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Application of a Community Battery-integrated Microgrid in a Blockchain-based Local Energy Market Accommodating P2P Trading

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ABSTRACT This paper presents the application of a community battery energy storage system (CBESS)-integrated microgrid (MG) in a blockchain-enabled local energy market (LEM). The proposed LEM balances the community energy requirement while facilitating frequent peer-to-peer (P2P) energy transactions between several energy users in the presence of both energy supplier and energy operator. The architecture is formulated by taking a number of local market and network constraints, that include residential battery energy storage system (RBESS) constraints; CBESS constraints; P2P traded price constraints; P2P traded power constraints; margin constraints of the stakeholders; power grid export and import constraints; and network energy balance constraints, so as to not only incentivise energy users but also reduce import/export from/to power grid while keeping the margins of energy supplier and energy operator unaffected. Different types of transactions data including energy users' P2P pricing bids and P2P traded energy volume are also stored in the blockchain database. Further, the developed LEM framework is also validated through a case study executed on an actual Australian power grid network, comprising 260 residential energy users; two energy suppliers; an energy operator; and a CBESS, and the performance of the proposed P2P trading-based LEM strategy is compared with the existing business-as-usual (BAU) that directs energy users to buy/sell energy at the time-of-use (ToU)/ feed-in-tariff (FiT) rate. The extensive and comparative simulation results confirm the superior performance of the proposed LEM mechanism in terms of minimising energy users' electricity bill; lowering power grid import and export; and retaining margins of energy suppliers and the energy operator; and thus, emphasise its application suitability in the current electricity market.

INDEX TERMS Blockchain, community battery, energy supplier, local energy market, energy operator, peer-to-peer energy trading, power grid.

I. INTRODUCTION

The local energy market (LEM) provides a marketplace, that is essentially a sub version of a typical electricity market operated and managed locally [1], to permit a number of energy users and stakeholders to trade among themselves respecting different market and network constraints [2]. A distributed ledger-based platform, such as blockchain [3], is usually used to accommodate bilateral and multilateral negotiations between the energy users and other residential energy service providers [4]. These sorts of mutual negotiations to settle energy and price locally are termed as peer-to-peer (P2P) energy trading [5]. There could be three types of energy users in general, namely 1) consumers; 2) prosumers (consumers who can generate energy) equipped with solar photovoltaic (PV) systems; and 3) prosumers equipped with solar PVs and residential battery energy storage systems (RBESSs) [6]. On the other hand, residential energy service providers primarily include energy suppliers and the energy operator [7].

Most of the recent studies focus on motivating energy users to join in the P2P trading-driven LEM. For instance, the authors in [8] prioritise energy users' preferences to decide on trading quantities, prices, partners, and periods. Energy users are also provided with the ability to trade individually or as a part of a group in [9]. While remaining as part of a power grid network, energy users attain the flexibility to stay aloof from the P2P trading (whenever opted for) in [10]. The application of P2P trading in cutting back the electricity costs of the energy users is also emphasised in [11]. In [12], the importance of formulating a robust P2P decision-making process is highlighted to guarantee notable energy cost minimisation. It is recommended in [13] to set the P2P trading price between the feed-in-tariff (FiT) rate and time-of-use (ToU) price so that both participating sellers and buyers can receive economic benefits in contrast with business-as-usual (BAU). This recommendation is further considered by the authors in [14], and the conducted research study figures out that both sellers and buyers can enlarge their savings by at least around 5% – which could be influential for energy users to join in the LEM.

Some other studies also analyse the benefits of the power grid (and thus energy operator), while P2P transactions are performed, with the intention to increase the acceptability of the LEM in practical power networks. For instance, local energy supply and demand is balanced with the help of P2P selling and buying orders in [15]. An incentivising mechanism is developed in [16] to reward the P2P users willing to serve the power grid in terms of local energy management. Further, grid-dependent demand is handled in a decentralised fashion through P2P trading in [17] to get rid of the supply constraint. As for the energy suppliers, their roles and integration importance are acknowledged in [18]. The impact of involvement of energy suppliers on impacting the features of a well-functioning LEM is analysed in [19]. Moreover, the aggregated prosumers-facilitated energy supplier concept is reported in [20] to design a futuristic LEM.

P2P trading in the community microgrid (MG) domain is also noticeable in the current literature as it can facilitate fruitful coordination and power sharing between distributed energy resources (DERs) and consumers [21]. In particular, the authors in [15] apply P2P trading in a community MG dictated by the engaging energy users. The diversified energy users' interests are also considered in [22] for the urban community MG system. An iterative auction framework is designed by the authors in [23] to conduct P2P trading in a community MG. The energy balance of a community MG is guaranteed in [24] through an innovative P2P trading strategy. To ensure flexible energy sharing in the community MG via P2P technique, a battery control based on two-stage aggregates is discussed in [25]. A P2P trading model, coordinated with aggregated MGs, is designed in [26] to avoid the penalty risk resulting from energy contracts' deviation. Furthermore, optimal sizing and economic scheduling of P2P trading-driven multi-MG and community-MG systems are also reported in [27] and [28] respectively. Moreover, the stochastic management of locally controlled energy-governed MGs is carried out in [29].

TABLE I
SUMMARY OF EXISTING LITERATURE AND PROPOSED WORK

Work Focus	Energy Users	Energy Suppliers and Operator	CBESS-based MG
Literature [8-14]	✓	✗	✗
Literature [15-20]	✗	✓	✗
Literature [21-29]	✗	✗	✓
Proposed Model	✓	✓	✓

For executing peer-to-peer (P2P) trading securely, recent research has mostly used the concept of blockchain technology. Overall, blockchain-based P2P trading platforms have different functions, including data securing, tracking, formulation, and energy trading, to show participants 'benefits. In blockchain, participants are given access to trading output to cross-verify transactions in a trustworthy way [30]. Recently, different blockchain-based P2P trading concepts have been designed. Particularly, authors in [31] develop blockchain-enabled a multi-time-scale autonomous energy trading framework. A blockchain-empowered P2P market flexibility model is proposed in [32], and cryptocurrency-driven token trading is formulated for active participants in [33]. 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 suppliers and operators – which are equally important to run the LEM in practice.

Undoubtedly, all the research studies reviewed above have created a significant base to articulate the potency of P2P trading both in LEM and MG domains. However, they are devout towards focusing on either energy users, energy suppliers and operators, or MG as illustrated in Table-I. Also, the integration between LEM and MG domains is missing. This could result in facilitating local energy balance and minimising export/import to/from the upstream power grid further, and thus, reducing the possibility of network congestion. That can also contribute towards cutting down energy transmission and costs substantially in the long run. Given this content, this paper focuses on integrating a community battery energy storage system (CBESS)-facilitated MG — which is assumed to be operated by the energy operator — into a LEM that not only rewards energy users engaged with P2P trading but also ascertains that both the energy operator and energy suppliers do not lose their portions while power grid import and export and are substantially decreased. The proposed CBESS-integrated LEM mechanism is also validated by dint of a case study in the context of Australia.

This paper contributes to the literature by making the following advantageous contributions:

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- A P2P trading strategy is proposed by incorporating various energy users, energy suppliers, and the authorised energy operator in a realistic LEM.
- A CBESS-based MG is integrated with the proposed blockchain-based LEM to ensure local energy balance, leading to lower import/export from/to the power grid.
- A case study with actual data from the Australian power network is showcased to demonstrate the monetary gains for all participating energy users, energy suppliers, and the energy operator and stimulate their presence.
- It is shown that the proposed P2P trading-driven LEM model minimises energy expenditures of all energy users substantially, curtails power grid's export and import considerably, and keeps the margins of other stakeholder unchanged to stimulate their engagement.

The structure of the paper is as follows. A CBESS-integrated LEM model is described briefly in Section II, the trading process involving energy suppliers is discussed in Section III. The following section (Section IV) proposes mathematical formulation to develop the designed P2P trading strategy. Section V provides the simulation results to validate the methodology, and Section VI contains the concluding remarks.

II. LEM AND CBESS-DRIVEN MICROGRID: OVERVIEW

LEM is one of the modern energy market solutions that is essentially a catalyst to share energy within the local community, to integrate DERs and minimise power grid problems to some extent. With the additional revenue streams, it encourages energy users to participate in P2P trading and promotes the utilisation of RBESSs [2]. One of the goals of LEM is to extend self-sufficiency within the local community to reduce dependency on the power grid, thus the energy operators are somewhat relieved from power quality and network congestion complexities [5].

Fig. 1 depicts the architecture of the studied blockchain-based LEM model, consisting of 260 energy users in total

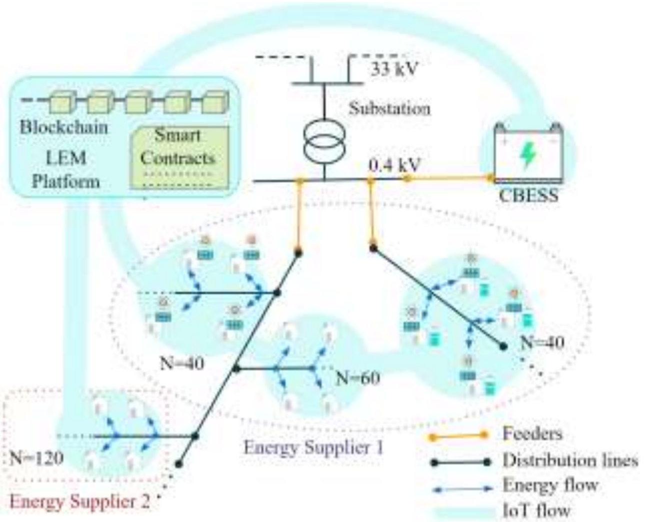

FIGURE 1. Architecture for the LEM and CBESS-driven microgrid.

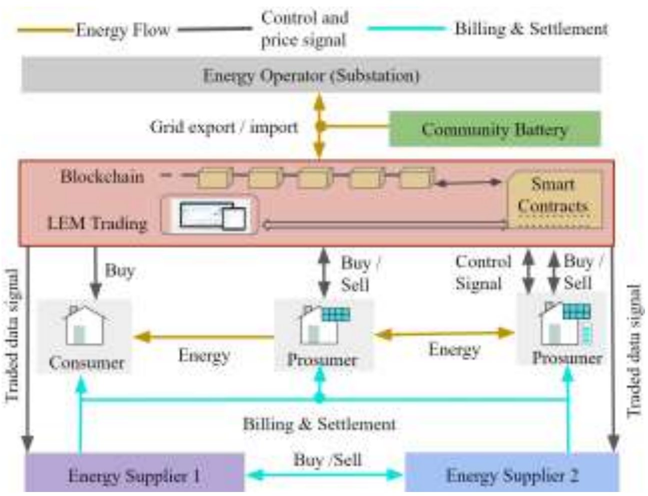

FIGURE 2. LEM integration with an energy operator and two energy suppliers.

(including all three types) and two energy suppliers under a single distribution substation and connected through two feeders [34]. As is captured in Fig. 1, Energy Supplier 1 has 140 energy users in total including 60 consumers; 40 prosumers with solar PV; and 40 prosumers with solar PVs and RBESSs [35]. In contrast, Energy Supplier 2 has 120 consumers only (no other types of energy users) [36]. Nevertheless, the installed average capacity of the solar PV system is assumed to be 6 kWp per prosumer and the size of RBESS per prosumer is considered as 3.3 kW/10 kWh [37]. Under the proposed LEM platform, solar PVs, RBESSs, and load profiles are continuously monitored and predicted in the forward-facing trading market. On top of it, energy users are permitted to put their offers to buy and sell local energy at rates below the ToU and above the FiT rates, respectively. They can decide on and hold their preferred trading quantities and prices through an energy user-friendly web-interface until they set their heart on changing trading parameters. The IoT flow between the proposed blockchain-based LEM platform, CBESS, and energy users is shown.

In short, a LEM platform allows energy users (both consumers and prosumers) to fulfil not only their energy requirements but also attain substantial monetary gains by engaging in P2P energy trading among themselves. They are also enabled to trade with the community MG and power grid while functioning as parts of the LEM framework. In this paper, the community MG, with 250kW/475kWh capacity [38], is assumed to be operated by the energy operator and is connected to the distribution substation through a separate feeder as demonstrated in Fig. 2. A blockchain-enabled LEM platform aims to optimise the energy cost portion of the tariff to reduce the overall tariff, so that energy users can receive monetary benefits (greater incentives are anticipated during peak ToU periods due to higher charges) without the energy supplier and network utility losing their portions. This figure also exhibits how trading among energy users is conducted in the LEM platform in the presence of two energy suppliers.

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TABLE II
THE RATES OF ENERGY SUPPLIER-1 [34, 35]

Energy Supplier-1	Peak (High season) [4pm-8pm]		Peak (Low season) [4pm-8pm]		Off-peak (8pm-4pm)	
	BAU	LEM	BAU	LEM	BAU	LEM
Daily supply charge (c/day)	118.2					
FiT (c/kWh)	5.00					
Energy operator fee (c/kWh) [31]	21.3	21.3	11.5	11.5	7.2	7.2
Energy supplier margin (c/kWh)	1.50	1.5	1.5	1.5	1.0	1.0
RET (c/kWh)	1.50	1.5	1.5	1.5	1.5	1.5
Platform cost (c/kWh)	0	0.75	0	0.75	0	0.75
Energy price (c/kWh)	10.8	9.44	20.6	19.2	10.8	8.2
Tariff (c/kWh)	**35.1**	**34.49**	**35.1**	**34.4**	**19.1**	**18.7**

TABLE III
THE RATES OF ENERGY SUPPLIER-2 [34, 36]

Energy Supplier-2	Peak (1pm-8pm]		Shoulder (7am-1pm), and (8pm-10pm)		Off-peak (10pm-7am)	
	BAU	LEM	BAU	LEM	BAU	LEM
Daily supply charge (c/day)	96.59					
FiT (c/kWh)	5.00					
Energy operator (c/kWh) [31]	21.3	21.3	11.5	11.5	7.2	7.2
Energy supplier margin (c/kWh)	1.5	1.5	1.5	1.5	1.0	1.0
RET (c/kWh)	1.5	1.5	1.5	1.5	1.5	1.5
Platform cost (c/kWh)	0	0.75	0	0.75	0	0.75
Energy price (c/kWh)	7.1	5.7	10.0	8.7	4.7	3.7
Tariff (c/kWh)	**31.4**	**30.7**	**24.5**	**24.0**	**14.5**	**14.2**

Note that it is not necessary to be customers of the same energy supplier to conduct P2P trading. A seller and a buyer could also be the customers of different energy suppliers. This cross trading in the LEM is described in the following section.

III. LEM CROSS TRADING AND BLOCKCHAIN INTEGRATION

This section explains the LEM cross trading concept, in which one Australian energy operator maintains the network [34], and two Australian energy suppliers designated as Energy Supplier-1 and Energy Supplier-2 are considered to serve 140 and 120 energy users, respectively [35-36].

Table-II describes the tariff structure (with various tariff components) of Energy Supplier 1 for both scenarios of BAU and LEM trading. The ToU tariff structure is considered to maximise the benefits of the energy users and increase LEM trading volume. Tariff components, such as daily supply charge; FiT rate; energy operator fee; renewable energy target (RET) charge; energy supplier's margin, and platform cost at peak and off-peak periods are illustrated in Table-II. Note that LEM platform cost applies when energy users participate in the P2P trading. While other tariff components remain mostly unchanged, energy component reduces in P2P compared to BAU depending upon the mutual bids offered by energy users. This leads to overall tariff reduction in P2P. Consequently, the financial interests of P2P buyers are confirmed. On the other hand, P2P sellers can sell at the P2P bought energy price, which is higher than the FiT rate as can be seen from Table-II. Consequently, P2P sellers also benefited.

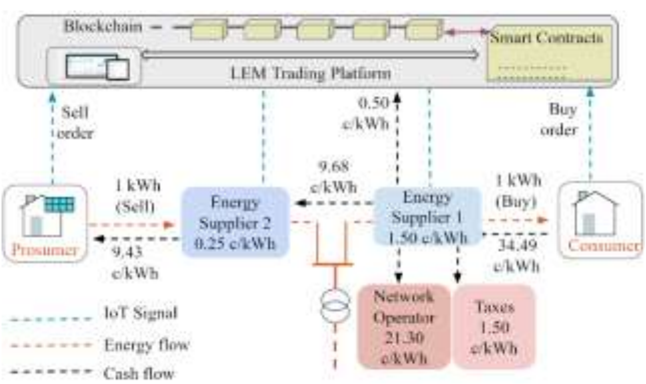

FIGURE 3. An example of LEM cross trading via two energy suppliers.

Likewise, the tariff structure of Energy Supplier 2, with various tariff components, is displayed in Table-III. Unlike Energy Supplier 1, Energy Supplier 2 contains shoulder periods along with peak and off-peak periods. Table II also points out that energy prices at off-peak periods are fewer than the FiT rate. Thus, P2P trading in the LEM platform during off-peak is not profitable for both sellers and buyers. However, energy users can target another two ToU periods to trade among each other in the LEM platform for economic gains. Nonetheless, how customers of Energy Supplier 1 and Energy Supplier 2 trade in the LEM platform is presented in Fig. 3 by a toy example. In this example, a prosumer (customer of Energy Supplier 2) and a consumer (customer of Energy Supplier 1) perform P2P trading to sell and buy 1 kWh of energy. The trading allows the prosumer to earn 9.43 c/kWh, which is 4 c/kWh more than the FiT rate. On the contrary, the consumer pays 34.48 c/kWh instead of 35.1 c/kWh. Energy Supplier 1 and Energy Supplier 2 receive their margins of 1.5 c/kWh and 0.25 c/kWh, respectively. Also, 0.5 c/kWh is attained by the LEM operator as the platform operational charge. P2P energy flow, cash flow, and internet-of-things (IoT) signals in LEM at a given time slot are shown in Fig. 3, where smart contracts are organised to register P2P trading information on a cloud platform and then documented on the blockchain for record and storage. Information about the energy traded volume is sent to the energy supplier for billing reconciliation at the end of a periodical billing cycle.

The Ethereum Virtual Machine (EVM), which is simply software that sits on top of Ethereum nodes for executions, carries out smart contracts settled between LEM users. The EVM measures the amount of computational work required to execute P2P transactions and smart contracts in "gas." The price of gas is expressed in Ether (ETH) and is often expressed in the smallest denomination possible (WEI). One

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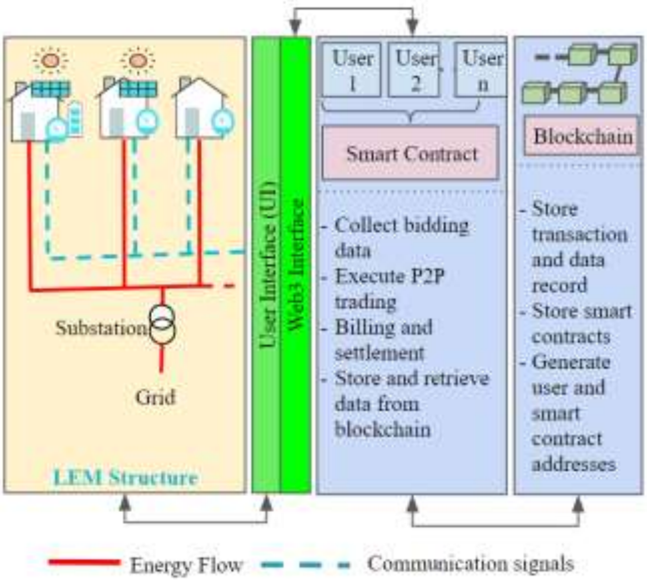

FIGURE 4. **LEM model integration with the blockchain platform.**

ETH is equivalent to 1018 WEI, and one ETH = 2334.63 AU$ [39]. Since it is a result of blockchain network congestion, it is dynamic in nature. On the Ethereum blockchain, the total cost Z in ETH for transactions and smart contracts that were carried out is determined. as [40]:

$$Z(ETH) = g \times z(gas) \tag{1}$$

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

Fig. 4 depicts the three layers that make up the complete blockchain platform process: the LEM architectural layer (virtual and physical); the interface layer; and the blockchain layer powered by smart contracts. 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. Users of the LEM can enter their bid quantities and prices in the UI before each P2P trading interval. On the other hand, the Web3 interface links LEM users to the blockchain layer that is powered by smart contracts. In the smart contracts-driven blockchain layer (monitored by an authorised admin), P2P bidding; mechanism for market clearing; and billing are settled in a decentralised fashion. Particularly, the data information and P2P transaction records are permanently preserved with a possibility of retrieval at any time. The admin, energy supplier, and energy users can all access this data to make final financial agreements. Lastly, prosumers inject the energy while consumers consume it from the physical network in the LEM architectural layer's physical domain.

IV. PROPOSED P2P-DRIVEN LEM FORMULATION

The intention of this work is to propose a P2P-driven LEM that enables energy users to reduce their electricity bills and energy suppliers to keep their margins unaffected. To formulate the LEM trading mechanism the following assumptions are made:

- Energy users are assumed to be connected at the same low-voltage (LV) distribution side of an electricity network [41].
- Prosumers equipped with solar PVs and prosumers equipped with solar PV and RBESSs trade as both sellers and buyers in the LEM based on their energy status. On the contrary, consumers only engage in the LEM as sole buyers [42].
- All sellers and buyers are directed to declare their preferred trading quantities and prices at the blockchain-based LEM platform. Sellers' order is arranged based on the least declared prices. Whereas buyers' orders are organised in accordance with the highest declared prices. Hence, the first P2P pair is constituted with the most economical seller and the most expensive buyer, and sequence continues for all sellers and buyers. If two sellers declare the same price, then their intended energy quantities are taken into account, whereby priority is offered to the seller with greater energy quantity. The same is true for the buyers.
- LEM prices are always kept between the FiT and ToU rates to enable all of them to receive better financial returns than BAU [43].
- Once selling and buying energy orders are matched in the LEM, the excess energy (if any) is utilised to charge the CBESS. On the other hand, it discharges if LEM has more energy deficit than available energy.

Let L be the set of feeder lines in a typical LV distribution network, where each feeder line is indicated by $l \in L$. Energy users are connected in different lines, and it is assumed that they participate in the LEM. The set of each energy user c is represented by C, where $c \in C$. The power imported by each energy user via P2P trading in the LEM at any time $t \in T$ is indicated by $\rho_{c,l}^{im-l}(t)$ and the import price is symbolised by $x_c^{im-l}(t)$. On the other hand, assume $\rho_{c,l}^{ex-l}(t)$ implies each energy user's power export to the LEM at a price signified by $x_c^{ex-l}(t)$. The proposed LEM platform enables each energy user to reduce its electricity cost following a set of LEM constraints, whereby $\rho_{c,l}^{im-l}(t), x_c^{im-l}(t)$, $\rho_{c,l}^{ex-l}(t)$, and $x_c^{ex-l}(t)$ are optimisation variables. The objective function of each LEM user can be represented as:

$$min[\left(\rho_{c,l}^{im-l}(t) \times x_c^{im-l}(t) - \rho_{c,l}^{ex-l}(t) \times x_c^{ex-l}(t)\right) \times \Delta t] \; ; \; \forall c \in C, \forall l \in L, \forall t \in T \tag{2}$$

Subject to:

Subsections (A-D) constraints as described in (3)-(39).

A. IN-HOUSE CONSTRAINTS

Let $\rho_{c,l}^{im}(t)$ and $\rho_{c,l}^{ex}(t)$ be the total imported and exported power, respectively, by an energy user $c \in C$ at time $t \in T$, where $T = \{t \in T, t > 0\}$. Note that a LEM user needs to import/export from/to the power grid if it can not trade at the LEM at any time $t \in T$. In other words, $\rho_{c,l}^{im}(t)$ and $\rho_{c,l}^{ex}(t)$ could be equal or greater than $\rho_{c,l}^{im-1}(t)$ and $\rho_{c,l}^{ex-1}(t)$, respectively, i.e., $\rho_{c,l}^{im}(t) \geq \rho_{c,l}^{im-l}(t)$ and $\rho_{c,l}^{ex}(t) \geq \rho_{c,l}^{ex-l}(t)$. Nevertheless, $\rho_{c,l}^{im}(t)$ and $\rho_{c,l}^{ex}(t)$ are calculated as follows:

$$\rho_{c,l}^{im}(t) = (\rho_{c,l}^{ld}(t) - \rho_{c,l}^{pv}(t) - \rho_{c,l}^{b(s)-}(t) + \rho_{c,l}^{b(l)+}(t); \forall c \in C, \forall t \in T \quad (3)$$

$$\rho_{c,l}^{ex}(t) = (\rho_{c,l}^{pv}(t) - \rho_{c,l}^{ld}(t) - \rho_{c,l}^{b(s)+}(t) + \rho_{c,l}^{b(l)-}(t); \forall c \in C, \forall t \in T \quad (4)$$

where $\rho_{c,l}^{b(s)-}(t)$ and $\rho_{c,l}^{b(s)+}(t)$ are self-discharged and self-charged power at time $t \in T$ respectively. Whereas peer-discharge and peer-charge in the LEM are represented by $\rho_{c,l}^{b(l)-}$ and $\rho_{c,l}^{b(l)+}$ respectively.

Further, $\rho_{c,l}^{ld}(t)$ and $\rho_{c,l}^{pv}(t)$ indicate power demand and solar PV generation at time $t \in T$. These are also bounded by maximum power demand $\rho_{c,l}^{ld(m)}(t)$ and maximum solar PV generation $\rho_{c,l}^{pv(m)}(t)$ respectively, such that [11]:

$$0 \leq \rho_{c,l}^{ld}(t) \leq \rho_{c,l}^{ld(m)}(t); \forall c \in C, \forall t \in T \quad (5)$$

$$0 \leq \rho_{c,l}^{pv}(t) \leq \rho_{c,l}^{pv(m)}(t); \forall c \in C, \forall t \in T \quad (6)$$

Moreover, $\rho_{c,l}^{b(s)+}(t)$ and $\rho_{c,l}^{b(s)-}(t)$ are also bounded by maximum charge $\rho_{c,l}^{b(m)+}(t)$ and maximum self-discharge $\rho_{c,l}^{b(m)-}(t)$, respectively such that [16]:

$$0 \leq \rho_{c,l}^{b(s)+}(t) \leq \rho_{c,l}^{b(m)+}(t); \forall c \in C, \forall t \in T \quad (7)$$

$$0 \leq \rho_{c,l}^{b(s)-}(t) \leq \rho_{c,l}^{b(m)-}(t); \forall c \in C, \forall t \in T \quad (8)$$

where $\rho_{c,l}^{b(s)+}(t)$ and $\rho_{c,l}^{b(s)-}(t)$ are calculated as follows:

$$\rho_{c,l}^{b(s)+}(t) \times \Delta t = min\left[min\left\{(\rho_c^{b(i)} \times \Delta t \times e_c^+), \left(\rho_{c,l}^{ld}(t) - \rho_{c,l}^{pv}(t)\right) \times \Delta t\right\}, \left((s_c^{(m)} \times y_c) - s_c(t-1) \times e_c^+\right)\right]; \forall c \in C, \forall t \in T \quad (9)$$

$$\left(\rho_{c,l}^{pv}(t) - \rho_{c,l}^{ld}(t)\right) \times \Delta t = min\left[min\left\{(\rho_c^{b(i)} \times \Delta t \times e_c^-), \left(\rho_{c,l}^{pv}(t) - \rho_{c,l}^{ld}(t)\right) \times \Delta t\right\}, \left(\left(s_c(t-1) - \left(s_c^{(n)} \times y_c\right)\right) \times e_c^-\right)\right]; \forall c \in C, \forall t \in T \quad (10)$$

where $\rho_c^{b(i)}$ and y_c refer to maximum instantaneous power and capacity of RBESS of an energy user $c \in C$ respectively. e_c^+ and e_c^- denote charging and discharging efficiencies, respectively. $s_c^{(m)}$ and $s_c^{(n)}$ are maximum and minimum state-of-charges (SoCs), respectively in percentages. The SoC $s_c(t)$ at time $t \in T$ is related with the initial instant SoC, $s_c(t-1)$, $s_c^{(m)}$ and $s_c^{(n)}$ as follows:

$$s_c(t) = s_c(t-1) + \left(\rho_{c,l}^{b(s)}(t) \times \Delta t \times e_c^+\right) - \left(\frac{\rho_{c,l}^{b(s)-}(t) \times \Delta t}{e_c^-}\right); \forall c \in C, \forall t \in T \quad (1)$$

$$\left(s_c^{(n)} \times y_c\right) \leq s_c(t) \leq \left(s_c^{(m)} \times y_c\right); \forall c \in C, \forall t \in T \quad (12)$$

$$s_c(t-1) = \left(s_c^{(i)} \times y_c\right) + \left(\rho_{c,l}^{b(s)+}(t-1) \times \Delta t \times e_c^+\right) - \left(\frac{\rho_{c,l}^{b(s)-}(t-1) \times \Delta t}{e_c^-}\right); \forall c \in C, \forall t \in T \quad (13)$$

where $s_c^{(i)}$ is the initial SoC in percentage. $\rho_{c,l}^{b(s)+}(t-1)$ and $\rho_{c,l}^{b(s)-}(t-1)$ imply initial state self-charged and self-discharged power, respectively.

B. P2P TRADING CONSTRAINTS

Let $\sum_{c \in C} \rho_{c,l}^{im-l}(t)$ and $\sum_{c \in C} \rho_{c,l}^{ex-l}(t)$ be the total imported and exported power via P2P in the LEM, where $\sum_{c \in C} \rho_{c,l}^{im-l}(t) \leq \sum_{c \in C} \rho_{c,l}^{im}(t)$ and $\sum_{c \in C} \rho_{c,l}^{ex-l}(t) \leq \sum_{c \in C} \rho_{c,l}^{ex}(t)$. The total imported and exported power in the LEM are required to be matched, such that [43]:

$$\sum_{c \in C} \rho_{c,l}^{im-l}(t) = \sum_{c \in C} \rho_{c,l}^{ex-l}(t); \forall t \in T \quad (14)$$

$\left(\sum_{c \in C} \rho_{c,l}^{im}(t) - \sum_{c \in C} \rho_{c,l}^{im-l}(t)\right)$ is imported either from the CBESS (via discharging) or from the power grid. Similarly, $\left(\sum_{c \in C} \rho_{c,l}^{ex}(t) - \sum_{c \in C} \rho_{c,l}^{ex-l}(t)\right)$ is exported either to the CBESS (via charging) or to the power grid.

Further, peer-charge $\rho_{c,l}^{b(l)+}(t)$ of an energy user $c \in C$ in the LEM is constrained by the peer-charging rate $\overline{\left(\rho_{c,l}^{b(l)+}(t)\right)}$ and peer-charging capacity $\left(\widehat{\rho_{c,l}^{b(l)+}(t)}\right)$ at time $t \in T$ as described in (15). $\overline{\left(\rho_{c,l}^{b(l)+}(t)\right)}$ and $\left(\widehat{\rho_{c,l}^{b(l)+}(t)}\right)$ are defined in (16) and (17).

$$\rho_{c,l}^{b(l)+}(t) \times \Delta t = min\left[\overline{\left(\rho_{c,l}^{b(l)+}(t)\right)}, \left(\widehat{\rho_{c,l}^{b(l)+}(t)}\right)\right]; \forall c \in C, \forall t \in T \quad (15)$$

$$\overline{\left(\rho_{c,l}^{b(l)+}(t)\right)} \times \Delta t = \left(\rho_{c,l}^{b(m)+}(t) \times \Delta t \times e_c^+\right) - \left(\rho_{c,l}^{b(s)+}(t) \times \Delta t\right); \forall c \in C, \forall t \in T \quad (16)$$

$$\left(\widehat{\rho_{c,l}^{b(l)+}(t)}\right) = \max\left[\left(\left(s_c^{(m)} \times y_c\right) - s_c(t-1) - \left(\rho_{c,l}^{pv(p)} \times \Delta t\right) - \left(\rho_{c,l}^{b(s)+}(t) \times \Delta t\right)\right), 0\right]; \forall c \in C, \forall t \in T \quad (17)$$

where $\rho_{c,l}^{pv(p)}$ denotes the peak solar PV power over the course of $|T|$.

Similarly, peer-discharge $\rho_{c,l}^{b(l)-}(t)$ of an energy user $c \in C$ in the LEM is also limited by the peer-discharging rate $\overline{\left(\rho_{c,l}^{b(l)-}(t)\right)}$ and peer-discharging capacity $\left(\widehat{\rho_{c,l}^{b(l)-}}(t)\right)$ at time $t \in T$ as demonstrated in (18). $\overline{\left(\rho_{c,l}^{b(l)-}(t)\right)}$ and $\left(\widehat{\rho_{c,l}^{b(l)-}}(t)\right)$ are defined in (19) and (20).

$$\rho_{c,l}^{b(l)-}(t) \times \Delta t = min\left[\overline{\left(\rho_{c,l}^{b(l)-}(t)\right)}, \left(\widehat{\rho_{c,l}^{b(l)-}}(t)\right)\right]; \forall c \in C, \forall t \in T \quad (18)$$

$$\overline{\left(\rho_{c,l}^{b(l)-}(t)\right)} \times \Delta t = \left(\rho_{c,l}^{b(m)-}(t) \times \Delta t \times e_c^-\right) - \left(\rho_{c,l}^{b(s)-}(t) \times \Delta t\right); \forall c \in C, \forall t \in T \quad (19)$$

$$\left(\widehat{\rho_{c,l}^{b(l)-}}(t)\right) = \max\left[\left(s_c(t-1) - \left(s_c^{(m)} \times y_c\right) - \left(\rho_{c,l}^{ld(p)}(t) \times \Delta t\right) - \left(\rho_{c,l}^{b(s)-}(t) \times \Delta t\right)\right), 0\right]; \forall c \in C, \forall t \in T \quad (20)$$

where $\rho_{c,l}^{ld(p)}$ represents the peak power demand over the course of $|T|$.

As for the price constraints in the LEM for P2P trading, it is required that $x_c^{im-l}(t)$ is lower than $x_c^{im-g}(t)$. Whereas $x_c^{ex-l}(t)$ is higher than $x_c^{ex-g}(t)$ to benefit both buying and selling energy users, such that:

$$x_c^{im-l}(t) < x^{im-g}(t) \; x_c^{ex-l}(t) > x^{ex-g}(t) \; ; \forall c \in C, \forall t \in T \quad (21)$$

where ToU and FiT rates are represented by $x^{im-g}(t)$ and $x^{ex-g}(t)$, respectively. Note that, $x^{im-g}(t)$ is a combination of energy price $x^{im-g1}(t)$; energy supplier's margin $x^{im-g2}(t)$; energy operator's margin $x^{im-g3}(t)$; and RET charge $x^{im-g4}(t)$ (if applicable) as illustrated in (22) [7].

$$x^{im-g}(t) = x^{im-g1}(t) + x^{im-g2}(t) + x^{im-g3}(t) + x^{im-g4}(t); \forall t \in T \quad (22)$$

Similarly, $x_c^{im-l}(t)$ comprises of P2P buy price $x_c^{im-l1}(t)$; LEM platform cost $x^{im-ll}(t)$; energy supplier's margin $x^{im-l2}(t)$; energy operator's margin $x^{im-l3}(t)$; and RET charge $x^{im-l4}(t)$ (if applicable) as described in (23).

$$x_c^{im-l}(t) = x_c^{im-l1}(t) + x^{im-ll}(t) + x^{im-l2}(t) + x^{im-l3}(t) + x^{im-l4}(t); \forall c \in C, \forall t \in T \quad (23)$$

where,

$$\left(x_c^{im-l1}(t) + x^{im-ll}(t)\right) < x^{im-g1}(t); \quad \forall c \in C, \forall t \in T \quad (24)$$

$$x^{im-l2}(t) \geq x^{im-g2}(t);\; ; \; \forall t \in T \quad (25)$$

$$x^{im-l3}(t) \geq x^{im-g3}(t);\; ; \; \forall t \in T \quad (26)$$

$$x^{im-l4}(t) \geq x^{im-g4}(t);\; ; \; \forall t \in T \quad (27)$$

C. CBESS CONSTRAINTS

Let $g \in G$ be the index of the CBESS. In this paper, $g = 1$ as one CBESS is considered. The CBESS charging and discharging operation along with SoC constraints can be expressed as follows [25]:

$$s_g(t) = s_g(t-1) + \left(\rho_{g,l}^{b+}(t) \times \Delta t \times e_g^+\right) - \left(\frac{\rho_{g,l}^{b-}(t) \times \Delta t}{e_g^-}\right); \forall g \in G, \forall t \in T \quad (28)$$

$$\left(s_g^{(n)} \times y_g\right) \leq s_g(t) \leq \left(s_g^{(m)} \times y_g\right); \forall g \in G, \forall t \in T \quad (29)$$

$$0 \leq \rho_{g,l}^{b+}(t) \leq \rho_{g,l}^{b(m)+}(t); \forall g \in G, \forall t \in T \quad (30)$$

$$0 \leq \rho_{g,l}^{b-}(t) \leq \rho_{g,l}^{b(m)-}(t); \forall g \in G, \forall t \in T \quad (31)$$

where $s_g(t)$ is the SoC of the CBESS at time $t \in T$, which is bounded by minimum and maximum SoCs, $\left(s_g^{(n)} \times y_g\right)$ and $\left(s_g^{(m)} \times y_g\right)$, respectively. $s_g^{(n)}$ and $s_g^{(m)}$ are expressed in percentages, where y_g signifies the CBESS capacity. e_g^+ and e_g^- refer to charging and discharging efficiencies respectively. $\rho_{g,l}^{b(m)+}(t)$ and $\rho_{g,l}^{b(m)-}(t)$, respectively denote maximum charged and discharged power of the CBESS. Charged and discharged power $\rho_{g,l}^{b+}(t)$ and $\rho_{g,l}^{b-}(t)$, respectively are limited by $\rho_{g,l}^{b(m)+}(t)$ and $\rho_{g,l}^{b(m)-}(t)$. $\rho_{g,l}^{b+}(t)$ and $\rho_{g,l}^{b-}(t)$ at $t \in T$ are computed as follows:

$$\rho_{g,l}^{b+}(t) \times \Delta t = \min\left[min\left\{\left(\rho_g^{b(t)} \times \Delta t \times e_g^+\right), \left(\sum_{c \in C} \rho_{c,l}^{ex}(t) - \sum_{c \in C} \rho_{c,l}^{ex-l}(t)\right) \times \Delta t\right\}, \left(\left(s_g^{(m)} \times y_g\right) - s_g(t-1) \times e_g^+\right)\right]; \forall g \in G, \forall t \in T \quad (32)$$

$$\rho_{g,l}^{b(s)-}(t) \times \Delta t = \min\left[min\left\{\left(\rho_g^{b(m)} \times \Delta t \times e_g^-\right), \left(\sum_{c \in C} \rho_{c,l}^{im}(t) - \sum_{c \in C} \rho_{c,l}^{im-l}(t)\right) \times \Delta t\right\}, \left(\left(s_g(t-1) - \left(s_g^{(n)} \times y_g\right)\right) \times e_g^-\right)\right]; \forall g \in G, \forall t \in T \quad (33)$$

D. NETWORK POWER CONSTRAINTS

The power bought and sold in the LEM of each energy user $c \in C$ at time $t \in T$ are also constrained by the maximum consumption and injection limits, indicated by $\rho_{c,l}^{im-l(m)}(t)$ and $\rho_{c,l}^{ex-l(m)}(t)$, respectively as demonstrated in (34) and (35) respectively. These are assumed to be prescribed by the energy operator [44-45]:

$$0 \le \rho_{c,l}^{im-l}(t) \le \rho_{c,l}^{im-l(m)}(t); \forall c \in C, \forall t \in T \quad (34)$$

$$0 \le \rho_{c,l}^{ex-l}(t) \le \rho_{c,l}^{ex-l(m)}(t); \forall c \in C, \forall t \in T \quad (35)$$

Besides, the total import and export balance in the power network with the proposed LEM framework can be evaluated as follows:

$$\sum_{c \in C} \rho_{c,l}^{im}(t) = \sum_{c \in C} \rho_{c,l}^{im-l}(t) + \rho_{g,l}^{b(s)+}(t) + \rho_{c,l}^{im-lg}(t); \forall t \in T \quad (36)$$

$$\sum_{c \in C} \rho_{c,l}^{ex}(t) = \sum_{c \in C} \rho_{c,l}^{ex-l}(t) + \rho_{g,l}^{b(s)-}(t) + \rho_{c,l}^{ex-lg}(t); \forall t \in T \quad (37)$$

where $\rho_{c,l}^{im-lg}(t)$ and $\rho_{c,l}^{ex-lg}(t)$ imply power imported and exported respectively from and to the power grid during the LEM operation. These are also required to be lower than grid import power $\rho_{c,l}^{im-g}(t)$and grid export power $\rho_{c,l}^{ex-g}(t)$ without the LEM operation to help the energy operator avoid network congestion in the network, such that:

$$\rho_{c,l}^{im-lg}(t) < \rho_{c,l}^{im-g}(t); \forall t \in T \quad (38)$$

$$\rho_{c,l}^{ex-lg}(t) < \rho_{c,l}^{ex-g}(t); \forall t \in T \quad (39)$$

V. RESULTS AND ANALYSIS

The proposed framework is simulated on the Matlab software and the smart contracts are written on REMIX IDE [46]. 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 results of the performed case study are illustrated and analysed to demonstrate how the proposed LEM platform benefits energy users, energy suppliers, the power grid, and the network operator. The proposed LEM model is also integrated with a CBESS-based MG to reduce the power grid's import and export further.

In order to design the LEM framework, a typical architecture, as displayed in Fig. 1, is considered which consists of two energy suppliers and different combinations of electricity consumers, prosumers equipped with solar PVs and prosumers equipped with solar PV and RBESS (260 in total). This study is based on real world data of a town in New South Wales (NSW), Australia (available in [47]). The load consumption and solar PV generation average profiles for 24 hours are depicted in Fig. 5, illustrating that their values are highest in the evening and afternoon times, respectively.

A. ENERGY USER'S DYNAMIC BIDDING

The energy users have the ability to select buy and sell prices dynamically and place bids into a trading platform between predefined ranges of FiT and grid buy price. These prices are matched according to the merit order with the respective buyer or seller rate and a midway price is chosen as the settlement rate. Fig. 5 shows the resulting trading

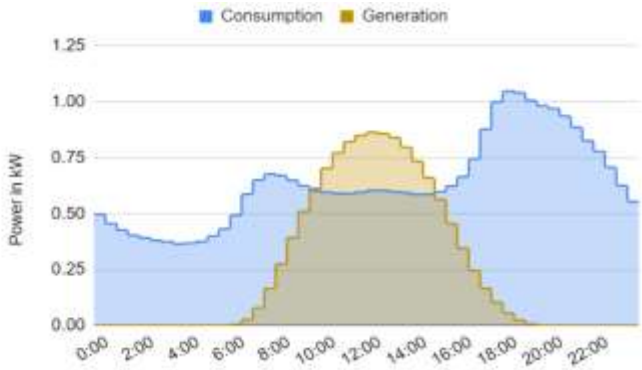

FIGURE 5. Average solar PV generation and consumption of the studied energy users.

prices in the LEM with CBESS scenario. They reflect the energy suppliers tariff rate periods as the limits of buy and sell prices are within FiT and grid buy price, therefore P2P prices during peak periods are elevated. The prices are split into buy and sell prices from a) solar PV to load, b) solar PV to BESS and c) BESS to load. As two energy suppliers were chosen for the case study, the P2P prices can be higher than one of the energy supplier grids buy rate. This can be observed in Fig. 7 between 8:00 and 3:00 pm that P2P prices exceed energy supplier's grid buy rate. However, those are bought prices of consumers in energy supplier 2's portfolio, which has a higher grid buy rate during that time.

B. PARTICIPATION OF ENERGY USERS AND THEIR BENEFITS ANALYSIS

The average electricity costs of electricity consumers, prosumers equipped with solar PVs, and prosumers equipped with solar PVs and RBESSs are depicted in Fig. 6. On average, participating in P2P-empowered LEM the reduction in electricity costs become 5%; 9%; and 23%, for consumers; prosumers equipped with solar PVs; and prosumers quipped with solar PVs and RBESSs, respectively, compared to BAU. The reduction in electricity cost for prosumers is due to additional income by P2P trading using their own traded

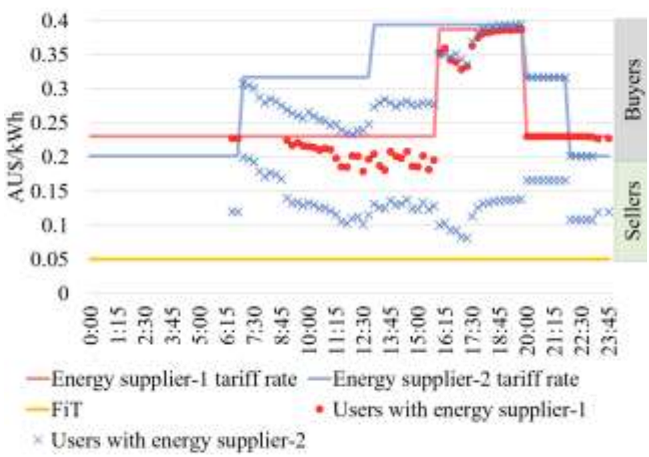

FIGURE 6. Energy suppliers' rates and energy users average P2P bidding prices.

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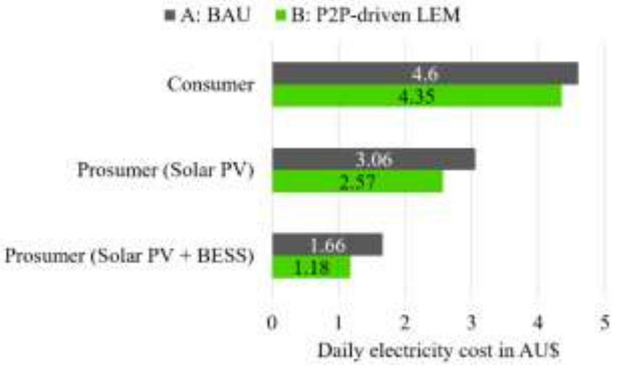

FIGURE 7. **Energy users' daily electricity cost (BAU vs P2P-trading LEM).**

price and reduced grid buying/selling volume. The electricity cost of prosumers equipped with solar PVs and RBESSs is further reduced due to their larger self- sufficiency, P2P trading in different ToU intervals and reduced grid buying/selling volume. That can encourage prosumers to make the largest investment on solar PVs and RBESSs to earn maximum benefits. Moreover, consumers are also benefiting moderately as being parts of the LEM platform without making any investment in DERs.

Fig. 7(a) and Fig. 7(b) show average daily residential load profiles for BAU vs LEM and BAU vs LEM with CBESS respectively. The results reveal that energy trading with the power grid decreased in the afternoon and evening periods owing to P2P trading in the LEM and trading with CBESS. To provide maximum monetary gains to energy users, RBESSs are charged during day (off-peak) and afternoon (shoulder) periods and discharged during evening (peak) periods. The LEM trading is exhibited in Fig. 7(a), where prosumers equipped with solar PVs have a larger contribution in P2P trading in afternoon times, and in the evening, prosumers equipped with RBESSs discharge to fulfil the load requirement. Fig 7(b) depicts that the CBESS further contributes to meeting load requirements in the late evening, and thus benefits energy users as another income stream.

C. REDUCTION IN POWER GRID'S EXPORT AND IMPORT BY CBESS-INTEGRATED LEM

The export and import of the power grid for a typical day are represented in Fig. 8; BAU and LEM are compared in Fig. 8(a) and BAU and proposed LEM with CBESS are compared in Fig. 8(b). As is seen from Fig. 8(a), in comparison with BAU, the LEM decreases the power grid export by 24% due to RBESS charging and P2P energy trading with neighbouring users during off-peak and shoulder times, and import is lessened by 26% due to RBESS discharging and P2P energy trading with neighbouring users during peak time.

Furthermore, Fig. 8(b) compares BAU and LEM with CBESS, and results show that due to the integration of CBESS with LEM, export and import are further decreased by 32% (off-peak and shoulder times) and by 39% (peak times), respectively. The significant reduction in imports and exports is due to the additional trading volume within energy users and CBESS. The CBESS is controlled by a network operator at the substation level and energy users perform trading at power grid's set prices. This clearly demonstrates that the integration of CBESS with the LEM is not creating

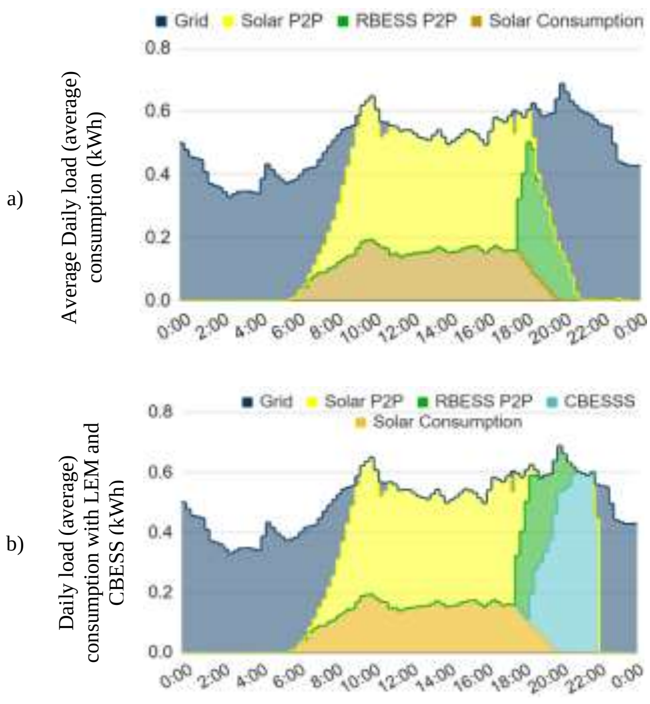

FIGURE 8. **Average daily residential load consumption.**

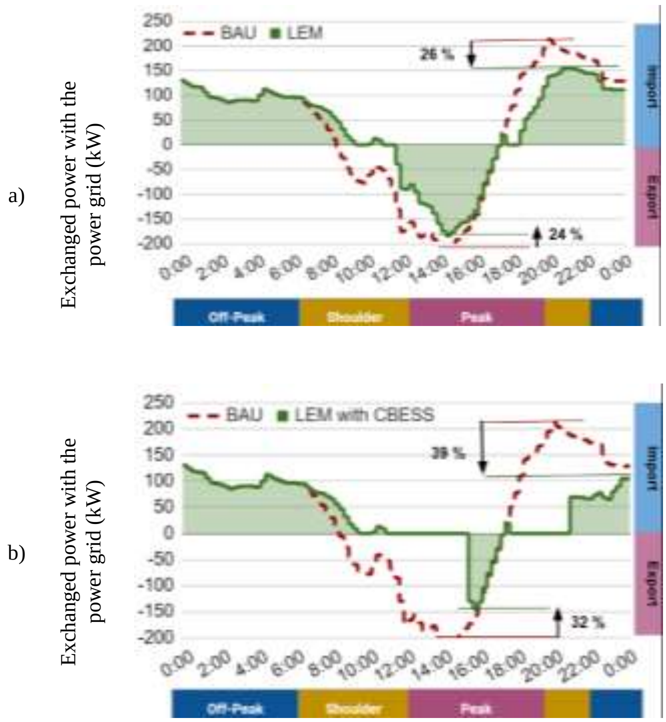

FIGURE 9. **Trading with a power grid.**

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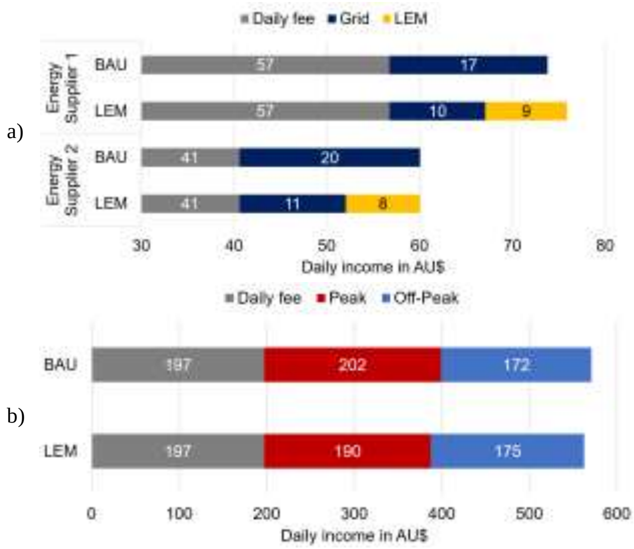

FIGURE 10. **Daily Income; a) Energy Supplier daily income margin, b) Network Operator income.**

any additional benefits for energy users but significantly reduces the power grid's import and export problem.

D. INCOME MARGINS OF ENERGY SUPPLIERS AND NETWORK OPERATOR

Energy suppliers' margins are maintained above or at BAU level as exhibited in Fig. 9(a). Overall, both energy suppliers have different daily fees because of their different number of energy users. Energy Supplier-2 has a larger income with the power grid trading because it consists of consumers only. However, Energy Supplier-2 includes prosumers equipped with RBESSs that reduce the income with the power grid due to energy users' self-sufficiency.

Energy supplier-1 retains a transaction fee of 0.25 c/kWh (an additional fee with all its prosumers) due to energy sold within the P2P trading-driven LEM. An increase in its margin over the course of a typical day by 5% is a result of an additional fees per kWh traded in the LEM and raised trading volume while RBESSs are charged from other energy users. Energy Supplier-2 (without any prosumers), on the other hand, retains the previous margin for every kWh consumed within the LEM. This justifies that energy suppliers can obtain more benefits, in terms of increasing their margins, if the number of prosumers grows within the LEM platform, resulting in an increased volume of P2P transactions.

Fig. 9(b) portrays the daily incomes of the network operator both in BAU and LEM scenarios. The results show that for both scenarios the daily fee is identical, that is AU$ 197, because the total energy trading volume does not change. However, due to LEM self-sufficiency, during off-peak and peak periods both power grid export and import are reduced, which marginally reduces the network income. Unlike energy users, the network operator may not receive financial returns largely from the LEM platform. But a well-functioning LEM can mitigate the adverse impacts of local penetration, such as voltage rise issue; increase in power losses; and congestion complexities for example, with the help of P2P trading, resulting in lowering both capital and operational expenses of the network operator.

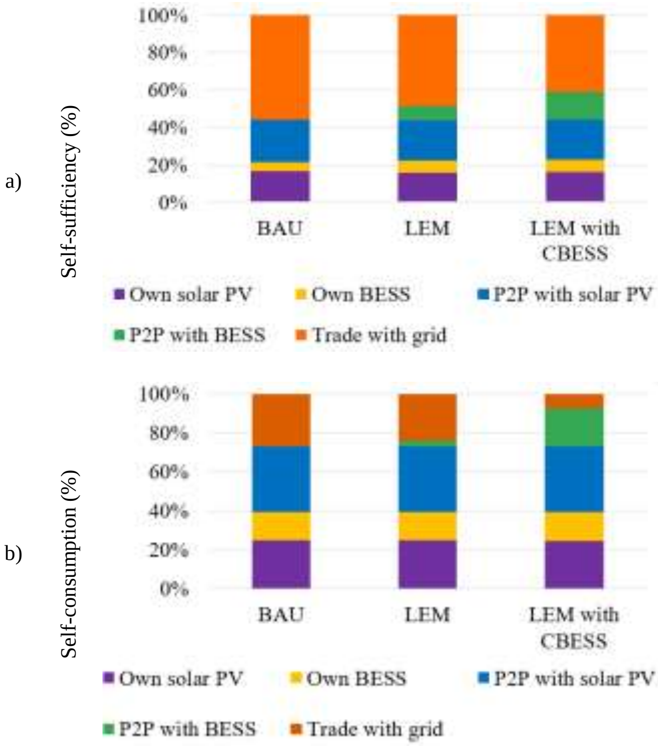

FIGURE 11. **Trading groups: BAU, LEM & LEM with CBESS.**

E. SELF-SUFFICIENCY AND SELF-CONSUMPTION

The LEM has an impact on the self-sufficiency and self-consumption of the trading group. Self-sufficiency is the ratio of energy provided and consumed by the community and the total consumption of all energy users. Self-consumption is the ratio of energy provided and consumed by the community and the total generation of all prosumers of the LEM. The LEM influences these values by increasing the consumption of locally generated electricity by charging BESS from peers, therefore reducing the energy volume exported to the main grid. The self-sufficiency and self-consumption analysis is split into the parameters a) Own PV referring to the direct use of self-generated solar, b) Own BESS meaning the charge and discharge of self-generated solar for the own household usage, c) Peers PV as the amount of energy traded from solar within the trading group and d) Peers BESS referring to the amount of energy shared from the BESS within the trading group.

Enabling the residential BESS to be shared with the community can increase the self-sufficiency by ~7.5 % to 51.5 % as shown in Fig. 11 and the self-consumption by ~ 3 % to 76.0 % as shown in Fig. 12. A CBESS increases these values greatly to 59.0 % and 92.5 % respectively.

F. COMPARATIVE ANALYSIS

In this section, the proposed LEM results are compared with recent research papers [48-49]. In [48], a minimization

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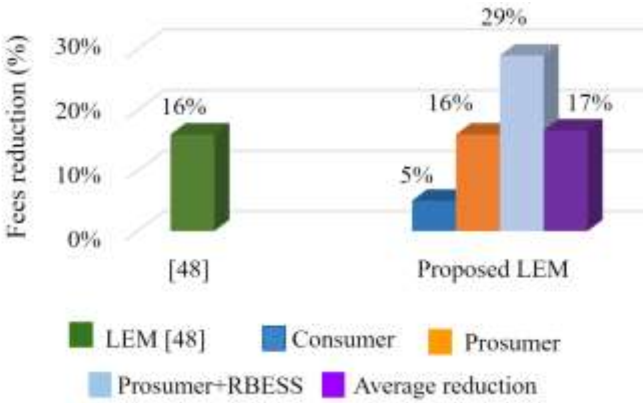

FIGURE 12. LEM fess reduction in proposed LEM vs [48].

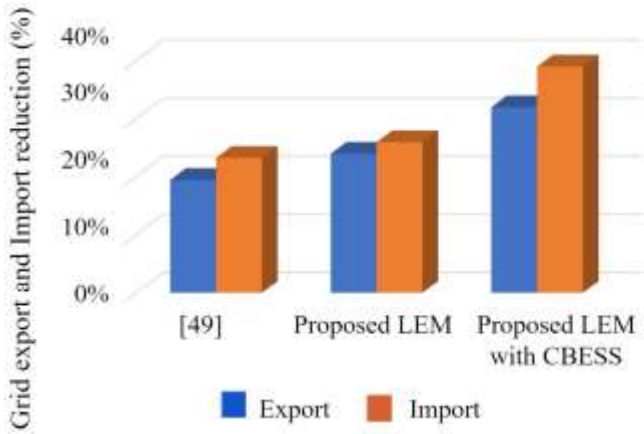

FIGURE 13. Reduction in grid import and export for proposed LEM vs [49].

objective function is used for regulated electricity price components and social welfare and the LEM results, including a reduction in total fees paid and an increase in self-sufficiency, are compared. In [49], the matchmaking between the buyer and seller is maximised, and the results of grid imports and exports are compared.

I. FEES PAID

As shown in Fig. 13, in [48] total fees paid for BAU are 286€, and in LEM they are reduced by 16%, to 239€. The proposed LEM architecture reduces electricity bills for consumers by 5%, prosumers by 16%, and prosumers with RBESS by 29%. On average, the proposed LEM structure reduces bills for participants by 17%.

II. SELF-SUFFICIENCY

The self-sufficiency of LEM in [48] has increased by 14% as shown in Table-IV. However, it is much more controlled in the case of the proposed LEM, and the results illustrate that LEM increased the self-sufficiency by 7.5%, and with the proposed LEM and CBESS it increased further to 15%.

III. GRID IMPORT AND EXPORT

The grid export and import were reduced by 19.5% and 23.3%, respectively, in [49] as shown in Fig. 14. However, the grid export and import were further reduced in the proposed LEM by 24% and 26%, respectively. It was found that the addition of CBESS with the proposed LEM caused the most reduction in export and import to 32% and 39%, respectively.

G. COST OF USING ETHEREUM BLOCKCHAIN

Table-V analyses the cost of running smart contracts on the Ethereum blockchain. Every activity on the blockchain is carried out by the EVM, and the related gas quantity in the fourth column indicates how much computational work is involved. The fifth column in Table II lists the gas cost for using LEM smart contracts to do a variety of tasks, such as user registration, bidding, P2P trading, billing, and settlement. As shown in Table-V, it is relatively expensive to run a P2P-driven LEM on the Ethereum blockchain platform. Congestion and the Ethereum network's slow transaction speed are to blame for this (approximately 15-17 transactions per second). Other blockchain platforms, such as Solana and Ploygon, can assist cut the cost by a factor of a hundred, and this could be a future extension of the created LEM model.

TABLE IV
SELF-SUFFICIENCY OF PROPOSED LEM VS [48]

Work Focus	BAU	LEM	LEM with CBESS
LEM [48]	55.4%	69.4%	X
Proposed LEM	43.9%	51.5%	59.0%

VI. CONCLUSION

A CBESS-integrated LEM framework has been proposed in this paper. The main objectives of this paper have been the development of a power network-compatible LEM model and its financial viability verification. The proposed LEM model has allowed various energy users, that include consumers; prosumers with solar PVs; and prosumers with solar PVs and RBESSs; to trade energy among themselves optimally in a P2P fashion respecting both market and network constraints, while the overall energy in the LEM is balanced primarily by the CBESS-facilitated MG. Further,

TABLE V
COST OF EXECUTING SMART CONTRACTS

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

the developed MG-integrated LEM mechanism has been verified on a real power grid in Australia and the simulation results have been compared with the existing BAU. It has been found from the comparative simulation results that energy users can reduce significant portions of their electricity costs; the power grid can minimise its imports and exports; and energy suppliers and the authorised energy operator can keep their margins unaffected by participating in the developed LEM model. Additionally, the self-sufficiency and self-consumption of the trading group can be increased, resulting in reducing the reliance on the upstream power grid and solar exports; and keeping local generation and consumption matched. Thus, the proposed LEM framework can be regarded as a beneficial model for both energy users and other stakeholders and can be put into practice in today's electricity market.

Further investigation can be carried out on how physical network constraints can be incorporated dynamically (e.g., via the concept of dynamic operating envelope) into the proposed CBESS-integrated LEM structure to maximise the local energy usage with customers' empowerment through P2P energy trading while wide-scale engagement of different stakeholders is always guaranteed. Moreover, the application of the blockchain technology in the proposed LEM framework can be analysed for the fast and secure settlement of P2P transactions. The suggested LEM model on the Solana blockchain will be validated in further work to speed up P2P trading and billing settlement.

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