A Local Energy Market Benefiting Power Grids and Energy Users: A P2P Trading-based Case Study

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Abstract—**The increasing amount of renewable generation creates challenges for the energy providers. variable renewable energy (VRE), as the name suggests, creates a varying or fluctuating electricity supply. A local energy market (LEM) helps to reduce the impact of fluctuating supply by strategically controlling the VREs and loads. Such a mechanism allows consumers and prosumers (customers who can generate solar PV energy, for instance), that are within a defined geography, to trade energy with one another in a peer-to-peer (P2P) fashion. LEMs have better financial outcomes for the consumers and prosumers. Therefore, it encourages better VRE technology diffusion while lowering the impact on the grid by reducing the imports and exports from the medium voltage grid. In this paper we outline the results of a LEM case study using real customer data in WA — to evaluate the performance of P2P trading in comparison with their BAU. The battery energy storage system (BESS) is included in the LEM model to introduce greater flexibility and capture the implications on electricity costs and grid export and import. Compared to BAU, the results of Powerledger's LEM platform shows that prosumers with BESS receive minimum electricity bills and ensure maximum reduction in power grid export 28 % and import 33 %.**

***Keywords—** Solar PV, BESS, Energy Supplier, Network Operator, local energy market, P2P energy trading.*

I. INTRODUCTION

Due to the economic, environmental, and technical benefits of a rooftop solar photovoltaic (PV) system, more than 20% of Australian residential consumers have already installed it [1]. In other words, a traditional customer is transforming into a prosumer — one who can produce energy locally and trade excess energy in return for financial rewards [2]. Feed-in-tariff (FiT) is, one of such, such an incentive scheme that allows prosumers to sell their excess energy to the electricity grid and earn money [3]. Initially, the FiT rate was set very high with a mission to attract traditional consumers to install solar PV systems at their premises. For instance, the rate was around 40 c/kWh in Western Australia (WA), resulting in one in three households in WA now owning a PV system[4].

However, for a number of reasons, such as solar production reaching grid parity and unplanned solar PV system installation — all of which are detrimental to the power grid [5], the rate has now plummeted to only 3 c/kWh in WA. This has created substantial dissatisfaction among prosumers [6]. Thus, an alternative approach is required to balance the grid needs and also make the proposition financially attractive to the prosumers [7]. Such an alternative approach could also serve into improving self-sufficiency, minimising the energy cost [8], dispatching flexibility, and promoting sustainability [9].

To this end, the concept of local energy market (LEM) has been proposed to address technical, regulatory, and policy-based challenges that existed at the prosumers' end [10-11]. A LEM allows prosumers and consumers to take part in a decentralised trading mechanism, known as peer-to-peer (P2P) energy trading, using a distributed blockchain based ledger [12]. P2P transactions can broadly be divided into financial and physical parts [13].

The financial part of P2P trading is driven by the bilateral negotiations between a number of prosumers and consumers in a forward-facing market environment without the direct involvement of any centralised entity like a grid operator [14]. The physical part of P2P trading, in contrast, is exercised in a hybrid way, in coordination with the financial settlements, either by iterative process [15] or optimised process [16-17].

To establish P2P trading as a preferable mechanism in comparison with the existing business-as-usual (BAU) — in which prosumers push excess energy back to the grid at the FiT rate and they and/or consumers purchase energy deficit from the grid at the time-off-use (ToU) prices [18], a large number of research studies have been executed recently. Prosumers' and consumers' preferences, in terms of choosing trading partners, and selecting trading quantities, prices, and periods, are prioritised in a competitive P2P market in [19]. They are also provided with the flexibility to remain as BAU customers whenever they wish in [20-21]. The authors in [22] also stress the importance to structure the decision-making processes of P2P trading so that both prosumers and consumers reduce their electricity bills significantly. This is one of the most significant features of P2P trading [23]. The use of battery energy storage systems (BESSs) is also emphasised in [24] to cut down the energy costs of both prosumers and consumers while they govern their local energy production, usage, and dispatch. Apart from it, the social attributes of P2P trading is also analysed in [25] to increase the acceptability of the framework.

Moreover, some grid's interests-centric P2P trading studies are also conducted to accommodate the mechanism in real electricity networks. The authors in [26] balance energy supply and demand in a local community through selling and

Fig. 1. Map of Australia showing the location of WAs town.

buying orders of P2P prosumers and consumers. They are also rewarded in [27] to serve the community. The applicability of P2P trading in determining the sizing of a clustered-microgrid is analysed further in [28-29]. Besides, the demand-side management is improved with the help of P2P trading in [30] as prosumers' and consumers' mutually agreed energy usage behaviours can significantly decrease grid dependent demand during peak periods. The peak demand tariff adjustment via P2P trading is also highlighted in [31] to ensure the grid does have unsustainable demand at all conditions and in [32] microgrid sizing and cost minimisation is performed for Australian case studies.

Clearly, the aforementioned studies pave the way to demonstrate the suitability of user-centric P2P trading strategies in various electricity networks. However, the contentment of energy suppliers and network operators, such as distribution service operators (DSOs) or distribution utilities or distribution network operators (DNOs), are not considered in this research. Making the DSOs/DNOs content is crucial for ensuring the viability of a P2P trade. If DSOs/DNOs are dissatisfied, they likely will not become part of a P2P community, and hence the technology diffusion of LEMs and VREs could significantly be impacted. As such, this paper proposes a LEM platform; whereby: 1) P2P trading is carried out between several prosumers and consumers in a most flexible manner, 2) both prosumers and consumers lower their energy bills remarkably, 3) Power grids interest is accounted by reducing the grid's export and import during peak solar PV and demand periods respectively. In the end, LEM trading ensures that energy supplier and network operator do not lose their margins. The bidding transparency and security can be guaranteed by decentralised technology such as blockchain.

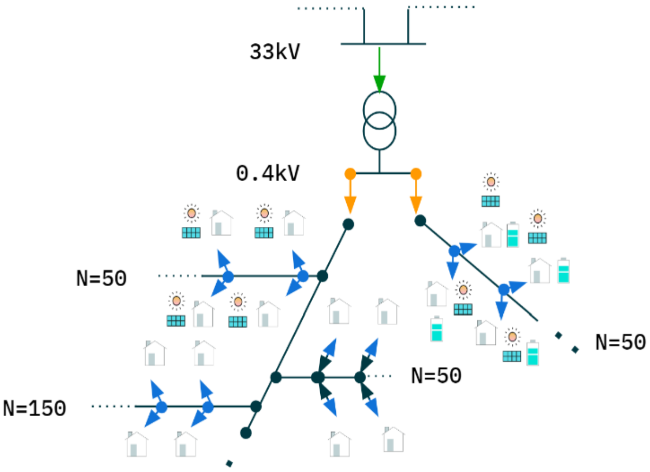

Fig. 2. Network architecture for the studied LEM.

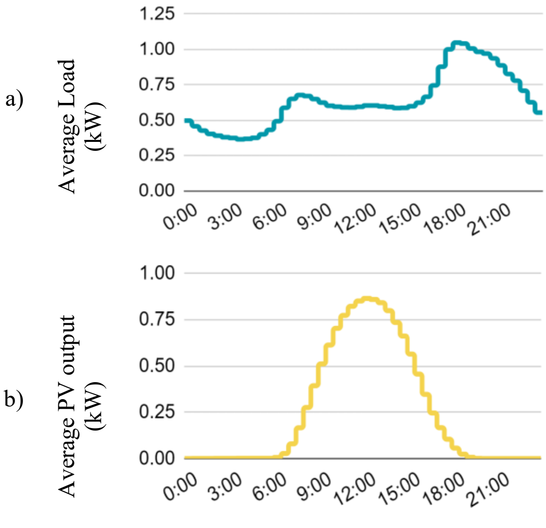

Fig. 3. Average a) load profiles and b) solar PV output.

The rest of this paper is structured as follows. Section II introduces the LEM architecture. Single energy supplier trading is explained in Section III. The methodology to solve market design is presented in Section IV. The following section (Section V) provides results and analysis. Lastly, concluding remarks are demonstrated in Section VI.

II. LEM ARCHITECTURE

A LEM facilitates each prosumer and consumer to trade energy via P2P trading and/or peer-to-grid (P2G) trading in an electricity network. At Powerledger, we have developed a P2P energy trading platform with a view to maximising financial benefits for the prosumers and consumers [33]. In this platform, they can submit their sell and buy offers respectively in forward-facing time intervals to conduct P2P transactions. A P2P trading-enabled LEM platform for a suburb in WA is depicted in Fig. 1. The electricity network architecture — that accommodates prosumers and consumers physically — is illustrated in Fig. 2. There are two feeders in the test network. First feeder contains 250 energy users (50 prosumers and 200 consumers). Second feeder contains 50 prosumers with BESSs. The installed capacity of a solar PV system is considered as 6 kWp per prosumer on average, while BESS size is 3.3 kW/12 kWh per prosumer. The average load profiles and solar PV outputs, taken from all 300 Energy users, are captured in Fig. 3(a) and Fig. 3(b) respectively.

III. ENERGY SUPPLIER

A single Energy Supplier in a WA suburb is considered for P2P trading in the LEM. In practice, 300 Energy users are catered by the Energy Supplier, that includes 200 electricity consumers; 50 prosumers with solar PVs; and 50 prosumers with solar PVs and BESSs. The retail electricity rates for both BAU and P2P scenarios are illustrated in Table-I. We have taken the ToU tariff structure into account to enhance P2P trading volume and monetary gains for the Energy users. As is noticed from Table-I, the daily supply charges, FiT rates,

TABLE I. ENERGY SUPPLIER'S TRADING RATES

Energy Supplier (Synergy) [34]	**Peak (2pm-8pm)**		**Shoulder (7am-2pm, 8pm-10pm)**		**Off-peak (10pm-7am)**	
	BAU	**LEM**	**BAU**	**LEM**	**BAU**	**LEM**
Daily supply (c/day)	105.14					
FiT (c/kWh)	10		2.75			
Network fee (c/kWh) [35]	26.87	26.87	16.04	16.04	9.96	9.96
RET (c/kWh)	1.5	1.5	1.5	1.5	1.5	1.5
Energy Supplier – 5% (c/kWh)	2.5	2.5	1.5	1.5	1	1
LEM transaction fee (c/kWh)	0	0.75	0	0.75	0	0.75
Energy/P2P price (c/kWh)	25.57	23.70	10.17	8.84	2.90	1.85
Tariff (c/kWh)	**55.77**	**54.66**	**29.21**	**28.63**	**15.36**	**15.06**

transmission and distribution network charges, renewable energy target (RET) rates, and Energy Supplier's margin remain the same for both BAU and P2P scenarios. The P2P trading also involves LEM transaction fees with a purpose to guarantee economic benefits for all the stakeholders. Note that LEM transaction fee 0.75 c/kWh includes both LEM platform fee 0.50 c/kWh and Energy Supplier (selling) fee 0.25 c/kWh. The energy prices vary depending on bids offered by the P2P Energy users. Each P2P Energy user is guided to trade at a rate higher than FiT rate but lower than ToU to extract maximum benefit from the LEM. Table-I demonstrates that Energy users receive maximum benefits during peak periods — when FiT rate is much lower than energy price — in contrast with shoulder and off-peak periods. P2P energy flow, cash flow, internet of thing (IoT) signals for a single Energy Supplier-based LEM are shown in Fig. 4.

IV. PROBLEM FORMULATION

To model P2P trading in the LEM, followings are assumed:

1. Residential energy users of the selected distribution network are under one substation.
2. Energy users trade their excess energy (prosumers with solar PV) and flexibility (prosumers with solar PV and BESS) within the LEM.
3. LEM trading takes place when buy and sell orders are within the limits of grid electricity price and FiT.
4. The contribution of prosumers with solar PVs and BESSs is equal or more than 15% for efficient LEM trading and peak demand reductions.

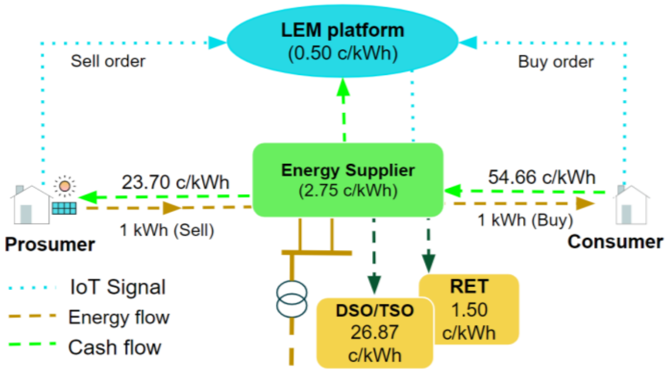

Fig. 4. Trading flow with Single Energy Supplier.

The main objectives are to cut down electricity cost at the household level, lower the grid's export and import, and keep energy supplier's and network operator's margins unaffected.

Assume a distribution substation with $f \in F$ feeders that locate LEM end-users. Each of them is symbolised by $m \in M$. The power imported by each LEM participant at any time $t \in T$ is indicated by $P_{m,f}^{im}(t)$ and the total ToU tariff is symbolised by$\sigma_m^{ex}(t)$. Note that $P_{m,f}^{ex}(t) = 0$ for consumers. The objective of our LEM platform is to reduce the total cost of energy consumption [36] of all participants, whereby both market and network constraints are considered. The objective functions can be represented as:

$$\min \left[\left(P_{m,f}^{im}(t) \times \sigma_m^{\mathrm{im}}(t) - P_{m,f}^{ex}(t) \times \sigma_m^{ex}(t)\right) \times \Delta t\right], \qquad (1)$$
$$\forall m \epsilon M, \forall f \epsilon F, \forall t \epsilon T$$

where Δt stands for the length of each time slot.

Subject to:

$$\rho_{m,f}^{c-} \leq \rho_{m,f}^{c}(t) \leq \rho_{m,f}^{c+}, \qquad \forall m \epsilon M, \forall f \epsilon F, \forall t \epsilon T \qquad (2a)$$

$$\rho_{m,f}^{d-} \leq \rho_{m,f}^{d}(t) \leq \rho_{m,f}^{d+}, \qquad \forall m \epsilon M, \forall f \epsilon F, \forall t \epsilon T \qquad (2b)$$

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

$$\sum_{i=1}^{|I|} P_i(t) = \sum_{j=1}^{|J|} P_j(t), \qquad I, J \subset M, \forall t \epsilon T \qquad (3)$$

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 I and J respectively, where $I, J \subset M$. Symbols i and j stand for each seller and each buyer, respectively.

$$\sigma^f(t) \leq (\sigma_m^{tr}(t) + \sigma^{pt}(t)) \leq \sigma^e(t), \quad \forall m \epsilon M, \forall t \epsilon T \qquad (4)$$

The LEM price constraint is illustrated in (4). $\sigma^e(t)$is the energy price (ToU) segment of tariff $\sigma^g(t)$. The FiT rate is symbolised by $\sigma^f(t)$. $\sigma_m^{tr}(t)$ and $\sigma^{pt}(t)$ refer to P2P trading for each participant $m \epsilon M$ and LEM platform cost respectively.

The LEM price constraint is illustrated in equation (4). $\sigma_m^{tr}(t)$ and $\sigma^{tr}(t)$ indicate P2P transaction price for each energy user $m \epsilon M$ and LEM platform cost per transaction, respectively.

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

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

where equations (5a) and (5b) represent the grid's export and import, symbolised by $P^{ex}(t)$ and $P^{im}(t)$, respectively, constraints. T^s and T^d are considered as the sets of peak solar

TABLE II. ENERGY USERS BILL REDUCTION

	Consumer	**Prosumer (PV)**	**Prosumer (PV+BESS)**
BAU vs LEM	6 %	32 %	59 %

periods and demand periods, respectively. $P^{ex(o)}(t)$ and $P^{im(o)}(t)$ are the grid's export and import without the LEM.

$$\sigma_x^{es}(t) \le \sigma_x^{es(o)}, \qquad \forall x \epsilon X, \forall t \epsilon T \tag{6a}$$

$$\sigma^{nt}(t) \le \sigma^{nt(o)}(t), \qquad \forall t \epsilon T \tag{6b}$$

The margin constraints of the energy suppliers and the network operator are described in equations (6a) and (6b). $\sigma_x^{es}(t)$ and $\sigma_x^{es(o)}$ imply each energy supplier's $x \epsilon X$ margin with and without the LEM, respectively. Similarly, the network operator's margin with and without the LEM are represented by $\sigma^{nt}(t)$ and $\sigma^{nt(o)}(t)$, respectively.

V. RESULT AND ANALYSIS

This section contains the results and analysis of the performed case study, that considers a typical suburb in WA with 300 energy users. Among the Energy users, there are 200 consumers — who play the role of only buyers. On the contrary, 50 prosumers (with solar PVs) and 50 prosumers (with solar PVs and BESSs) function as both sellers and buyers depending upon their energy status.

A. *Electricity Cost Saving and Benefits to Energy users*

The average electricity costs of consumers, prosumers with solar PV, and prosumers with solar PVs and BESSs are depicted in Fig. 5. On average, Table-II shows that through P2P trading in the LEM they reduce their electricity costs by 6%, 32%, and 59%, respectively, compared to BAU. That encourages prosumers to make the largest investment on solar PVs and BESS to earn maximum benefit. Other side, consumers are also benefiting as part of the LEM platform without making any investment on DERs.

Fig. 6 (a) and Fig. 6 (b) reveal that energy sold to the power grid is decreased in the afternoon and evening time because of P2P transactions in the LEM. Also, BESSs are charged during day (off-peak) and afternoon (Shoulder) time to store energy by P2P trading. BESSs are discharged during the evening (peak) time to participate in P2P trading and earn maximum benefit.

B. *Power Grid's Export and Import Reduction*

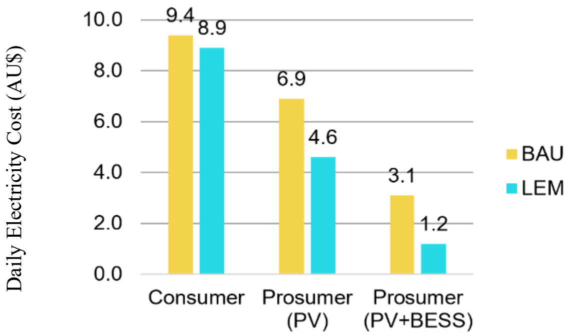

Fig. 5. Energy users daily electricity cost reduction.

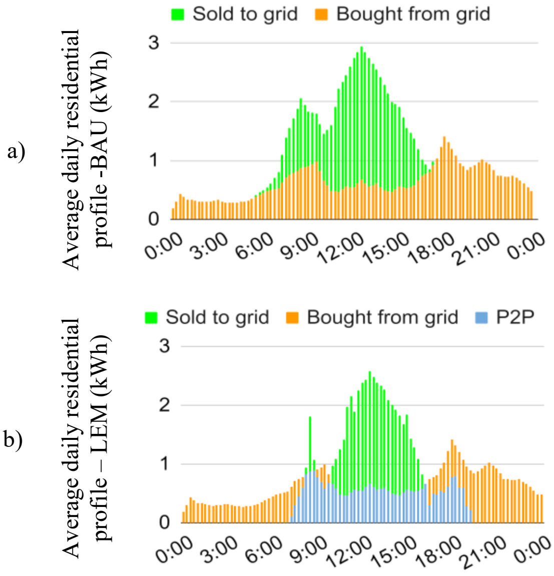

Fig. 6. Energy Users load consumption in BAU vs LEM.

The export and import of the power grid for a typical day are represented in Fig. 7; in which BAU and our proposed LEM are indicated by Schema A and Scenario B respectively. As is seen from Fig. 7, in comparison with Schema A, our proposed LEM decreases the power grid export by 28% due to BESS charging and energy trading with neighbouring users in off-peak and shoulder time. Further, the power grid import is lessened by 33% due BESS discharging and energy trading with neighbouring users during peak time.

Fig. 8 portrays that the energy supplier's margins are kept at or above BAU level. An increase in daily margin is a result of additional fee per P2P traded kWh as well as increased P2P trading volume due to BESS charging from other prosumers. Note that the network operator may not be getting profit like the LEM energy users owing to reduced BAU trading. However, P2P trading in the LEM lessens the renewable penetration into the electricity network significantly that can eventually cut down the capital expenditures and operational expenditures of the electricity grid, leading to encourage the network operator to permit more consumers to turn into prosumers.

VI. CONCLUSION

On average, it has been found that using Powerledger's proposed LEM platform, consumers, prosumers with solar

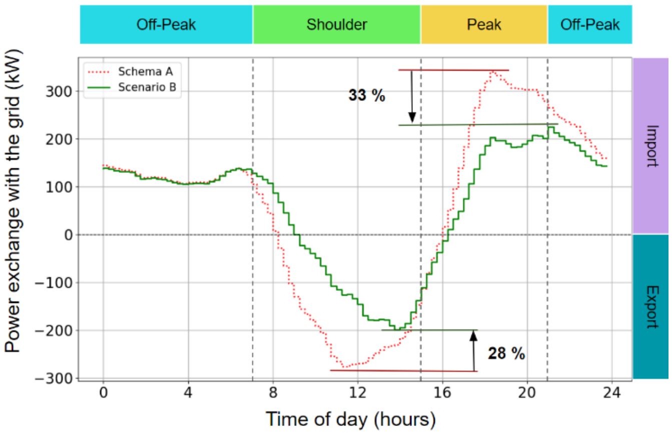

Fig. 7. Grid export and import comparison

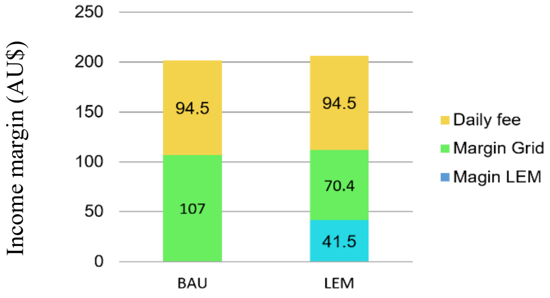

Fig. 8. Energy supplier daily income margin.

PVs, and prosumers with solar PVs and BESSs, can reduce their electricity bills on average by 6%, 32%, and 59% respectively. Such a reduction in bills would motivate residential energy users to participate in P2P trading through the LEM platform. Additionally, the grid has been able to cut down export and import by 28% and 33%, respectively. This enables the grid to reduce or defer capital expenses for network augmentation.

LEM promotes decarbonisation, digitalisation, and decentralisation of energy using P2P trading and customer empowerment. At Powerledger, we are promoting LEMs using the latest technology. Future work can deal with considering the impact of cross energy suppliers' inclusion in our LEM platform. Also, we suggest further study on the monetary benefits to both energy suppliers and network operators and ways of creating a win-win scenario for all stakeholders.

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