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P2P Trading-enabled Local Energy Market Supplemented with Blockchain Technology: An Australian Case Study

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***Abstract*— In this paper, a framework is proposed for integration of peer-to-peer (P2P) trading-based local energy market (LEM) with the blockchain technology. The proposed LEM model allows prosumers and consumers to trade electricity among each other ensuring the presence of the retailer and network utility – who are also essential parts of a P2P network. The P2P contracts settled between various prosumers and consumers are governed by mutually agreed upon smart contracts – which are then written in an Ethereum blockchain to record and store bidding history, P2P transactions, and settlements. An effective formulation is also presented to capture P2P trading quantities and prices among participating prosumers and consumers in a decentralised fashion with an appropriate analysis of financial viability. Finally, a case study is conducted in a real Australian context; in which the engagement of both prosumers and consumers are taken into account, and the performance of the proposed blockchain-enabled LEM is compared with business-as-usual (BAU) to demonstrate the model's superiority.**

***Keywords*— Local energy market, peer-to-peer trading, Ethereum blockchain, retailer, and network utility.**

I. INTRODUCTION

In recent years, environmental sustainability has been marked as one of priorities while dealing with meeting up energy demand in the Paris Agreement [1]. This is where mainstream distributed energy resources (DERs) are finding their application in producing and storing clean energy, and providing resiliency at the electricity market [2-3]. At the residential level, solar photovoltaic (PV) systems are playing the role of small-scale DERs in most parts of the world including Australia [4-5]. In fact, Australia is one of the few countries that actually has already seen around 20% of its electricity consumers install solar PV and turn into prosumers [6-7].

In the last decade, an incentivising scheme has been introduced – commonly known as feed-in-tariff (FiT) – to reward prosumers in lieu of excess solar PV energy. Initially, the FiT rates were higher to attract substantial consumers [8], but it did not stay long owing to a number of policies that have been undertaken centrally. Currently, FiT rate is very marginal; e.g.; declined to only 3 c/kWh in Western Australia (WA) [9]. The plummeted FiT rate has impacted existing prosumers adversely to make further investments on small-scale DERs. On top of it, other consumers are not getting enough motivation to install solar PVs. Consequently, an alternative approach needs to be introduced to regain satisfaction at the residential level and continue clean energy exchanging in the power grid.

Given this context, a user-centric market mechanism -- termed as local energy market (LEM) – has been conceptualised in recent years. LEM essentially is a sub-electricity market platform that emphasises on technical, economic, and environmental feasibility-ensured energy management, trading, and services to benefit consumers [10]. Peer-to-peer (P2P) energy trading is one of the most striking facilitation of the LEM that can allow energy users (both prosumers and consumers) to negotiate and exchange energy at mutually agreed prices [11], resulting in better financial returns in comparison with business-as-usual (BAU) – energy is sold/bought at FiT/time-of-use (ToU) price.

The overall financial analysis of P2P trading can be classified into two categories in general -- that include a secure database to store and track contracts and settlements, and an appropriate trading formulation to evaluate users' monetary gains appropriately. Recently, blockchain has emerged as the most appealing technology to assist in storing and tracking P2P-related information [12]. The authors in [13] apply smart contracts on blockchain to match supply with demand. A cryptocurrency-empowered P2P trading via tokens is structured. The P2P market flexibility is also documented in an immutable manner in [14]. Other blockchain-based multi-scale P2P trading frameworks are developed in [15].

As for motivating and incentivising energy users, several studies have also been undertaken. For instance, the bilateral trading feature is highlighted. The application of motivational psychology is brought in the P2P trading mechanism in [16-17]. While energy users' attitudes and behaviours are analysed thoroughly, the electricity cost reduction is labelled as the most influential factor in [18] to expedite energy users' engagement in the P2P trading. Different optimisation techniques are also adopted to clear the P2P market optimally, including game theory [19]; auction theory [20]; and other constraint optimisations [21].

Although aforementioned studies have contributed recently to propel the P2P trading in the LEM, the presence of the retailer and network utility is missing. Since they are also an integral part of an electricity network, this paper considers their participation in the P2P trading-driven LEM without losing their BAU presence. Further, a mechanism is proposed to incentivise energy users more than BAU to retain their satisfaction. The proposed LEM model is also integrated with the blockchain technology to store trading contracts, history of energy bids and settlements. Moreover, a case study is performed with real Australian data to validate the proposed blockchain-enabled P2P trading strategy in the LEM in terms of economic feasibility.

The remainder of the paper is structured as follows. A brief overview of P2P trading-driven LEM is provided in Section II followed by its deployment on the blockchain platform (in Section III). Section IV presents the P2P trading formulation in the LEM. The simulation results are illustrated

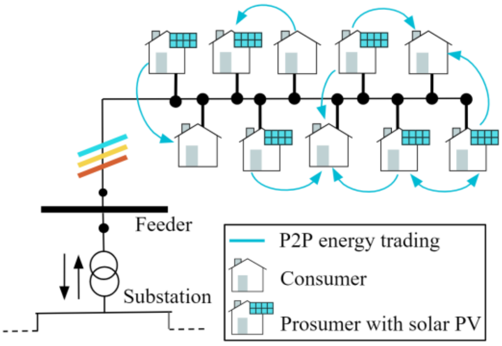

Fig. 1. Grid architecture for the studied P2P trading-based LEM.

in Section V. Finally, the concluding remark is outlined in Section VI.

II. LEM: A Brief Overview

In the LEM, energy users are provided with an opportunity to satisfy their energy requirements by P2P energy trading among each other and to perform energy exchange with the upstream grid. Energy users are directed to carry out P2P transactions to gain substantial returns from their investments on local energy technologies. LEM platform permits energy users to declare their selling and buying bids in the forward-facing market and P2P trading is executed following a decentralised market clearing mechanism. A typical Australian residential suburb is considered to mimic the LEM operation; in which the participation of prosumers, consumers, the retailer, and the network utility is ensured as depicted in Fig. 2. The residential data are taken from [22], and the tariff structure as per BAU (along with its variation due to the LEM introduction) is illustrated in Table-I.

As is displayed in Table-I, network costs; retailer's margins; energy prices are altered in accordance with peak, shoulder, and off-peak ToU slot settlements. Whereas, FiT rate and renewable energy target fee (if applicable) are kept unvaried over the course of a typical day. A blockchain-based LEM platform aims at playing optimally with the energy cost portion of the tariff to reduce the overall tariff so that energy users can receive benefits (greater incentives are envisaged during peak ToU periods owing to higher charges) while the retailer and network utility do not lose their portions. LEM platform also incurs a small amount of charge to benefit the admin, LEM operator for example. However, the charge is

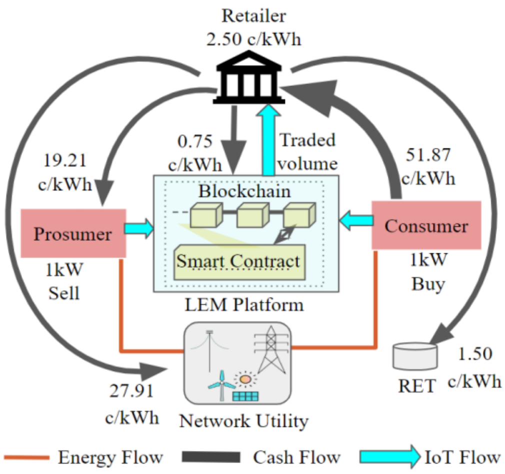

Fig. 2. An example of P2P energy flow, cash flow, IoT signals in LEM.

TABLE I. Energy User's Tariff Rates

A typical retailer's tariff in Australia [23]	Peak (4pm-8pm)		Shoulder (7am-4pm) and (8pm-10pm)		Off-peak (10pm-7am)	
	BAU	LEM	BAU	LEM	BAU	LEM
FiT (c/kWh)	7.60					
RET (c/kWh)	1.50					
Network cost (c/kWh)	27.91	27.91	6.19	6.19	3.98	3.98
Retailer margin (c/kWh)	2.50	2.50	1.50	1.50	1	1
LEM Transaction fee (c/kWh)	0	0.75	0	0.75	0	0.75
Energy/P2P cost (c/kWh)	20.96	19.21	16.07	14.31	11.22	9.77
Tariff (c/kWh)	**52.87**	**51.87**	**25.25**	**24.25**	**17.70**	**16.70**

defined in a way that the LEM tariff is always lower than that of BAU. An example of P2P energy flow, cash flow, internet-of-things (IoT) signals in LEM at a given time slot is captured in Fig. 2, in which a smart contract is organised to document P2P trading information on a virtual platform and then it is written on the blockchain for permanent record and storage. The trading information is also passed to the retailer for an accurate billing at the end of a periodical billing cycle.

III. LEM Deployment on the Blockchain Platform

A protocol is adopted to organise chronologically arranged blocks, that are distributed; secure; immutable; encrypted; and constitute the blockchain platform. To perform P2P trading in the LEM platform, a number of rules and regulations are set, which are accomplished using computerised codes known as smart contracts. The mutually agreed upon smart contracts' unique addresses are produced and stored in the blockchain platform as scripts.

In this paper, smart contracts settled between LEM users are executed by Ethereum virtual machine (EVM) – which is essentially a software that resides on top of Ethereum nodes for executions. The amounts of computational efforts exercised by the EVM to carry out P2P transactions and smart contracts are measured in 'gas'. Gas price is the amount of Ether (ETH) paid for each unit of gas and usually measured in the smallest denomination of Ether (WEI). One ETH is equivalent to 10^{18} WEI, and one ETH = 2334.63 AU$ [24]. It is dynamic in nature as it is a function of blockchain network congestion. The total cost Z in ETH for executed transactions and smart contract in Ethereum blockchain is calculated as [25]:

$$Z(ETH) = g \times z(gas) \qquad (1)$$

where g represents the gas amount and $z(gas)$ denotes the gas price measured in *WEI.*

The deployment of LEM on the blockchain platform is exhibited in Fig. 3. The entire process consists of three layers: LEM architectural layer (virtual and physical); interfacing layer; and smart contracts-driven blockchain layer. In the LEM architectural layer (virtual), prosumers and consumers declare their interests to participate in the LEM based on their energy status (either sellers or buyers); In the interfacing layer, LEM users are connected through user interface (UI) and Web3 interface. UI allows LEM users to place their bidding quantities and prices at set time interval. On the other hand, the Web3 interface connects LEM users to the smart contracts-driven blockchain layer. In the smart contracts (monitored by an authorised admin), P2P bidding; mechanism for market

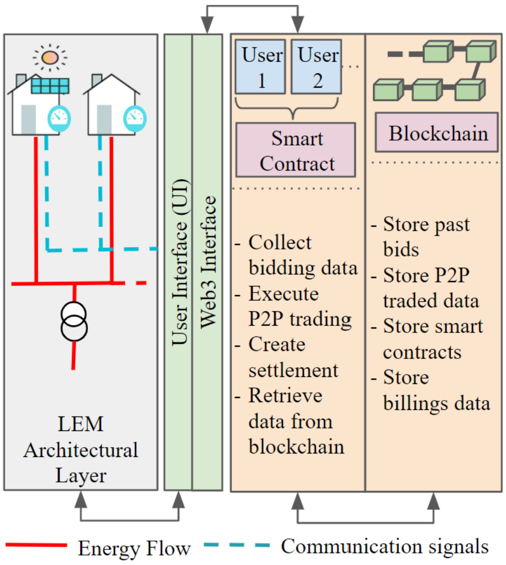

Fig. 3. A model to integrate LEM with the blockchain technology.

clearing; and billing are settled in a decentralised fashion. In particular, past bids, P2P trading records and billing information are preserved permanently with a provision to retrieve whenever necessary. All of this information is also made available to the admin, retailer, and the energy users for final economic arrangements. Lastly, in the physical domain of LEM architectural layer, prosumers inject the energy while consumers consume it from the physical network (e.g., distribution network) – where they are located.

IV. LEM Trading Formulation in the LEM

Let $y \in Y$ be the index of each energy user in the LEM at a given time period $x \in X$, where the sets of energy users and time periods are denoted by Y and X respectively. The proposed blockchain-enabled LEM mechanism focuses on increasing/decreasing the selling/buying prices of each energy user. Hence, the objective function can be expressed as follows:

$$Max\ \Sigma \left[\left(E_y^x(sell) \times z_y^x(sell) \right) - \left(E_y^x(buy) \times z_y^x(buy) \right) \right]; \quad \forall y\, \epsilon Y, \forall x\, \epsilon X \quad (2)$$

where $E_y^x(sell)$ and $E_y^x(buy)$ symbolise energy amounts sold and brought by each user $y \in Y$ in the LEM with unit price $z_y^x(sell)$ and $z_y^x(buy)$ respectively at time $x \in X$. $E_y^x(sell)$ and $E_y^x(buy)$ are bounded by maximum possible energy sold amount $\overline{AE_y^x(sell)}$ and maximum possible energy brought amount $\overline{E_y^x(buy)}$ amount enforced by the LEM operator.

However, the objective function – described in (2) – is confined by a number of energy constraints – that are written below:

$$E_y^x(sell) = E_y^x(PV) - E_y^x(load); \quad \forall y\, \epsilon I \subset Y, \forall x\, \epsilon X \quad (3)$$

$$E_y^x(buy) = E_y^x(load) - E_y^x(PV); \quad \forall y\, \epsilon J \subset Y, \forall x\, \epsilon X \quad (4)$$

$$\textstyle\sum_{y \in I \subset Y} E_y^x(sell) = \sum_{y \in I \subset Y} E_y^x(buy); \quad I, J \subset Y, \forall x\, \epsilon X \quad (5)$$

where (3) and (4) calculate $E_y^x(sell)$ and $E_y^x(buy)$ from solar PV generation $E_y^x(PV)$ and self-demand $E_y^x(load)$ at each time slot $x \in X$. $E_y^x(PV)$ and $E_y^x(load)$ are bounded by maximum solar PV generation $\overline{E_y^x(PV)}$ and maximum self-demand $\overline{E_y^x(load)}$ respectively.

The total selling and buying quantities in the LEM are matched in (5) so that they are equal at all time slots, i.e., $\forall x\, \epsilon X$. If the total selling quantity is more than the total buying quantity, $\left(\sum_{y \in I \subset Y} E_y^x(sell) - \sum_{y \in I \subset Y} E_y^x(buy) \right)$ is traded with the grid at the FiT rate of $z^x(ft)$. Likewise, $\left(\sum_{y \in I \subset Y} E_y^x(buy) - \sum_{y \in I \subset Y} E_y^x(sell) \right)$ is traded with the grid at the ToU price $z^x(tou)$ if the opposite is true. Sets I and J refer to sets of sellers (only prosumers) and buyers (prosumers and consumers), such that $Y = I \cup J$.

Note that $z^x(tou)$ comprises energy price $z^x(eng)$; retailer margin $z^x(retm)$; network cost $z^x(netw)$; and RET $z^x(ret)$as depicted in Table-I.

Nonetheless, the objective function is also subject to some price constraints. Particularly, $z_y^x(sell)$ and $z_y^x(buy)$ in (2) are constrained by $z^x(fit)$ and $z^x(eng)$ respectively to benefit both sellers and buyers in the LEM. Their mathematical relation is represented in (6).

$$z_y^x(sell) > z^x(fit) \text{ and } \left(z_y^x(buy) + z_y^x(pt) \right) < z^x(eng); \quad \forall y\, \epsilon Y, \forall x\, \epsilon X \quad (6)$$

where $z_y^x(pt)$ is the LEM platform charge paid by each buyer in J.

The proposed LEM model also keeps the margin of the retailer $z^{x+}(retm)$, network cost $z^{x+}(netw)$, and RET $z^{x+}(ret)$ unchanged during all time slots, such that

$$z^{x+}(retm) = a \times z^x(retm); \quad \forall x\, \epsilon X \quad (7)$$

$$z^{x+}(netw) = b \times z^x(netw); \quad \forall x\, \epsilon X \quad (8)$$

$$z^{x+}(ret) = c \times z^x(ret); \quad \forall x\, \epsilon X \quad (9)$$

where factors $a, b, c = 1$ in this study.

V. Simulation Results

In this section, the proposed blockchain-facilitated LEM trading mechanism is applied to conduct a case study on a typical Australian suburb – that contains prosumers; consumers; the retailer; and the network utility. The schematic diagram of the considered network, where prosumers and consumers are connected in a single feeder, is provided in Fig. 1. The retailer and the network utility are considered to be connected with prosumers and consumers through communication signals as described in Fig. 2.

Nevertheless, the proposed framework is simulated on the Ethereum blockchain and the smart contracts are written on REMIX IDE [26]. The Ethereum blockchain is created using a Ganache CLI v6.12.2 and web3.py library acts as a bridge between user interface (UI) and blockchain. The average load

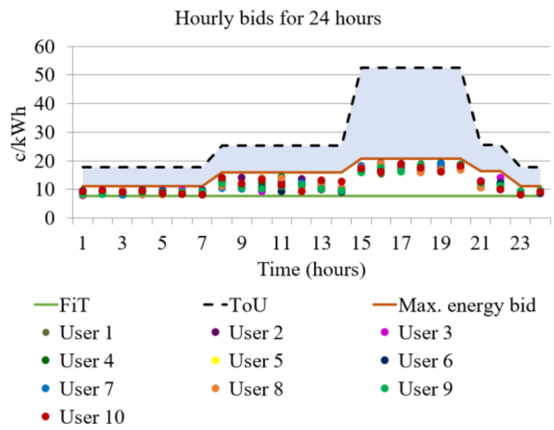

Fig. 4. Hourly bid prices for the LEM users for a period of 24 hours.

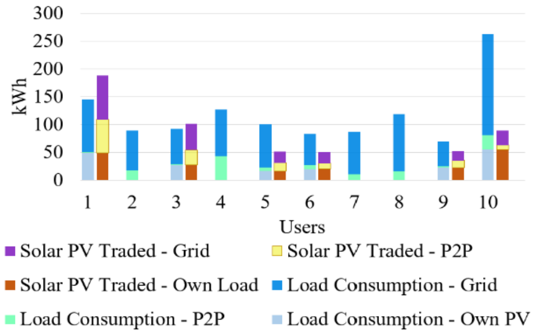

Fig. 5. Energy traded by the energy users for a period of 1 week.

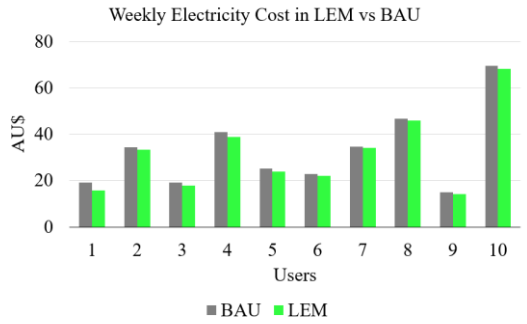

Fig. 7. Weekly electricity cost comparison between BAU and LEM.

and solar PV generation of ten LEM users (six prosumers and four consumers) for a period of 24 hours is considered. In particular, energy users 2; 4; 7; and 8 are considered as consumers while others play the role of prosumers. The average peak load of energy users is found to be 1.71 kW at 19:00 pm, and maximum solar PV generation on average is 2.32 kW recorded at 12:00pm. With these data, the proposed LEM model is compared with BAU to validate the performance.

A. Energy Users' Bidding in the LEM

Fig. 4 illustrates the hourly energy bid prices placed by the energy users for a period of 24 hours of a typical day in Australia. LEM users place their selling/buying bids within the range of FiT and energy portion of ToU prices to achieve the most significant financial gains and quicker return of investment on renewables. Prosumers are given the first priority to trade in the LEM (both for selling and buying) due to their significant investments in renewables followed by the consumers' priority. It is expected that prosumers and consumers benefit more during peak hours (from 2pm to 8 pm) as the difference between ToU and FiT prices are the highest. The overall cost reduction of the participating energy users is evaluated in Subsection V-C.

B. Energy users' Trading in the LEM

Fig. 5 reveals the amounts of traded energy by energy users in the LEM over the course of a typical week. The solar PV energy is either self-consumed or traded with the grid and other LEM users. Contrarily, energy demand is met either from the grid or from the solar PVs' energy (both from self-generation and peers'-excess). For instance, energy user 10 (who acts as a prosumer) has 262 kWh weekly demand in total. This amount is fulfilled in three ways: self-solar PV consumption (55 kWh); P2P trading (26 kWh); and grid import (181 kWh). Clearly, the energy user has to buy a greater amount of energy grid as the solar PV supply runs out at around 5 pm (please see Fig. 4), and the peak demand period stays up to 8 pm.

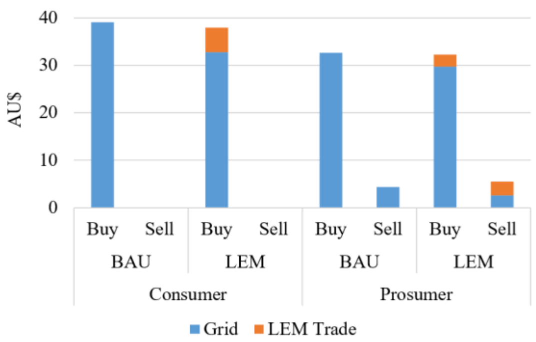

Fig. 6. Electricity cost distribution among consumers and prosumers.

C. Energy Users' Electricity Cost Reduction

Fig. 6 demonstrates the average electricity cost of prosumers and consumers in the LEM in contrast with BAU, which suggests that consumers can buy in the LEM at a cheaper price. On the other hand, prosumers buy and sell at cheaper and higher prices respectively. That is reflected in the overall cost expenditure of each energy user illustrated in Fig, 7. As is noticed from Fig. 7, all prosumers and consumers are able to cut down their energy expenses. For example, user 1; being a prosumer; is able to reduce its electricity cost by 17% – which is the highest benefit among all considered energy users due to the fact of trading 57 kWh in the LEM for a period of 1 week. Contrarily, user 7 (who is a consumer) is the least beneficiary – managing to decrease its cost by 1% because of trading only 10.37 kWh in the LEM. Strikingly, all of the energy users bring down their electricity bill (figuring 3% and 5% on average for consumers and prosumers respectively). This finding is definitely motivational for them to join in the LEM framework.

D. Cost of Using Ethereum Blockchain

The cost of executing smart contracts in the Ethereum blockchain is analysed in Table-II, in which every operation in the Ethereum blockchain is executed by the EVM, and the amount of computational effort is represented by the associated gas amount in the fourth column. The gas price for exercising LEM smart contracts (to execute numerous functions that include user registration; bidding; P2P trading; billing; and settlement) on Ethereum blockchain is given in the fifth column of Table-II.

The cost of operating a P2P-driven LEM on the Ethereum blockchain platform is relatively high as indicated in Table-II. This is because of the congestion as transaction speed of Ethereum network is low (approximately 15-17 transactions per second). The cost can be reduced by 100 folds with the

TABLE II. COST OF EXECUTING SMART CONTRACTS

SI#	Action	Executor	Gas Amount	Gas Price (GWAI)	Total Cost (ETH)	Total Cost (AU$)
1	Deploy Smart Contract	Admin	3928062	20	0.0786	183.41
2	User Register	Users	43967	20	0.0009	2.053
3	Bidding	Energy users	113234	20	0.0023	5.28
4	Calculation	Admin	362957	20	0.0073	16.95
5	Billing	Admin	101403	20	0.0020	4.73
6	Settlement	Admin	59259	20	0.0012	2.76

help of other blockchain platforms like Solana and Ploygon for example, which could be a potential extension of the developed LEM model.

VI. CONCLUSION

In this paper, the deployment of P2P-driven LEM on the blockchain platform has been presented with an actual case study in the Australian context. A mechanism has been demonstrated to establish bilateral bidding, transactions, and billing settlement among various LEM users by dint of smart contracts. The Ethereum blockchain has been adopted to write smart contracts and store all trading-related information. To execute P2P trading quantity and price negotiations between different energy users, a mathematical framework has also been proposed confirming the engagement of the retailer and network operator. To end with, a case study has been performed to evaluate the efficacy of the proposed blockchain-enabled P2P trading in the LEM. It has been found from the simulation results that the developed framework can minimise the electricity expenditure of each LEM energy user while keeping the blockchain operational cost reasonable.

The future work will validate the proposed LEM model on Solana blockchain to quicken P2P trading and billing settlement economically. In addition, the application of advanced forecasting and machine learning algorithms will be incorporated to guarantee security with no/less prediction errors.

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