environment using optimisation modelling language YALMIP, MOSEK solver and OpenDSS is used for the LVND modelling. A summary of results obtained from the two test cases is provided in Table 1.

Table 1 Summary result of Local Electricity Market

	Base case	Local Market
Total Cost (€)	587.15	514.46
Grid supply (KWhr)	5601.167	5191.359
Grid feed-in (KWhr)	380.362	0
P2P transaction (KWhr)	-	1051.646
Cost of grid supply (€)	621.37	514.46
Revenue from grid feed-in (€)	34.23	0

Trading in LEM enables local energy communities to reduce their dependency on electricity imported from the grid, as shown in Table 1 with grid supply declining by 7.32%. LEM also causes its' participants with excess electricity to engage in P2P transactions with other market participants rather than exporting electricity to the grid at feed-in tariff. As a result, grid feed-in drops to zero with the introduction of LEM. It demonstrates that the LEM promotes the consumption of locally generated electricity, which is predominantly green energy. It can also be noted that the amount of P2P transactions is higher than the amount of grid feed-in in base case. Due to the presence of ES, energy arbitrage is also taking place as many participants buy electricity from the grid at lower tariff hours to sell to other participants at high-tariff hours.

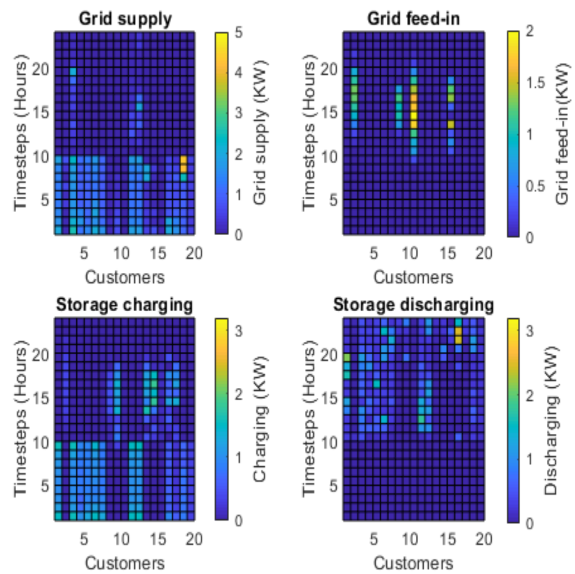

Fig. 2. Grid interaction and storage operation in base case.

For a detailed analysis of market outcome, storage operation and the interaction of market participants with grid and other peers, we focused on 24 hours' operation of June 21, the day with maximum PV generation in June 2020. Fig. 2 shows that the customers mainly buy electricity from the grid up to 10:00 am and charge their ES in the base case. This is because of the lower tariff from midnight up to hours 10:00 and motivates the customers to charge their ES in early hours to utilise stored electricity for the rest of the day (when the electricity price is high) to meet their demand. As the base case does not have provisions for P2P trading, customers with PV and ES (customers 2, 8-10 and 13-15) buys less electricity from the grid compared with the customers with ES only as can be seen in Fig. 2. This is evident as customers with PV and ES cover a certain share of their demand from self-generated electricity. Some of the customers with excess energy (customers 2, 8, 10 and 15) sells electricity back to the grid at a feed-in tariff.

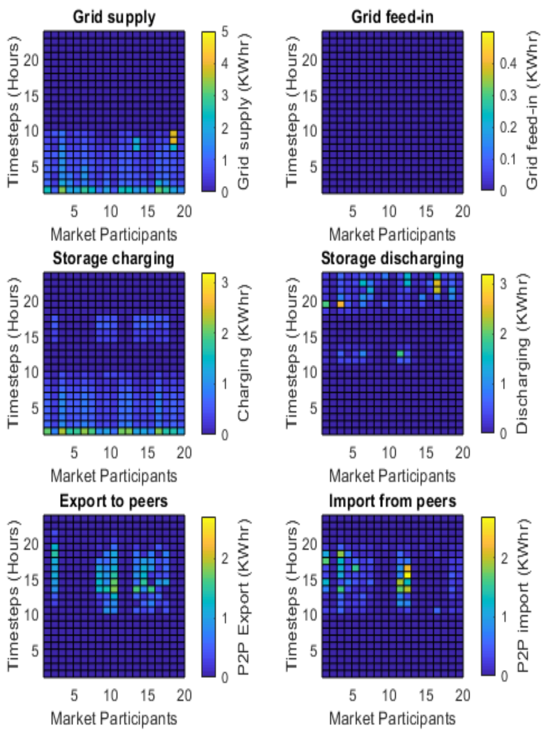

Fig. 3. Grid interaction, storage operation and P2P transactions in local market case.

In the LEM test case, there is no grid feed-in happening, as seen in Fig. 3, and the customers acting as market participants are now engaged in trading among peers instead of selling back to the grid. Another interesting observation from grid supply in Fig. 3 is that market participants with PV and ES are also buying electricity from the grid at low tariff hours to charge storage facilities. For the rest of the day, the stored energy is used to meet their demand and/or to sell excess electricity to other market participants in need, usually market participants with ES only. This is a typical manifestation of energy arbitrage based on the differential retail tariff across the day boosted by the provision of local trading among peers.

Table 2 Summary results of network simulation

	Base case	Local Market
Total active power flow (KWhr)	18086	18072
Total reactive power flow (KVARhr)	5916	5909
Active power losses (in %)	0.9344	0.9794

Table 2 shows that the LEM does not change significantly the active and reactive power flow in the feeder downward of substation across the entire simulation period. Though LEM is successful in maximising local consumption of locally generated electricity and reduction in electricity supplied by the grid (through substation) as presented in Table 1, P2P transactions have contributed significant power flow across the feeder and hence the power losses have increased.

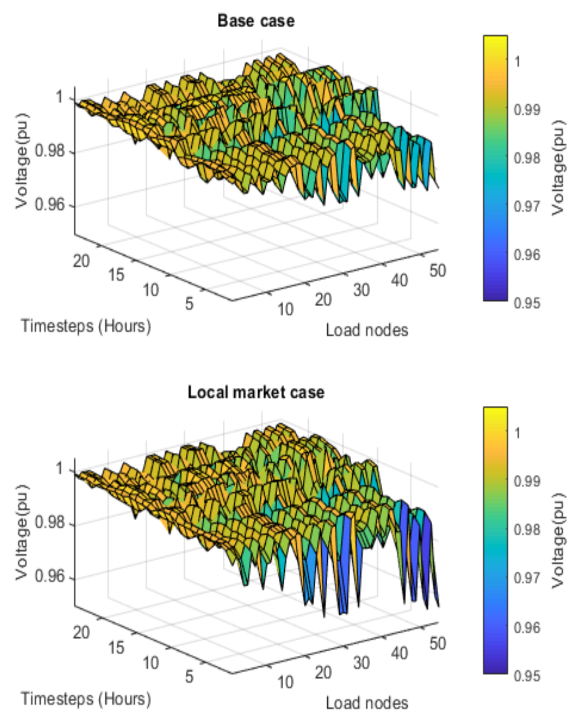

Fig. 4. Voltage profiles of all load nodes for the day with maximum PV generation.

Fig. 4 illustrates the impact of trading in LEM on the voltage profiles at the load node points. In general, voltage profiles have deteriorated with the implementation of the local electricity market with worse being at hours 00:00 associated with high grid supply.

To better understand the impact of LEM on voltage for the entire simulated month, the frequency distribution of voltage of all the nodes for both cases is presented in Fig. 5. It is observed that the voltages at some of the hours within the voltage band of 0.984-0.994 (marked in the green box) are pushed to the edges due to the introduction of LEM. Though this does not cause any extension in the overvoltage side, however, the voltage at certain hours (around 100 hours) is reaching close to the lower limits as shown on the under-voltage side (marked in red box). It needs to be mentioned that in any of the cases, the voltage is actually not violating the $\pm 10\%$ threshold limits that are existent in the distribution grid code. Nevertheless, with more penetration of LEM participants in the distribution grid, the observed situation is expected to exacerbate, demanding the measures from DSO.

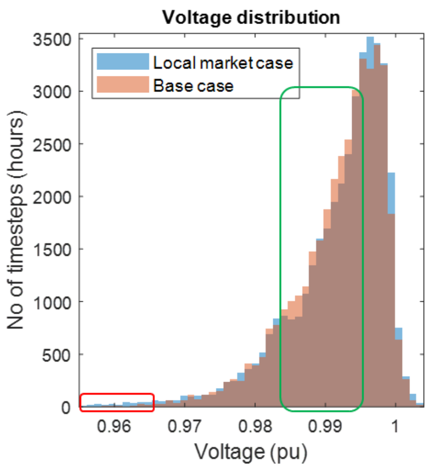

Fig. 5. Voltage distribution for all nodes, June 2020.

4. CONCLUSIONS

The paper presents an electricity market model for the local energy community with customers all having battery storage and part of them with PV systems. The proposed LEM succeeds in reducing the cost associated with buying electricity from the grid through P2P transactions. LEM also enables local consumption of locally generated, green electricity. This paper also analyses the impact of LEM on the LV network hosting the market participants. As the market formulation does not consider network constraints, aggregated active, reactive power flow and active power loss across the simulation horizon has not undergone a significant change after the introduction of the LEM. Voltage profiles have seen deterioration at certain load nodes due to the change of battery storage schedule prompted by the LEM.

Though the network has not incurred major network limits violations for the number of market participants, however, the result implies that scaling up the number of market participants in the host feeder will provide more insights on network operational performance. An extension of this work is investigating the LEM algorithm adapted to deal with the uncertainty of DER assets to demonstrate the extended impact study concerning the 3 phase network unbalance issues.

ACKNOWLEDGEMENT

This work is partly supported by BEYOND project, funded by joint programming initiative ERA-Net Smart Energy Systems, EU Horizon 2020, grant agreement no 775970 and IEA task GO-P2P. The authors in IERC thankfully acknowledge the support from the Department of the Environment, Climate and Communications and the Sustainable Energy Authority of Ireland.

REFERENCES

[1] European Commission, "The strategic energy technology (SET) plan," Luxembourg: Publications Office of the European Union, 2019.

[2] R. Wilson, "Architecture of power markets," *Econometrica,* vol. 70, no. 4, pp. 1299-1340, 2002.

[3] C. Defeuilley, "Retail competition in electricity markets," *Energy Policy,* vol. 37, no. 2, pp. 377-386, 2009.

[4] A. Ibn SAIF and S. K. Khadem, "Consumer-centric Electricity Market: Review of key European projects," in *17th International Conference on the European Energy Market (EEM)*, Stockholm, 2020.

[5] S. Bjarghov et al., "Developments and Challenges in Local Electricity Markets: A Comprehensive Review," *IEEE Access,* vol. 9, pp. 58910-58943, 2021.

[6] T. AlSkaif and G. van Leeuwen, "Decentralized Optimal Power Flow in Distribution Networks Using Blockchain," in *International Conference on Smart Energy Systems and Technologies (SEST)*, Porto, Portugal, 2019.

[7] . J. Qin, R. Rajagopal and P. Varaiya, "Flexible market for smart grid: Coordinated trading of contingent contracts," *IEEE Transactions on Control of Network Systems,* vol. 5, no. 4, pp. 1657-1667, 2017.

[8] M. L. Di Silvestre and e. al., "A Technical Approach to the Energy Blockchain in Microgrids," *IEEE Transactions on Industrial Informatics,* vol. 14, no. 11, pp. 4792-4803, 2018.

[9] J. Guerrero, A. C. Chapman and G. Verbič, "Decentralized P2P Energy Trading Under Network Constraints in a Low-Voltage Network," *IEEE Transactions on Smart Grid,* vol. 10, no. 5, pp. 5163-5173, 2019.

[10] B. P. Hayes, S. Thakur and J. G. Breslin, "Co-simulation of electricity distribution networks and peer to peer energy trading platforms," *International Journal of Electrical Power & Energy Systems,* vol. 115, p. 105419, 2020.

[11] R. Faia, T. Pinto, Z. Vale and J. M. Corchado, "A Local Electricity Market Model for DSO Flexibility Trading," in *2019 16th International Conference on the European Energy Market (EEM)*, Ljubljana, Slovenia, 2019.

[12] A. Lüth, J. M. Zepter, P. C. del Granado and R. Egging, "Local electricity market designs for peer-to-peer trading: The role of battery flexibility," *Applied Energy,* vol. 229, pp. 1233-1243, 2018.

[13] ESB Networks, "The Dingle Project," [Online]. Available: https://www.esbnetworks.ie/who-we-are/innovation/esb-networks'-dingle-project. [Accessed 03 September 2021].

[14] CRU, "Domestic Electricity and Gas Bills in Ireland," [Online]. Available: https://www.cru.ie/wp-content/uploads/2020/12/CRU20125-Factsheet-Domestic-Electricity-and-Gas-Bills-in-Ireland-CRU20125.pdf. [Accessed 08 June 2021].

[15] IEEE PES AMPS DSAS Test Feeder Working Group, "European low voltage test feeder," [Online]. Available: https://site.ieee.org/pes-testfeeders/. [Accessed 10 September 2021].