A Win-Win Local Energy Market for Participants, Retailers, and the Network Operator : A Peer-to-Peer Trading-driven Case Study

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***Abstract*— What are the outcomes of using a local energy market (LEM) to trade electricity between participants, retailers/suppliers and the network operator? Such a question is becoming increasingly important for electrical grids as more and more solar photovoltaics (PVs) and battery energy storage systems (BESS) are introduced. This paper presents the formulation and economic analysis of a peer-to-peer (P2P)-driven LEM to determine its suitability for each of the players in the market. To do so, a framework is proposed to define the objective function of the LEM while the financial and network parameters are considered. Then, the designed model is deployed on an actual Australian suburb containing 300 participants — 200 consumers, 50 prosumers with solar PVs, and 50 prosumers with solar PVs and BESSs. This research examines the case of two retailers/suppliers and the network operator to evaluate the financial gains which are compared to the business-as-usual (BAU), where consumers buy electricity from the grid while prosumers sell excess energy back to the grid, via feed-in-tariff (FiT) mechanism. The simulation results emphasise that with a LEM: 1) all participants save money, with prosumers owning solar PVs and BESSs gaining the most; 2) the income margin of the retailer with only consumers remains unaffected, but it is slightly increased for other retailer with prosumers; and 3) the network operator sees a slight increase in its income and grid congestion will reduce.**

Keywords*— prosumer, solar PV, BESS, retailer, network operator, local energy market, P2P energy trading.

I. Introduction

In recent years, due to the rapid intake of solar in the distribution grid, several electricity customers are turning into prosumers [1]. These prosumers could have numerous goals in mind, such as becoming self-sufficient, reducing energy cost, dispatching flexibility, and attaining sustainability [2-3]. They are also required to maximise self-consumption, or curtail or sell their excess energy to the grid while purchasing energy deficit from the grid through suppliers or retailers [4]. This transition could bring a lot of benefits for different electricity stakeholders, and to materialise the implementation, a number of policy and regulation-related changes might be required.

Thus the concept of local energy market (LEM) has emerged [5]. A LEM is typically a marketplace that balances local supply and demand, and uses a decentralised approach to carry out peer-to-peer (P2P) energy transactions [6-7]. P2P energy trading is a part of LEM. P2P allows flexible energy trading between different consumers and prosumers without the involvement of a third party market operator [8]. Most of the research in P2P energy trading is concentrated in the user-centric direction. This means that such research identifies methods to motivate consumers and prosumers to join in the P2P framework. In such a research, end-users' preferences are considered so that they can select exchanged quantity, price, and trading partners while settling bilateral transactions in competitive markets [9].

In fact, prosumers, who are located at a defined electricity network topology, are provided with the flexibility to declare their preferred P2P trading time in the LEM [10]. The electricity cost reduction is marked as one of the most influential factors [11-12], in that it can accelerate the users' participation in the LEM to carry out P2P transactions. Research demonstrated in [13-14] shows that energy requirements are increasing with the times, and accordingly, renewable penetrations are accelerating in distribution networks. Therefore, it is very important to correctly design and manage the renewables with respect to load and grid requirements [15]. A well-functioning decision-making strategy is prioritised in [16] to ensure adequate monetary gains for the users. The authors in [17-18] used ToU tariff and recommend to trade at a price that is lower than the time-of-use (ToU) price but higher than the feed-in-tariff (FiT) price. The purpose is to benefit both participating buyers and sellers compared to the business-as-usual (BAU). A case study conducted in [19] highlights those buyers and sellers can obtain 12.61% and 4.36% savings, respectively, by involving in P2P trading. However, these articles do not take the interests of the retailers into account.

On the contrary, some research studies, very limited compared to the user-centric ones, also focus on developing P2P mechanisms that try to integrate retailers. This is important as retailers are responsible to supply electricity to end-users, and thus disregarding them could call off all the efforts paid in recent years to establish P2P trading as a lucrative model [20]. As such, the fundamental features of a retailer-integrated LEM are discussed in [21]. A futuristic

Fig. 1. Map of Australia showing the location of New South Wales (NSW) state.

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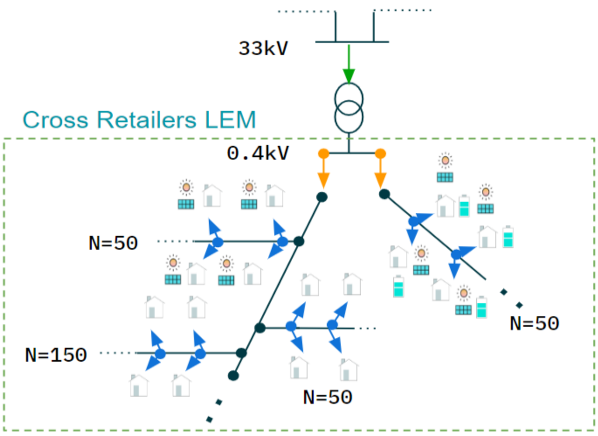

Fig. 2. Network architecture for the proposed LEM.

retailer-based LEM strategy is also proposed in [22-23], where the role of a retailer is played by the aggregated prosumers. However, these retailer-centric studies can be extended by guaranteeing economic benefits for the consumers and prosumers.

To this end, this paper stresses the importance of including retailers in the LEM, in which consumers and prosumers trade through P2P negotiations for maximum possible monetary gains. Some prosumers are also equipped with battery storage systems (BESSs) to increase trading flexibility in the market, resulting in greater financial returns. The proposed LEM model is simulated using actual energy and price data to evaluate the electricity cost reduction for consumers, prosumers, and prosumers with BESS, as well as income margin for retailers, and income for the network operator. The main twofold contributions of this paper are summarised as follows:

- A framework is proposed to integrate consumers, prosumers, retailers, and the network operator in the LEM so that the conducted P2P transactions remain valid in practice.
- A case study is performed with actual energy and price data and compared with the business as usual (BAU) to demonstrate the monetary gains for all participants, retailers, and the network operator.

The remainder of this paper is organised as follows. Section II provides the brief introduction of the LEM model. Cross retailer trading is described in Section III. The following section-IV formulates the methodology to solve market design. Results and analysis are given in Section V. Finally, concluding remarks are outlined in Section VI.

II. Development of a Local Energy Market

In an electrical network, a LEM gives the option to each consumer and prosumer to fulfil their energy requirement by performing P2P energy trading with each other. Participants have options to do traditional trading BAU and P2P energy trading to get maximum benefit with their access power. Poweledger has designed a P2P-based LEM platform using its own technology [24]. LEM platform enables participants to put their buy and sell offers in forward-facing time intervals. The case model was based in New South Wales (NSW), as shown in Fig. 1, AusGrid open access residential data [25-26]. Grid architecture as shown in Fig. 2 consists of 300 participants, 200 are consumers, 50 are prosumers with solar PV systems, and 50 prosumers are with solar PV systems and BESSs. The installed average capacity of solar PV system is

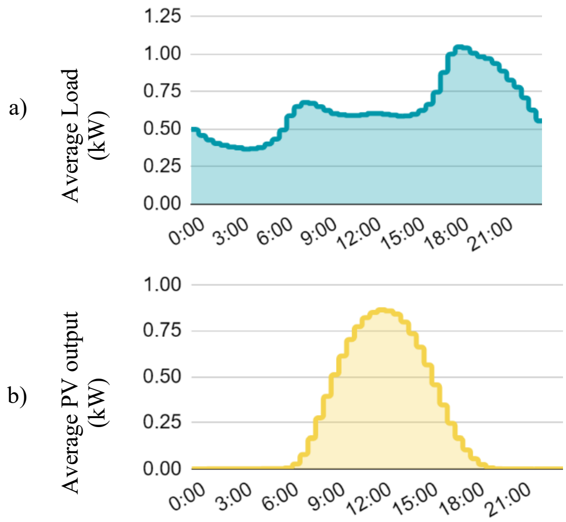

Fig. 3. Average a) load profiles and b) solar PV output.

6 kW per prosumer. The size of BESS per prosumer is 3kW/12.5 kWh. Fig. 3 shows the average load profiles and solarPV output of AusGrid over the course of 24 hours. The average is taken from 300 participants.

III. Model for Trading of Cross Retailers

In this paper, the concept of cross retailer trading is introduced, where Energy Australia (Retailer-1) and AGL (Retailer-2) are considered for NSW, Australia. Retailer-1 has 150 participants including 50 consumers, 50 prosumers with solar PV, and 50 prosumers with solar PVs and BESSs. Retailer-2 has 150 participants consisting of consumers. Table-I shows the rates of the network operator, retailers, LEM transaction fee and energy fee for both BAU and P2P energy trading. In order to get maximum benefit and increase P2P trading volume, ToU tariff structure is considered. The rates of daily supply, FiT, network distribution and transmission, renewable energy target (RET), and retailer margin are fixed at different ToU for both trading scenarios. The LEM transaction fees only apply when P2P transactions happen and ensures all the stakeholders are getting their benefits. Energy price is fixed for BAU, but it varies for P2P trading depending upon bids placed by the participants. Each participant ensures to place a bid within their set limits of tariff and FiT to gain maximum benefit with LEM participation. It is noticed from Table-I that prosumers can get maximum benefit of P2P trading during peak time when energy price is much higher than the FiT compared to shoulder and off-peak time. However, for retailer-2 in off-peak time energy price is

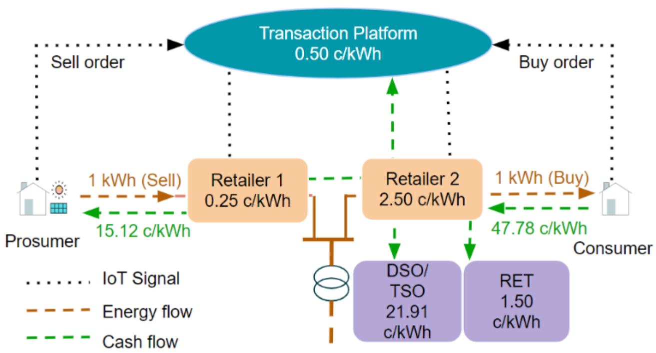

Fig. 4. P2P energy flow, cash flow, IoT signals for two retailers-facilitated LEM.

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TABLE I. RETAILER'S LEM TRADING RATES

	Retailer 1 (Energy Australia) [27]						**Retailer 2 (AGL)** [28]					
	Peak (2pm-8pm)		Shoulder (7am-2pm, 8pm-10pm)		Off-peak (10pm-7am)		Peak (2pm-8pm)		Shoulder (7am-2pm, 8pm-10pm)		Off-peak (10pm-7am)	
Scenarios	BAU	LEM	BAU	LEM	BAU	LEM	BAU	LEM	BAU	LEM	BAU	LEM
Daily supply (c/day)	87.39						98.89					
Fit (c/kWh)	7.60						5.0					
Network (c/kWh) [29]	27.91	27.91	6.19	6.19	3.98	3.98	27.91	27.91	6.19	6.19	3.98	3.98
RET (c/kWh)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Retailer – 5% (c/kWh)	2.5	2.5	1.5	1.5	1	1	2.5	2.5	1.5	1.5	1	1
LEM transaction fee (c/kWh)	0	0.75	0	0.75	0	0.75	0	0.75	0	0.75	0	0.75
Energy/P2P (c/kWh)	20.96	19.21	16.06	14.81	11.22	10.11	16.84	15.12	10.84	9.69	6.14	5.14
Tariff	**52.87**	**51.87**	**25.25**	**24.75**	**17.70**	**17.34**	**48.75**	**47.78**	**20.03**	**19.63**	**12.62**	**12.37**

lower than the FiT, and not advisable to do P2P trading in off-peak time. For each P2P transaction, there could be single or cross retailers, i.e. seller and buyer could be the customers of the same retailer, or different retailers. Fig. 4 demonstrates the peak-time P2P energy flow, cash flow and IoT signals for two retailers-facilitated LEM. The LEM transaction fee 0.75 c/kWh includes the LEM platform fee 0.50 c/kWh and retailer-2 (selling) fee 0.25 kWh.

IV. PROBLEM FORMULATION AND METHODOLOGY

To formulate the concept of P2P energy trading, following assumptions and objectives are considered:

A. Assumptions

a. Prosumers and consumers are part of the same distribution substation.
b. Excess solar PV energy is shared among prosumers and consumers.
c. The use of BESS increases flexibility for LEM.
d. Trading takes place if buy and sell orders are matched, and do not exceed boundaries set by the grid buy rate and FiT.
e. Efficient LEM trading and demand peak reductions require share of prosumers with BESS > 15 %.

B. Objectives

a. To decrease electricity cost for all consumers, prosumers with solar PV and prosumers with solar PV and BESS.
b. To lower the grid's export and import.
c. To maintain BAU margin for the retailers and network operator.

C. Framework Modelling

Let LEM participants, each denoted by $n \in N$, be accommodated by a distribution substation with $z \in Z$, feeders. The power imported by each LEM participant at any time $t \in T$ is indicated by $P_{n,z}^{im}(t)$ and the total ToU tariff is symbolised by $\gamma_n^{im}(t)$. On the other hand, assume $P_{n,z}^{ex}(t)$ implies power export to the distribution network at a price signified by $\gamma_n^{ex}(t)$. Note that $P_{n,z}^{im}(t) = 0$ for consumer. The objective of our LEM platform is to reduce the total cost of energy consumption of all participants, whereby both market and network constraints are considered. The objective functions can be represented as:

$$\min \left[\left(P_{n,z}^{im}(t) \times \gamma_n^{\mathrm{im}}(t) - P_{n,z}^{ex}(t) \times \gamma_n^{ex}(t)\right) \times \Delta t\right], \quad \forall n\epsilon N, \forall z\epsilon Z, \forall t\epsilon T \qquad (1)$$

where Δt stands for the length of each time slot.

Subject to:

$$\rho_{n,z}^{c-} \leq \rho_{n,z}^{c}(t) \leq \rho_{n,z}^{c+}, \qquad \forall n\epsilon N, \forall z\epsilon Z, \forall t\epsilon T \qquad (2a)$$

$$\rho_{n,z}^{d-} \leq \rho_{n,z}^{d}(t) \leq \rho_{n,z}^{d+}, \qquad \forall n\epsilon N, \forall z\epsilon Z, \forall t\epsilon T \qquad (2b)$$

where equations (2a) and (2b) indicate BESS charging and discharging constraints. $\rho_{n,z}^{c}(t)$ is the BESS charged power. $\rho_{n,z}^{c-}$ and $\rho_{n,z}^{c+}$ imply minimum and maximum charging capacities of each energy-user. Whereas, BESS discharged power is denoted by $\rho_{n,z}^{d}(t)$, where minimum and maximum discharging capacities are represented by $\rho_{n,z}^{d-}$ and $\rho_{n,z}^{d+}$, respectively.

$$\sum_{a=1}^{|A|} P_a(t) = \sum_{b=1}^{|B|} P_b(t), \qquad a, b \subset N, \forall t\epsilon T \qquad (3)$$

where equation (3) demonstrates the power balance in the LEM, i.e., the total sellers' traded power should be equal to the total buyers' traded power. The sets of LEM sellers and buyers are signified by A and B respectively, where $A, B \subset N$. Symbols a and b stand for each seller and each buyer, respectively.

$$\gamma^{fit}(t) \leq (\gamma_n^{tr}(t) + \gamma^{pt}(t)) \leq \gamma^{eng}(t), \ \forall z\epsilon Z, \forall t\epsilon T \qquad (4)$$

The LEM price constraint is illustrated in (4). $\gamma^{eng}(t)$ is the energy price (ToU) segment of tariff $\gamma^{tou}(t)$. The FiT rate is symbolised by $\gamma^{fit}(t)$. $\gamma^{tr}(t)$ and $\gamma^{pt}(t)$ refer to P2P trading for each participant $n\epsilon N$ and LEM platform cost respectively.

$$P^{i}(t) < P^{i(o)}(t), \qquad \forall t\epsilon T^{i} \subset T \qquad (5a)$$

$$P^{j}(t) < P^{j(o)}(t), \qquad \forall t\epsilon T^{j} \subset T \qquad (5b)$$

where equations (5a) and (5b) represent the grid's export and import, symbolised by $P^{i}(t)$ and $P^{j}(t)$, respectively, constraints. T^{i} and T^{j} are considered as the sets of peak solar periods and demand periods, respectively. $P^{i(o)}(t)$ and $P^{j(o)}(t)$ are the grid's export and import without the LEM.

$$\gamma_y^{rt}(t) \leq \gamma_y^{rt(o)}, \qquad \forall y\epsilon Y, \forall t\epsilon T \qquad (6a)$$

$$\gamma^{nt}(t) \leq \gamma^{nt(o)}(t), \qquad \forall t\epsilon T \qquad (6b)$$

The margin constraints of the energy suppliers and the network operator are described in equations (6a) and (6b). $\gamma_y^{rt}(t)$ and $\gamma_y^{rt(o)}$ imply each energy supplier's $y\epsilon Y$ margin with and without the LEM, respectively. Further, the network

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TABLE II. PARTICIPANTS BILL REDUCTION

	Consumer	Prosumer (PV)	Prosumer (PV+BESS)
BAU vs LEM	1.5 %	4.6 %	18.1 %

operator's margin with and without the LEM are represented by $\gamma^{nt}(t)$ and $\gamma^{nt(o)}(t)$, respectively.

V. CASE STUDY AND RESULTS

In this paper, the LEM trading mechanism is applied to conduct a case study on an Australian suburb, containing existing consumers, prosumers, retailers, and the network operator. The trading period is set every 15 minutes apart. The P2P energy trading results (Case B) are compared with the BAU (Case A) to analyse the advantages of using the P2P trading-based LEM platform for participants, retailers, and the network operator.

A. Participants daily electricity cost reduction

It is evident from Table-II that if the participants trade in the LEM, the electricity bill reduction for consumer, prosumer with PV, and prosumer with PV and BESS become 1.5%, 4.6%, and 18.1%, respectively. The small reduction in energy usage cost for consumers (A vs. B) is a result of the small difference of grid buy rate (Peak: 52.87 c/kWh) and maximum LEM buy rate (Peak: 51.81 c/kWh). The bill reduction is maximum for prosumers with PV and BESS, as prosumers can sell excess solar PV to the neighbours. Prosumers can also make additional money from BESS charging during off-peak time and sell excess BESS-stored energy in shoulder and peak time, at a higher price compared to the FiT.

Fig. 5 illustrates that energy sold to the grid is reduced in the afternoon time due to P2P transactions in the LEM, and BESSs are charged to store energy through P2P trading to discharge in peak time. As depicted in Table-II, prosumers with BESS decrease the bill as they get charged in off-peak and shoulder time and discharged in peak time to make maximum profit. The total exported energy to the superior grid is reduced to 46.3% and the total imported energy from the superior grid is reduced to 66.6%.

B. Retailers' Daily Income Margin

The retailer margins are kept at or above BAU level and are shown in Fig. 6 and illustrated as:

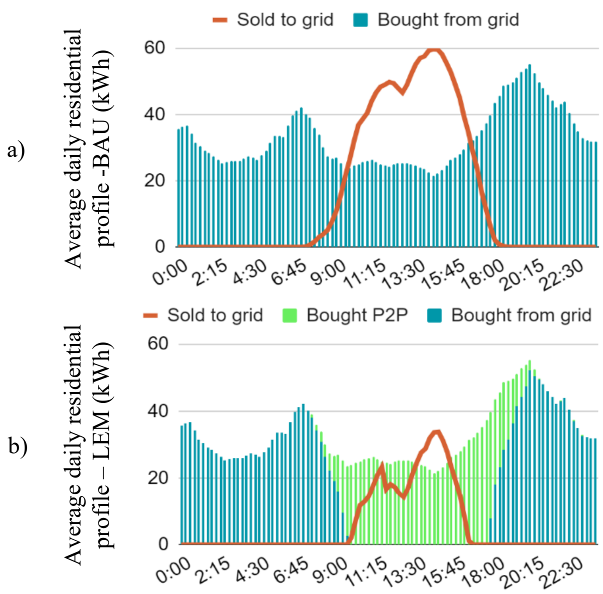

Fig. 5. Trading with power grid.

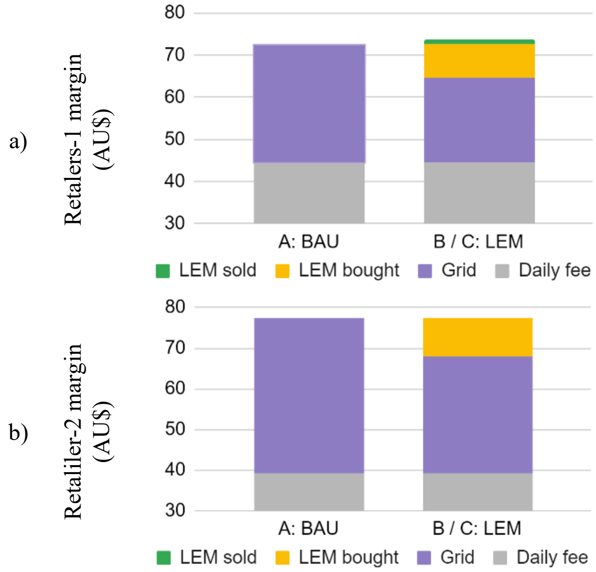

Fig. 6. Retailers daily income margin.

1) Retailer-1: With all the prosumers retains an additional transaction fee of 0.25 c/kWh sold within the LEM from prosumers in its portfolio. Increase in daily margin by 4.1 % is a function of additional fee per LEM traded kWh as well as increased trading volume due to BESS charge from peers.

2) Retailer-2: Without any prosumers retains previous margin for every kWh consumed within its portfolio (from grid and within LEM). Retailers will get more benefit as the number of prosumers will grow within the LEM platform that will also increase the transaction volume and for every transaction retailers will get their additional fee which will increase their margin.

C. Network Operator's Daily Income

Network operator income is captured in Fig. 7. Income is marginally increased from Case A to Case B due to an increase in trading volume during mid-day when BESS is charged from other peers. Overall, the network operator is not earning a large profit, compared to participants, due to reduced BAU trading. The LEM reduced the renewable penetration into the electricity network, which in turn, can eventually bring down the grid capital expenditure and operational expenditures. This encourages the network operator to allow more consumers to become prosumers in the distribution network. Also, participants can have more opportunities to make larger benefits within LEM.

VI. CONCLUSION

In this paper, the development and financial viability of a LEM design has been proposed. In this model, various end-users, including consumers, prosumers with solar PVs, and prosumers with solar PVs and BESSs, can carry out frequent P2P energy trading. This is done while the economic interests of all the stakeholders are maintained. The objective function of the proposed P2P trading-based LEM platform has been determined considering all the fees and network charges. The developed mechanism has then been tested on a real Australian suburb with various participants, retailers, and the network operator. The simulation results have shown superior performance of the proposed trading strategy in comparison

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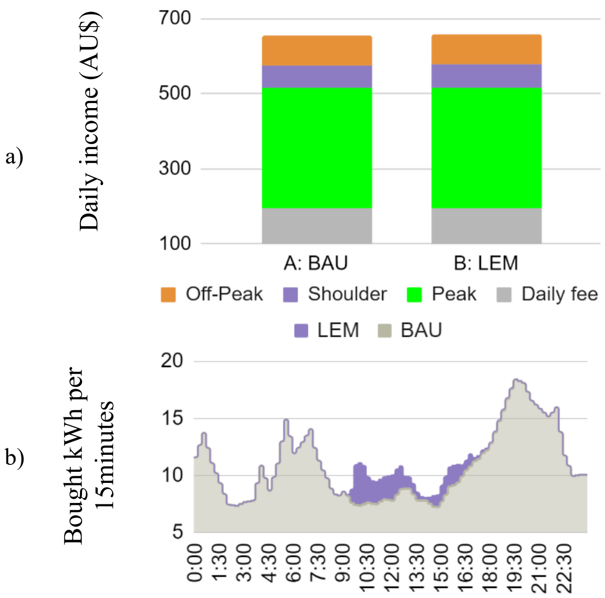

Fig. 7. Netword operator income.

with the BAU in terms of cutting down electricity costs for participants, reducing grid's imports and exports, marginally increasing or keeping unaffected income margin for retailers, and minimal increasing income for the network operator.

Future works include the contribution of community battery-based microgrid with LEM platform and the dynamic network condition in to maximise local energy penetration through P2P trading.

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