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# Blockchain-integrated Local Energy Market and P2P Trading Benefits for Participants and Stakeholders

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**Abstract**— This paper presents a local energy market (LEM) model to conduct peer-to-peer (P2P) energy trading between a number of participants by dint of the Ethereum-based blockchain technology. The proposed LEM mechanism is structured by considering relevant functional constraints while energy trading is arranged between several participants in the presence of other stakeholders including energy retailer and network operator. LEM participants' mutual bidding intended P2P trading, actual settlement, and final billing are executed using the smart contracts in Ethereum blockchain to record LEM transactions and related data in an unchangeable and distributed fashion. Lastly, a case study is performed in an Australian suburb with 300 LEM participants, and the simulation results are benchmarked with an existing business-as-usual (BAU) scenario. The simulation results outline that the formulated LEM mechanism 1) reduces the electricity cost of participants remarkably while improving their self-sufficiency, 2) minimises power grid export and import, and 3) retains income margins for the energy retailer and network operator.

**Keywords**— Blockchain, local energy market, peer-to-peer trading, energy retailer, network operator.

## I. INTRODUCTION

Modern energy sector is experiencing a major transition due to the rapid uptake of distributed energy resources (DERs). The proliferation of small-scale DERs at the residential level is also conspicuous. For instance, Australia has already experienced remarkable installation of solar photovoltaic (PV) systems, figuring more than 20% of its residential customers [1-2]. Feed-in-tariff (FiT) is the most common scheme to incentivise these solar PV owners – often termed as prosumers. However, the FiT rate is getting scaled down – due to a number of policies adopted by the authority. For example, it is now around 3 c/kWh in Western Australia (WA). This has created a substantial dissatisfaction among existing prosumers and made it difficult to convince other non-solar customers to become prosumers [3].

To this end, the perception of local energy market (LEM) has come to the light over the past few years – which aims at propelling clean energy integration into the electricity network by creating a sub-electricity market to manage energy scheduling, trading, and services in both technically- and economically-feasible manner [4]. LEM can facilitate peer-to-peer (P2P) energy trading among prosumers and consumers to receive phenomenal financial returns in contrast with the business-as-usual (BAU) – in which energy is bought/sold at time-of-use (ToU)/FiT prices [5]. However, several challenges exist to establish a functional P2P trading model as it needs to incorporate multifarious goals of prosumers and consumers while settling the market efficaciously [6].

Recently, several interesting proposals have been made to structure P2P trading as a participant-centric strategy. Participants' behaviour; attitudes; and subjective norms are prioritised to organise P2P trading in [7]. How place attachment; climatic variations; and political orientation

influence trading are also analysed in [8-9]. Moreover, the most striking factor that really motivates participant to engage in P2P trading; i.e., electricity cost reduction; is identified in [10], and the commensurate determination of P2P trading source size and price to lower electricity cost are emphasised in [11]. The authors in [12] also adopt advanced constraint optimisations to formulate P2P bidding virtually, analyse price components associated with P2P trading, and accelerate local energy usage respectively with an intention to cut down energy usage expenditure. In [13-14] authors used different optimisation techniques for sizing and profit maximisation of renewable energy resources and proposed architecture for energy trading.

As for executing P2P trading securely, most contemporary research studies rely upon blockchain technology. This is because the blockchain platform can store transaction history of different participants on a reliable and secure database. In addition, participants are provided with access to the database to cross-verify transactions in a trustworthy fashion [15]. As such, various blockchain-enabled P2P trading mechanisms to have been proposed. For instance, a multi-time-scale autonomous energy trading framework based on blockchain is developed in [16]. A blockchain-empowered P2P market flexibility model is designed in [17]. The authors in [18] formulate a cryptocurrency-driven token trading for active participants. Furthermore, smart contracts on the blockchain are also applied for automated P2P market settlement. However, both participant- and blockchain-oriented case studies do not consider the incorporation of energy retailers and network operators – which are equally important bodies as energy retailers systematise the electricity bill while network operators monitor the local energy flow.

Given this context, this paper presents a blockchain-integrated LEM framework, in which solar PV - and battery energy storage system (BESS)-facilitated P2P trading (considering export and import limits assigned by the network operator) is carried out in a decentralised way ascertaining the financial interests of participants, energy retailers, and the network operator. The proposed framework is also validated with real-field data in the context of Australia – where the National Electricity Market is undergoing an unprecedented price hike and a well-functioning LEM has the potential to offer productive services at the residential level. The main contributions are:

- A blockchain-integrated LEM framework – is proposed for P2P trading governed through smart contracts.
- A LEM business model is developed to monetise not only P2P participants but also energy retailers and the network operator.
- Finally, a case study is conducted using real-world energy and price data and the performance is judged in comparison with the BAU practised in Australia.

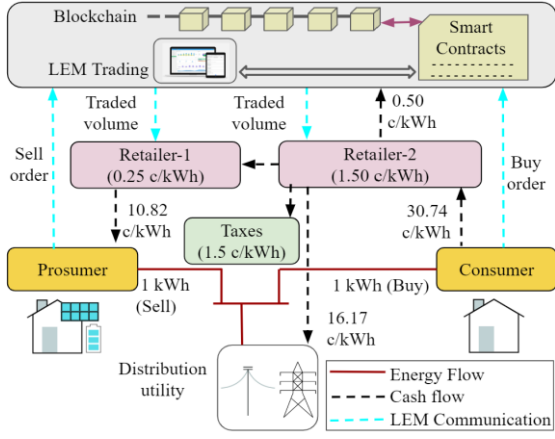


Fig. 1. An example of P2P energy trading between a prosumer and a consumer in the presence of two retailers and a network operator.

The remainder of the paper is organised as: Overviews of the LEM framework and blockchain-integrated structure are discussed in Section II and Section III respectively. The proposed business model formulation is demonstrated in Section IV. Numerous simulation results are presented in Section V, and the paper is wrapped up in Section VI.

## II. AN OVERVIEW OF LEM FRAMEWOK

In the LEM, participants are given an opportunity to execute P2P energy trading among each other to satisfy the energy demand while energy exchange with the grid becomes the second priority. LEM participants are directed to place their P2P trading bids in a forward-facing market to receive maximum returns from their locally produced energy. An example of P2P energy trading at the LEM platform between two participants (e.g., a prosumer and a consumer) in the presence of two retailers and a network operator is exhibited in Fig. 1, in which Retailer-1 has 60 prosumers with solar PVs and BESSs, 60 prosumers with solar PVs, and 30 consumers. Whereas Retailer-2 has 150 consumers only as displayed in Fig. 2. A ToU tariff structure with peak and off-peak time slots is considered to maximise P2P trading volumes to attain maximum monetary gains. Fig.1 illustrates how various TOU tariff components, such as network operator margin; retailers' margin; and taxes, are retained while P2P trading price is settled between a prosumer and a consumer in the LEM platform.

## III. BLOCKCHAIN INTEGRATION INTO LEM

Blockchain is a distributed, secure, and encrypted database incorporating a chronologically arranged set of

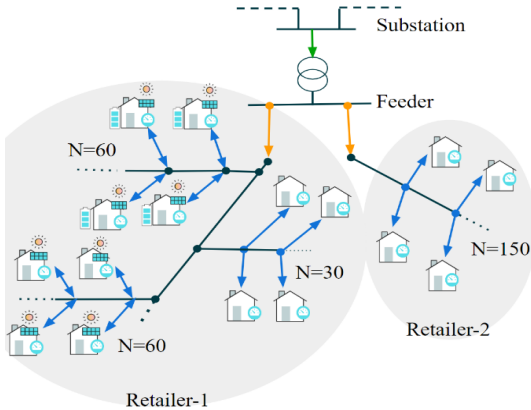


Fig. 2. Considered LEM architecture

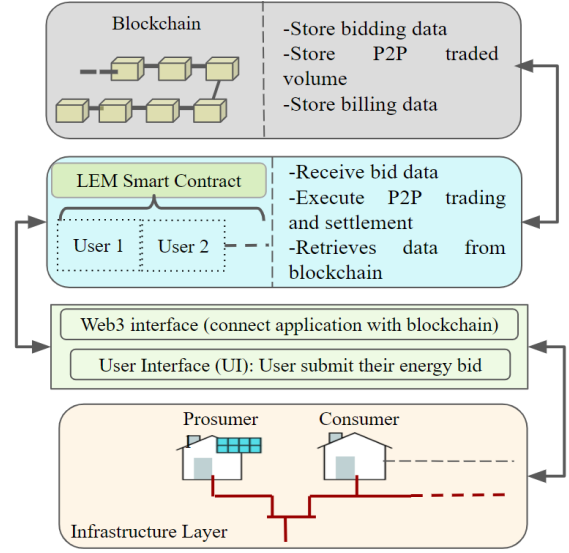


Fig. 3. Blockchain integration with LEM.

transactions designated as blocks – that are driven by consensus protocols and immutable characteristically. Smart contracts are the agreements between participants written and executed in a blockchain to guarantee the occurrence of transactions automatically. Ethereum is one of the blockchain platforms for creating decentralised applications. Ethereum provides the smart contracts that allows the computation of the state of the Ethereum network after each new block is added to the chain.

Fig. 3 shows the Ethereum based blockchain integration into LEM, where energy exchange takes place at the first infrastructure layer and participants are physically connected through a distribution lines. In the second layer, decentralised application (DApp) connects users with smart contract and blockchain. In the third layer, smart contract are created for the energy users, received bidding data, performed P2P bidding and settlement. In the final layer, blockchain technology is used to store bidding data, record P2P transactions and billing information.

DApp contains the user interface (UI) and web3 interface which allows participants to place their bid orders and view information about energy traded. On other side, admin not only can view P2P trading information on UI screen but also have permissions to deploy smart contract, execute P2P trading, billing and settlement. In the architecture as overall, participants receive the financial benefit through local P2P trading, admin organises the LEM trading activity, and blockchain provides a platform for P2P trading.

## IV. PROPOSED LEM BUSINESS MODEL FORMULATION

The main objective of the proposed LEM business model is to minimise the electricity cost of all participants (both prosumers and consumers) without hampering the financial interests of energy retailers and the network operator. Let  $a \in A$  be the index of each participant in  $A$ . If buying and selling costs are denoted by  $C_{a,i}^{buy}$  and  $C_{a,i}^{sell}$  at each P2P trading slot  $i \in I$ , the proposed objective function of of each participant  $a \in A$  is given by:

$$\text{Min } \Sigma \{C_{a,i}^{buy} - C_{a,i}^{sell}\}; \forall a \in A, \forall i \in I \quad (1)$$

subject to price, energy, and BESS constraints.

where  $C_{a,i}^{buy}$  and  $C_{a,i}^{sell}$  are defined at each trading slot  $i \in I$  with length  $\Delta i$  as:

$$C_{a,i}^{buy} = u_{a,i}^{buy} \times P_{a,i}^{buy} \times \Delta i; \forall a \in A, \forall i \in I \quad (2)$$

$$C_{a,i}^{sell} = u_{a,i}^{sell} \times P_{a,i}^{sell} \times \Delta i; \forall a \in A, \forall i \in I \quad (3)$$

In (2) and (3),  $u_{a,i}^{buy}$ ,  $a \in B$ , and  $u_{a,i}^{sell}$ ,  $a \in S$ , refer to unit buying and selling costs respectively in c/kWh – where the sets of buyers and sellers are symbolised by  $B \subset A$  and  $S \subset A$  respectively. Further, buying and selling quantities are indicated by  $P_{a,i}^{buy}$ ,  $a \in B$ , and  $P_{a,i}^{sell}$ ,  $a \in S$ , respectively – which are calculated in (4) and (5) as follows:

$$P_{a,i}^{buy} = P_{a,i}^{ld} - P_{a,i}^{sol} - P_{a,i}^{dis(o)} + P_{a,i}^{cha(p)}; \forall a \in B, \forall i \in I \quad (4)$$

$$P_{a,i}^{sell} = P_{a,i}^{sol} - P_{a,i}^{ld} - P_{a,i}^{cha(o)} + P_{a,i}^{dis(p)}; \forall a \in S, \forall i \in I \quad (5)$$

where  $P_{a,i}^{ld}$  and  $P_{a,i}^{sol}$  are power demand and solar PV generation of each participant  $a \in A$ . In (3),  $P_{a,i}^{ld} > P_{a,i}^{sol}$ . On the other hand,  $P_{a,i}^{sol} > P_{a,i}^{ld}$  in (4). BESS-charged power via in-house and peers are signified by  $P_{a,i}^{cha(o)}$  and  $P_{a,i}^{cha(p)}$  respectively. Whereas  $P_{a,i}^{dis(o)}$  and  $P_{a,i}^{dis(p)}$  imply BESS-discharged power via in-house and peers respectively. Note that BESS is considered to be charged and discharged via in-house and/or peers.

*Price constraints*

$$u_{a,i}^{buy} < u_{a,i}^{eng} < u_{a,i}^{tou} \text{ and } u_{a,i}^{sell} > u_{a,i}^{fit}; \forall a \in A, \forall i \in I \quad (6)$$

$$u_{a,i}^{ret(p)} \geq u_{a,i}^{ret} \text{ and } u_{a,i}^{nop(p)} \geq u_{a,i}^{nop}; \forall a \in A, \forall i \in I \quad (7)$$

where  $u_{a,i}^{fit}$  denotes FiT rate in c/kWh in (6).  $u_{a,i}^{tou}$  (also in c/kWh) is the ToU price – which consists of energy price  $u_{a,i}^{eng}$ , energy retailer margin  $u_{a,i}^{ret}$ , network operator margin  $u_{a,i}^{nop}$ , and taxes  $u_{a,i}^{tar}$  (if applicable) paid by each LEM participant  $a \in A$  as per BAU. In a P2P trading slot  $i \in I$ , energy retailer margin and network operator margin are represented by  $u_{a,i}^{ret(p)}$  and  $u_{a,i}^{nop(p)}$  respectively in (7) while  $u_{a,i}^{tar}$  (if applicable) remains the same.

*Power constraints*

$$P_{a,i}^{buy} \leq P_i^{imp(max)} \text{ and } P_{a,i}^{sell} \leq P_i^{exp(max)}; \forall a \in A, \forall i \in I \quad (8)$$

$$\sum_{a=1}^{|B|} P_{a,i}^{buy} = \sum_{a=1}^{|S|} P_{a,i}^{sell}; \forall i \in I \quad (9)$$

$$(\sum_{a=1}^{|B|} P_{a,i}^{buy} - \sum_{a=1}^{|S|} P_{a,i}^{sell}) < P_i^{imp(tot)}; \forall i \in I \text{ and}$$

$$(\sum_{a=1}^{|S|} P_{a,i}^{sell} - \sum_{a=1}^{|B|} P_{a,i}^{buy}) < P_i^{exp(tot)}; \forall i \in I \quad (10)$$

(8) describes that  $P_{a,i}^{buy}$  and  $P_{a,i}^{sell}$  are limited by maximum import limit  $P_i^{imp(max)}$  and maximum export limit  $P_i^{exp(max)}$  – which are predefined by the network operator to maintain the operational safety of the electricity network. The P2P buying and selling quantities are matched in (9). Any mismatch at a given trading slot  $i \in I$  is settled outside the LEM at either ToU or FiT price, but the electricity grid-friendly constraints to handle mismatch is illustrated in (10) – where total power import and export as per BAU are symbolised by  $P_i^{imp(tot)}$  and  $P_i^{exp(tot)}$  respectively.

*BESS constraints (in-house management)*

$$O_{a,i} = O_{a,i-1} + (e_a^{cha} (P_{a,i}^{cha(o)} \times \Delta i)) - \left( \frac{(P_{a,i}^{dis(o)} \times \Delta i)}{e_a^{dis}} \right);$$

$$\forall a \in A, \forall i \in I \quad (11)$$

$$O_a^{min} \leq O_{a,i} \leq O_a^{max}; \forall a \in A, \forall i \in I \quad (12)$$

$$E_a^{cha(min)} \leq (P_{a,i}^{cha(o)} \times \Delta i) \leq E_a^{cha(max)}; \forall a \in A, \forall i \in I \quad (13)$$

$$E_a^{dis(min)} \leq (P_{a,i}^{dis(o)} \times \Delta i) \leq E_a^{dis(max)}; \forall a \in A, \forall i \in I \quad (14)$$

(11)-(14) capture BESS constraints for in-house charging and discharging, where  $O_{a,i}$  is the state-of-charge (SOC) – limited by minimum and maximum SOCs indicated by  $O_{a,i}^{min}$  and  $O_{a,i}^{max}$  respectively.  $e_a^{cha}$  and  $e_a^{dis}$  are charging and discharging efficiencies respectively.  $E_a^{cha(min)}$  and  $E_a^{cha(max)}$  indicate minimum and maximum charging capacities respectively. Whereas minimum and maximum discharging capacities are signified by  $E_a^{dis(min)}$  and  $E_a^{dis(max)}$  respectively.

*BESS constraints (P2P trading)*

$$P_{a,i}^{cha(p)} \times \Delta i = \min \{ \underline{E_{a,i}^{cha}}, E_{a,i}^{cha(ca)} \};$$

$$\forall a \in A, \forall i \in I \quad (15)$$

$$\underline{E_{a,i}^{cha}} = (E_{a,i}^{cha(max)} \times e_a^{cha}) - (P_{a,i}^{cha(o)} \times \Delta i);$$

$$\forall a \in A, \forall i \in I \quad (16)$$

$$E_{a,i}^{cha(ca)} = O_{a,i}^{max} - O_{a,i-1} - (P_{a,i}^{sol(pk)} \times \Delta i) - (P_{a,i}^{cha(o)} \times \Delta i); \forall a \in A, \forall i \in I \quad (17)$$

$$P_{a,i}^{dis(p)} \times \Delta i = \min \{ \underline{E_{a,i}^{dis}}, E_{a,i}^{dis(ca)} \}; \forall a \in A, \forall i \in I \quad (18)$$

$$\underline{E_{a,i}^{dis}} = (E_{a,i}^{dis(max)} \times e_a^{dis}) - (P_{a,i}^{dis(o)} \times \Delta i);$$

$$\forall a \in A, \forall i \in I \quad (19)$$

$$E_{a,i}^{dis(ca)} = O_{a,i-1} - O_a^{min} - (P_{a,i}^{ld(pk)} \times \Delta i) - (P_{a,i}^{dis(o)} \times \Delta i); \forall a \in A, \forall i \in I \quad (20)$$

BESS charging constraints via peers are shown in (15)-(16).  $P_{a,i}^{cha(p)}$  is bounded by peer-charging rate  $\underline{E_{a,i}^{cha}}$  and available charging capacity  $E_{a,i}^{cha(ca)}$ .  $P_{a,i}^{sol(pk)}$  is solar PV power at the peak time. (17)-(20), on the contrary, demonstrate BESS discharging constraints via peers.  $P_{a,i}^{dis(p)}$  is constrained by peer-discharging rate  $\underline{E_{a,i}^{dis}}$  and available discharging capacity  $E_{a,i}^{dis(ca)}$ .  $P_{a,i}^{ld(pk)}$  implies power demand at the peak time.

## V. CASE STUDY AND ANALYSIS

In this section, the proposed LEM framework is validated in an actual Australian suburb with real-world residential data [19]. The complete LEM architecture with participants, retailers and the network operator are depicted in Fig. 2. The existing ToU tariffs and FiT rates in Australia are taken from [20-21]. Nevertheless, proposed architecture is tested on local Ethereum. Ganache-CLI v6.12.2 is used to create personal Ethereum Blockchain in desktop and the smart contracts. The LEM platform cost is considered as 0.5 c/kWh as demonstrated in Fig. 1. The P2P transactions among participants are conducted every 15 mins apart and the

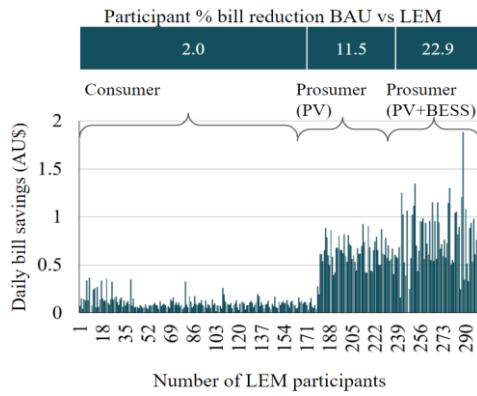


Fig. 4. All participants' savings (AUS) and percentage bill reduction on average of consumers, prosumers (PVs), and prosumers (PVs and BESSs)

performance is compared with an existing BAU practice in Australia in terms of electricity cost reduction, grid import and export minimisation, impacts on retailers' and network operator's margins, and self-sufficiency.

#### A. Daily Electricity Cost Reduction of Participants

It can be seen in Fig. 4 that if the LEM participants trade via P2P, the energy bill reduction for consumers, prosumers with PVs, and prosumer with PVs and BESSs become 2%, 11.5%, and 22.9%, respectively on average. The average energy usage cost reduction for consumers (BAU vs LEM) is small (e.g., within 0.5 AUS) due to the fact of insignificant difference of grid buy rate and maximum buy rate in the LEM. There is an appropriate reduction in electricity bill (i.e., around 1 AU\$ on average) for prosumers with PVs on average as they sell their excess power in the LEM at a price much higher than the FiT rate. Strikingly, the energy usage cost reduction is significant for prosumers with both PVs and BESS as they sell excess solar PV power to other peers and make additional money by selling/buying BESS power at a higher/cheaper rate.

Fig. 5 captures the daily in-house power management profile of one sample LEM participant (i.e., a prosumer with solar PV and BESS). The consumption (blue in colour) shows the total consumption before solar and BESS. The yellow curve shows the total solar PV generation before being absorbed by load and BESS. The BESS charging (positive) and discharging (negative) are displayed in green. The main meter curve (red in colour) is the net of all other values and shows the energy exchange at the grid connection point.

#### B. Power Trading with Grid Minimisation

It is evident from Fig. 6 that power sold and bought to and from the grid are minimised by 10.8% and 17.1% respectively with to the introduction of the proposed P2P trading-empowered LEM framework. The power sold to the

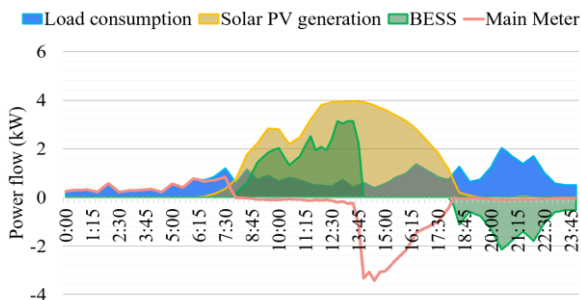


Fig. 5. Participants power flow analysis

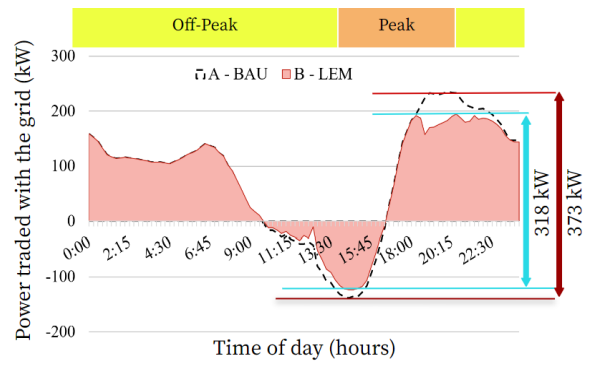


Fig. 6. Power trading with the grid comparison.

grid during off-peak hours is lowered because excess solar PV power are sold to charge the BESSs of other LEM participants. In this case, both solar power sellers and BESS power buyers are incentivised more than the FiT and off-peak ToU prices respectively. Likewise, the reduction in brought power from the grid during peak demand is caused as some LEM participants buy power from the discharge of BESSs of other participants. Here, BESS discharge sellers and demand buyers trade at an optimised LEM rate which is higher than the FiT rate but lower than the peak ToU price.

#### C. Retailer's and Network Operator's Margins

The daily fee paid to the retailer remains the same in case of BAU and proposed LEM. However, the grid fee (that is the retailer's margin in ToU price) is reduced as energy is traded at the P2P rate. Since the retailer gets its margin for every P2P transaction, Retailer-1 with different types of LEM participants (as its customers) receives increased amount of margin (i.e., 2% more than BAU) as noticed from Fig. 7(a). Contrarily, the margin of Retailer-2 is kept unvaried (please see Fig. 7(a) as it has only consumers).

As observed from Fig. 7(b), the network operator's income margin is marginally increased in LEM by 0.4% compared to BAU due to an increase in trading volume during mid-day when BESSs are charged from other participants through the LEM platform. Although the network operator may not receive attractive economic gains in terms of enlarging its margin, the proposed LEM framework can assist them in reducing their budget to maintain the network infrastructure against congestion, peak demand supply, and solar soak as the proposed LEM model brings down trading with the grid during off-peak and peak periods.

#### D. Self-sufficiency of Participants

Self-sufficiency is defined as the amount of total power demand satisfied locally (not from the grid), e.g., using solar PV and BESS. Fig. 8 shows the average self-sufficiency of the participants in the LEM in contrasting with BAU. The proposed LEM enhances the self-sufficiency of participants

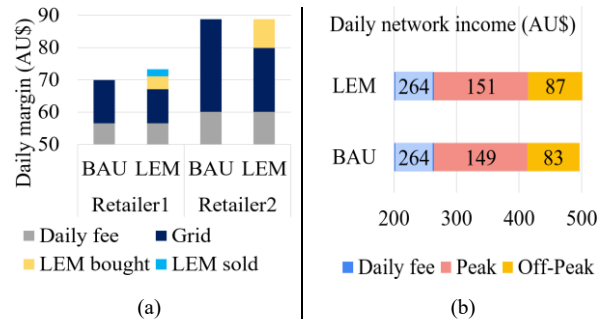


Fig. 7. Daily income margin of a) retailers, and b) network operator

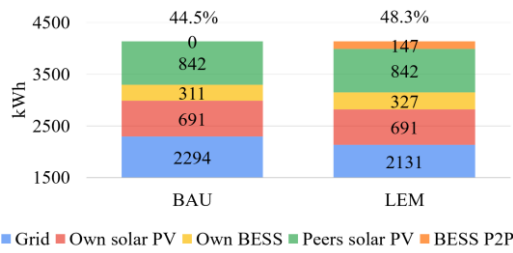


Fig. 8. Self-sufficiency BAU vs LEM

by 4%, which is motivational to encourage electricity customers to join in the LEM.

## VI. CONCLUSION

In this paper, a P2P trading-facilitated LEM model has been presented using Ethereum-enabled blockchain technology. The proposed LEM structure has considered a number of operational constraints while allowing participants to trade in the P2P market in a decentralised fashion in the presence of retailers and the network operator. Further, smart contracts have been executed in Ethereum blockchain to record P2P bidding and transactions settled among participants. Lastly, a case study has been performed in the context of an Australian suburb, where the participation of 300 participants has been considered – 180 consumers, 60 prosumers with solar PVs, and 60 prosumers with solar PVs and BESSs. It has been found from the simulation results that the proposed LEM framework has successfully reduced participants electricity cost, minimised power export/import to/from the grid, retained/slightly increased income margins for retailers and the network operator, and improved self-sufficiency of the participants.

The findings of this paper can contribute greatly motivate electricity consumers to take part in the LEM flexibly. In addition, retailers can get an option to buy less energy from the National Electricity Market (which is volatile in Australia with sudden price hike) to satisfy its contracted consumers and save money. Moreover, the network operator can get relief of local congestion problem and subsequent investments caused by excessive unused local penetration. The future work will incorporate advanced techniques to improve the privacy and security of blockchain technology in the proposed LEM model. Another blockchain platform, such as Solana, will also be tested to speed up P2P transactions and settlement in the LEM.

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