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Singapore Local Energy Market Development Using Blockchain Enabled P2P Trading

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***Abstract*—The proposed system develops a peer-to-peer (P2P) energy trading-based Local Energy Market (LEM) solution which optimizes distributed energy resources (DERs). The blockchain-based trading platform allows secure and transparent P2P energy trading in a grid-connected power network. In the P2P network, a participant with a surplus of renewable energy (such as solar photovoltaic (PV)) can trade excess with any other participants with an energy deficit. However, in business-as-usual (BAU), it has been fed back to the power grid or curtailed - which can be extremely costly to the grid. The energy traded through solar PV and battery energy storage system (BESS) via P2P trading is cheaper than the respective tariff of the grid.**

The main aim of the LEM is to mitigate power outages and accelerate the transition to clean energy through increased rooftop solar PV installation by motivating consumers and prosumers to invest in DERs. The LEM implements a marketplace for optimizing distributed energy resources (DERs). In doing so, the LEM can minimize lost energy from existing DER capacity, provide a financial incentive to generate renewable energy beyond the site it is generated at, and improve the savings and profits compared to a BAU case. Simplified, a LEM provides participants with cheaper, greener, and more reliable energy. The LEM maximizes a participant's yield from their solar PV panels, increasing the investment's profitability.

Due to the benefits provided, implementing LEM accelerates renewable energy deployment with no government incentives. These benefits are achieved by utilizing a low-energy, high-speed proprietary Blockchain in tandem with the microservice-based architecture used in the software, which develops a secure trading network that is both easily scalable and highly resilient.

***Keywords*—Local energy market; peer-to-peer; blockchain; power grid; network operator; electricity cost reduction.**

I. INTRODUCTION

The emergence of the local energy market (LEM) concept has recently motivated customers and network operators to improve the traditional pool-based supply and demand matching process. Using LEMs, electricity traders can buy and sell renewable energy at prices that suit their preferences [1]. Any excess energy not utilized by the LEM can be returned to the power grid through FiT [2]. Furthermore, the LEM approach can facilitate the flow of renewable energy through the electricity network while adhering to thermal and network constraints [3]. Advantages of LEM include multilateral settlement agreements among participants, flexible market operation, secure and transparent transaction execution, incorporation of the interests of network operators, reduced electricity costs, and the reduction of energy imports/exports from/to the grid, as well as fostering social cohesion [4]. Due to its decentralized and flexible features, the LEM presents an attractive alternative to the feed-in-tariff (FiT) scheme, benefiting both energy sellers and buyers [5].

Peer-to-peer (P2P) trading is a great feature of a LEM that allows consumers and prosumers (consumers who generate energy locally) to negotiate the amounts and prices of energy in a decentralized way. This includes the involvement of retailers and network operators [6-7]. There are three types of P2P trading structures in the LEM: fully decentralized, community-driven, and hybrid or coordinated [8]. Hybrid P2P trading combines decentralized and centralized mechanisms, where energy quantity and price negotiation occur without central intervention, but the market's physical constraints are managed centrally [9-10]. In a fully decentralized market, P2P trading occurs without a central authority's control [11]. Due to its structural suitability, hybrid P2P trading is considered the most appropriate structure for the LEM [12-13]. In contrast, a community manager usually manages a community-based energy trading market [14-15].

The modern approach to P2P trading in the LEM strongly emphasizes accommodating the individual preferences of LEM participants. LEM allows participants to select their desired partners, trading periods, and preferred prices for P2P transactions [16]. Using blockchain technology to facilitate trading with multiple peers is permitted in [17-18], enabling participants to choose the most suitable partners for better monetary gains. Both single and group trading options are considered in [19]. Reports from [20] and [21] also suggest that factors such as place attachment, climate change, differences in trust, and political orientation have been found to influence P2P trading decisions in the LEM. Making sound P2P trading decisions is emphasized in [22]. Research has been conducted by authors in [23] and [24] to analyze the attitudes, behaviors, and subjective norms of LEM participants to expedite trading decisions.

These research studies significantly impact attracting participants and network operators to the LEM. However, most existing models focus either on the prosumers or the network operator, which leaves a possibility for further development. Therefore, this paper presents a local energy trading model that utilizes blockchain technology to involve participants and network operators in the LEM simultaneously.

The remainder of the paper is structured as follows. An 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 P2P trading. The formulation in the LEM. The simulation results are illustrated in Section V. Finally; the concluding remark is outlined in Section VI.

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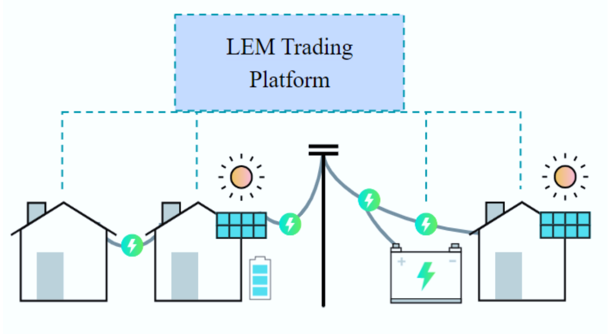

Fig. 1. Diagram of LEM set-up.

II. LEM MODEL AND TECHNICAL FEASIBILITY

LEM is designed for socially close and geographically distinct communities, consisting of consumers, prosumers with solar PV or solar PV with battery, and commercial and industrial (C&I) participants, as shown in Fig. 1. LEM matches locally generated electricity and demand in defined time intervals (i.e., 15 min). If the generated energy is surplus to what the said consumer requires, it can be traded within the network to wherever it is needed following the trading rules. Both energies bought from the supplied PV and a P2P trade will be cheaper than the standard grid price. This blockchain technology allows for secure and accurate trading information in a trust less system, allowing all parties to agree on the data mutually. All participants have Access to the blockchain-based dashboard to view all the energy bought and sold more transparently and securely. The LEM provides consumers with affordable, reliable, and sustainable energy by leveraging DERs in the network more efficiently.

The LEM software operates and produces a live trading proof on a dashboard screen. This trading provides financial benefits and information security through blockchain technology. It provides value for sellers as the P2P sell price will be greater than that of the FiT and less than the grid buy price. The smaller the FiT, the greater the margin can be. For participants who need more energy than what has been produced by their solar array, they will preferentially buy P2P energy traded between participants. This price point would be.

Cheaper than buying directly from the grid without diminishing the margin taken by the operators. This price point fluctuates based on energy demand, which is essential to make energy more valuable at peak times and less valuable off-peak. At the price point, buyers and sellers at every interval will benefit from participating in the trading group, having no negative consequences for other stakeholders in the energy grid. The trading platform charges a minimal fee per transaction the network operator executes for enabling trades to all trading group members. By facilitating these trades, all participants are given the ideal situation. LEM platform is built on microservice-based architecture, supported by high throughput, low energy proprietary blockchain, allowing the service to be easily scalable when the project expands. This study used Singapore electricity tariff breakdown, as shown in Fig. 2. With some of the information publicly available from Solarvest, it is possible to estimate with high confidence. Fig. 3 shows the energy, cash, and internet-of-time (IoT) flows between the consumer and prosumers and illustrates the structural tariff distribution of buyers S$28.85 among different stakeholders.

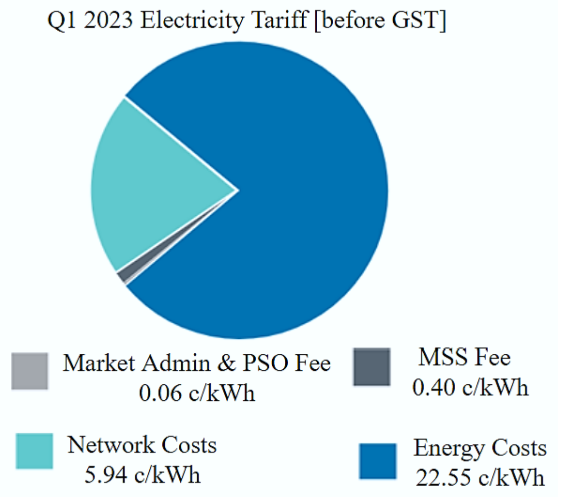

Fig. 2. Diagram of Singapore electricity tariff breakdown [25].

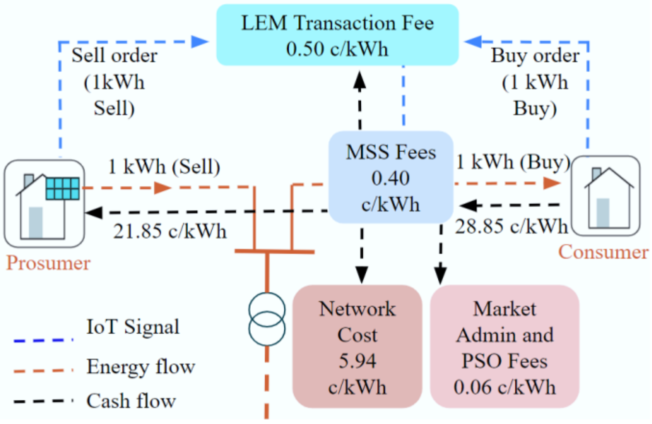

Fig. 3. Energy and cash flows among consumers and prosumers.

III. IMPLEMENTATION OF BLOCKCHAIN TECHNOLOGY

Implementing the LEM platform has much work exploring and testing the P2P trading concept in various case studies for different regions and various types of participants, ensuring a well-developed and holistic view of the developed platform. The overall development steps of the trading platform are shown in Fig. 4.

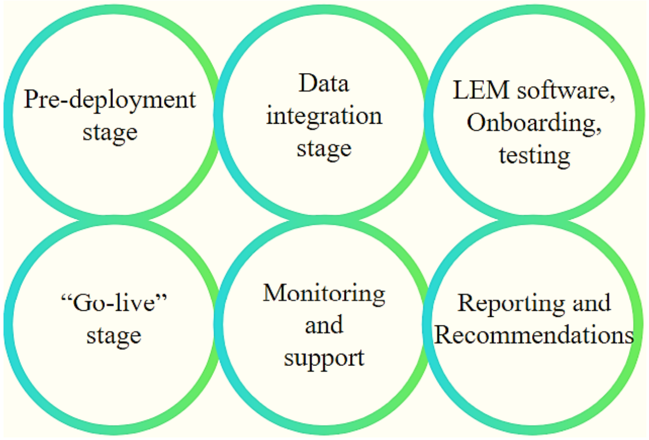

Fig. 4. Implementation Plan for the LEM.

Another major step for the LEM developments is to integrate with blockchain technology. Fig. 5 shows the blockchain integration where prosumers and consumers relate to the smart contract. This integration is through

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decentralized applications (dApp), encompassing the user interface (UI) and the web3 interface. While LEM participants' bids are arranged with the help of UI, the web3 interface connects that UI with the smart contract-driven blockchain database. The smart contract collects participant bidding data, receives P2P trading output, creates a settlement record, and retrieves data from the blockchain database. All past bids, P2P trading records, and billing data are stored on the blockchain platform.

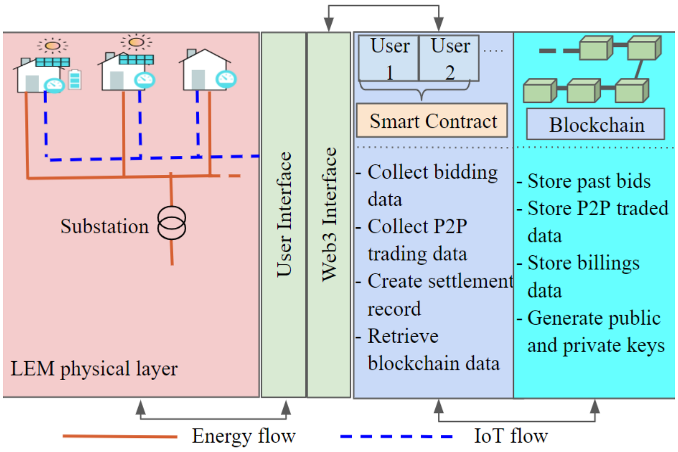
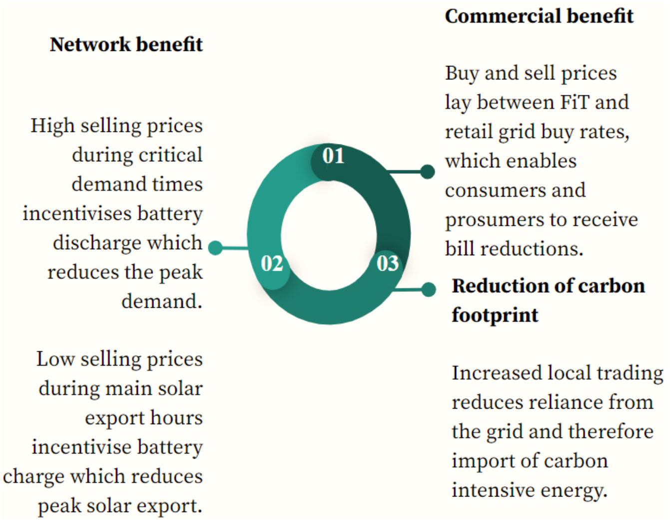


Fig. 5. Diagram of Singapore electricity tariff breakdown [20].

IV. DELIVERABLES AND OUTCOMES

The desired milestones include savings of individual participants, which is correlated to an increase in return on investment (ROI). Increasing the ROI directly increases the value of the investment, which would lead to an increase in the business/commercial use of energy. The system also increases profitability as more meters and prosumers participate in the trading group as more P2P trades happen. By increasing the utility of solar and allowing it to be a more reliable source of energy for the people of Singapore, there will be less demand for imported energy, lowering dependence on imported liquefied natural gas (LNG). Through the commercial benefit of LEM, it encourages customers to invest more and more in DERs. Savings are greater for Prosumers than consumers, encouraging consumers to purchase DERs for themselves. By increasing the number of prosumers in the network, the benefits of it will be magnified for all parties involved, as shown in Fig. 6. This also supports the Singapore Government's' Green Plan, which aims to quadruple Solar deployment in the country. With the support of the P2P trading-based LEM platform, Solarvest can be a key player in this step of the clean energy movement.



High selling prices during critical demand times incentivises battery discharge which reduces the peak demand.

Low selling prices during main solar export hours incentivise battery charge which reduces peak solar export.

Buy and sell prices lay between FiT and retail grid buy rates, which enables consumers and prosumers to receive bill reductions.

Increased local trading reduces reliance from the grid and therefore import of carbon intensive energy.

Fig. 6. Impacts and outcomes of P2P Trading-based LEM.

V. OBJECTIVE FUNCTION

The primary objective of the proposed business model is to minimize the electricity buy cost while the electricity sell cost is maximized for each LEM participant to ensure the electricity bill reduction. Further, it guarantees the minimization of both grid import and export. Moreover, the margin of the network operator is always higher than BAU (or kept unchanged).

These objectives are subject to three constraints. Constraint 1: LEM trading price is always higher than the FiT rate but lower than the time-of-use (ToU) price. Constraint 2: LEM trading quantities are always bounded by the mutual exchange limits provided by the network operator. Constraints 3: BESS operational constraints are always considered while settling P2P transactions in the LEM.

The proposed business model objectives are illustrated in mathematical form in (1).

$$\begin{aligned}&Objective\ function\ =\\&min\,\{Electricity\ buy\ cost - Electricity\ sell\ cost\} +\\&min\,\{Grid\ import\ +\ Grid\ export\} +\\&max\,\{Network\ operator\ margin\}\end{aligned} \tag{1}$$

Subject to: Constraint 1, Constraint 2, and Constraint 3.

$$\sum_{a=1}^{|A|} P_a(t) = \sum_{b=1}^{|B|} P_b(t), \qquad a, b \subset N, \forall t \epsilon T \tag{2}$$

Where equation (2) demonstrates the power balance in the LEM, i.e., the total sellers' traded power should equal the total buyers' traded power. The sets of LEM sellers and buyers are signified by A and B, respectively, where $A, B \subset N$. Symbols a and b stand for each seller and each buyer, respectively.

$$\gamma^{fit}(t) \le (\gamma_n^{tr}(t) + \gamma^{pt}(t)) \le \gamma^{eng}(t), \ \forall z \epsilon Z, \forall t \epsilon T \tag{3}$$

The LEM price constraint is illustrated in (3). $\gamma^{eng}(t)$ is the energy price (ToU) segment of the tariff $\gamma^{tou}(t)$. The FiT rate is symbolized by $\gamma^{fit}(t)$. $\gamma^{tr}(t)$ and $\gamma^{pt}(t)$ refer to P2P trading for each participant $n \epsilon N$ and LEM platform cost, respectively.

$$P^i(t) < P^{i(o)}(t), \qquad \forall t \epsilon T^i \subset T \tag{4a}$$

$$P^j(t) < P^{j(o)}(t), \qquad \forall t \epsilon T^j \subset T \tag{4b}$$

Where equations (4a) and (4b) represent the grid's export and import, symbolized by $P^i(t)$ and $P^j(t)$, respectively, constraints. T^i and T^j are considered as the sets of peak solar periods and demand periods, respectively. $P^{i(o)}(t)$ and $P^{j(o)}(t)$ are the grid's export and import without the LEM.

$$\gamma_y^{rt}(t) \le \gamma_y^{rt(o)}, \qquad \forall y \epsilon Y, \forall t \epsilon T \tag{5a}$$

$$\gamma^{nt}(t) \le \gamma^{nt(o)}(t), \qquad \forall t \epsilon T \tag{5b}$$

The energy suppliers and the network operators' margin constraints are described in equations (5a) and (5b). $\gamma_y^{rt}(t)$ and $\gamma_y^{rt(o)}$ Imply each energy supplier's $y \epsilon Y$ margin with and without the LEM, respectively. Further, the network

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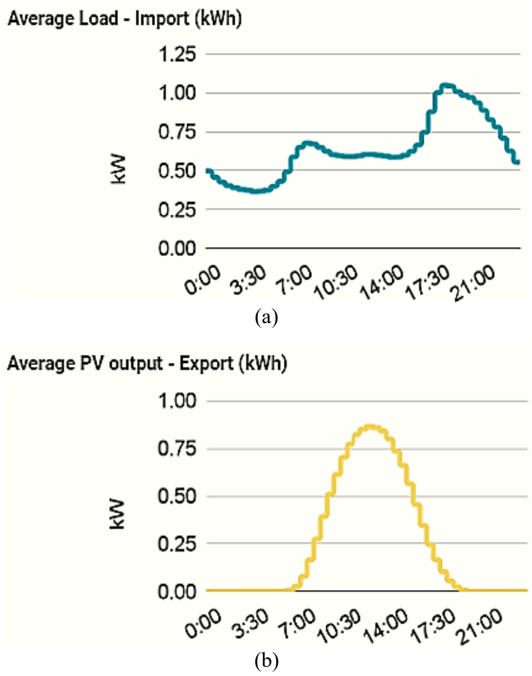
operator's margin with and without the LEM is represented by $\gamma^{nt}(t)$ and $\gamma^{nt(o)}(t)$, respectively.

VI. RESULTS AND ANALYSIS

This research project involved a LEM network architecture with a total of 100 participants, and they were divided into 60 consumers, 20 prosumers with solar PVs, and 20 prosumers with BESSs and solar PVs. The prosumers had an average solar PV system size of 6 kW and an average BESS size of 3.3 kW/12.5 kWh. The network operator managed settlements for all 100 participants, including the consumers and prosumers. Fig. 7 [26] shows the average load profiles of all participants and the average solar PV generation. The study used P2P trading in the LEM, with prosumers bidding to sell their excess energy at a price between the FiT rate and the energy portion of the grid ToU buy price. Consumers paid network fees on top of the energy fee for P2P trading, which was lower than the respective grid ToU buy price. The P2P trading-based LEM system was conducted in Singapore's context, with time intervals of 15 minutes. Smart contracts were written using REMIX IDE and tested on the Ethereum blockchain using Ganache CLI v6.12.2. The web3.py library connected the user interface with the smart contract and blockchain database. In the LEM, energy bidding rates are randomly selected for 40 prosumers and 60 consumers who are network operator customers. Prosumers place selling bids at a price greater than the FiT rate but lower than the energy portion of the grid buy price. The prices of prosumers in c/kWh are shown in Fig. 2. On the other hand, consumers pay extra fees (as demonstrated in Fig. 3) on top of energy fee while doing P2P trading in LEM, but it is lower than the respective grid buy price.

A. *Participants' daily electricity bill reduction*

Fig. 8 displays the average daily decrease in electricity bills for different groups: consumers, prosumers with solar PVs, and prosumers with solar PVs and BESSs in two scenarios, BAU and LEM. In the LEM scenario, the bill reduction for all groups is lower than the BAU scenario, with reductions of S$12, S$26.8, and S$30.8 for consumers, prosumers with solar PV systems, and prosumers with solar PV systems and BESSs, respectively, over a month. All participants are experiencing a reduction in their electricity bills, with those who invested in DERs receiving the greatest reduction.



(a)

(b)

Fig. 7. Average profiles of LEM participants.

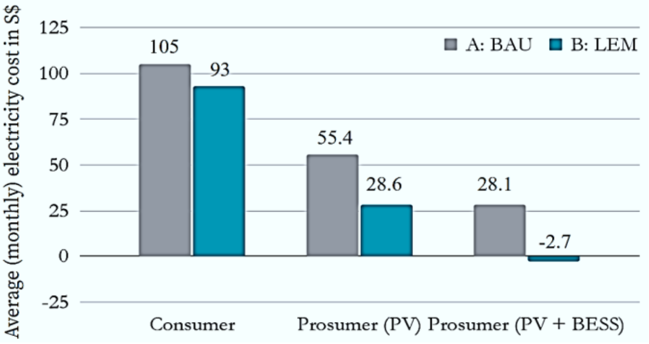


Fig. 8. Monthly electricity bill comparison between BAU and LEM.

B. *Reduction in grid import and export*

Fig. 9 displays the electricity export and import profiles of the network under consideration in three different scenarios: BAU (Case-0), BAU with BESS (Case A), and LEM with BESS (Case B). Compared to BAU, the proposed LEM shows a significant reduction in peak power sold/bought to/from the power grid during afternoon/evening hours, nearly 34%/37%, largely due to P2P contracts in LEM. Using BESS for discharging and energy trading with neighboring uses during peak times also reduces power grid import. Furthermore, using BESS to offset demand during periods of high spot prices in the evening reduces costs related to grid imports.

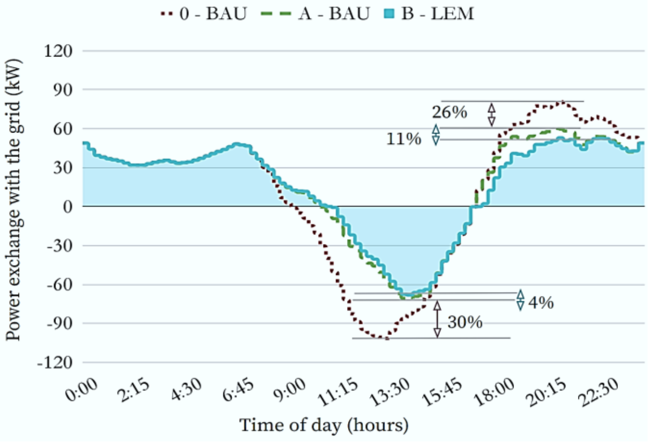


Fig. 9. Reduction in grid import and export through LEM.

C. *Network Monthly Income Margin*

The LEM structure based on P2P energy trading, as planned in this study, ensures that the income of the network operator remains higher than the levels observed in BAU. This comparison is illustrated in Fig. 10. The increase in monthly income is attributed to an additional fee per kWh traded through P2P and increased P2P energy trading volume resulting from BESS charging and discharging among prosumers. Including BESS in the LEM, network leads to an improvement of 1.1% in network, market admin, and MSS feels, as observed in Fig. 10.

The network operator may not be making profits like the LEM participants due to decreased BAU trading. But P2P trading in the LEM significantly reduces renewable energy penetration into the electricity network, which can eventually lead to reduced capital expenditures (CapEx) and operational

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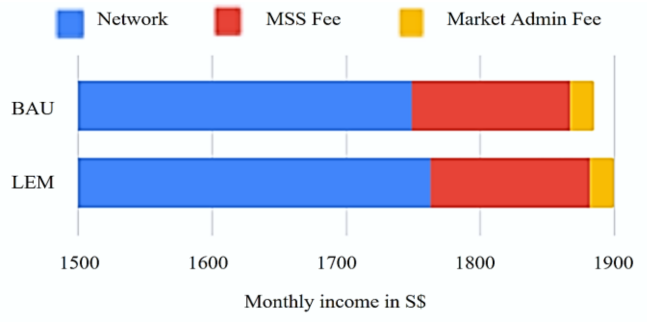

Fig. 10. Monthly income margin for the network operator.

expenditures (OpEx) of the electricity grid. This may encourage the network operator to allow more consumers to become prosumers. While the margin of the network operator may not increase significantly with the LEM, it can reduce its budget for power grid operation and maintenance because of less export/import to/from the power grid, resulting in long-term benefits. The costs associated with the execution of different functions of the smart contracts in the Ethereum blockchain. The cost of operating a P2P trading-driven LEM on the Ethereum blockchain platform is found to be significantly higher than that of the Polygon blockchain. This is because the transaction speed of the Ethereum network is much lower (approximately 15-17 transactions per second) compared to Polygon. Because of Ethereum's low transaction speed, the network congestion is also high, resulting in higher gas fees. Therefore, the Polygon blockchain is suggested as the most suitable blockchain to accommodate the proposed LEM trading.

VII. CONCLUSION

This paper introduced the P2P energy trading-based LEM mechanism and evaluated its financial feasibility. A platform using blockchain technology has been created for the LEM, enabling various types of users, such as consumers and prosumers with solar PVs and BESSs, to trade energy regularly. This is done while complying with technical and operational limitations, such as power balance, prices, and the functional limitations of BESS. The individuals and groups involved in the project, including the network operator, are assured of receiving financial advantages.

The simulation results have been compared to the conventional BAU, and the suggested LEM trading method has demonstrated better performance. The outcomes indicated that the suggested LEM presents a more significant reduction in bills, ranging from 15.7% to 22.4%, for prosumers compared to other incentive plans. This is achieved through P2P trading, which allows trading within the FiT and grid purchase energy price range.

The usage of BESS has reduced the difference between maximum grid import and export to 36% and 35%, respectively, using the operational principle to control the charging or discharging behavior at set regular time intervals. The LEM preserves the income of the network operator, and P2P trading lowers the influx of renewable energy into the network. This can eventually decrease the CapEx and OpEx of the network operator. It is possible in the future to enhance the efficiency of a LEM by integrating a community BESS and electric vehicles (EVs). This expansion would enable the LEM to contribute to grid stabilization and lower energy demand peaks, benefitting the network operator. Moreover, the community BESS would also ease the grid burden caused by variable renewable energy sources, leading to decreased energy wastage and curtailment costs. Using blockchain settlements would ensure transparency and clarity for users and application hosts. Incorporating these strategies would increase the self-sustainability of prosumers and the community, hastening the transition to sustainable energy and supporting sustainability objectives.

Further research may focus on deploying the LEM framework on the Solana blockchain and leveraging tokenization in blockchain-based decentralized energy systems to establish more efficient and robust energy markets. More research is required to create legal and regulatory frameworks that enable energy decentralization and tokenization.

VIII. ACKNOWLEDGMENT

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