DECENTRALISED ENERGY MANAGEMENT USING BLOCKCHAIN IN VIRTUAL POWER PLANTS WITH BATTERIES TO REDUCE NETWORK CONGESTION

Nabin B. Ojha[1], Liaqat Ali[1], Ehsan Pashajavid[1], Arindam Ghosh[1], and S.M. Muyeen[2]*

[1]*School of Electrical Engineering, Computing and Mathematical Sciences, Curtin University, Perth, Australia*
[2]*Department of Electrical Engineering, Qatar University, Doha, Qatar*
**LIAQUATNEDUET@IEEE.ORG*

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Abstract

This paper presents a blockchain based Virtual Power Plant (VPP) framework aimed at enhancing economic returns and reducing grid reliance for customers equipped with distributed energy resources (DERs). The proposed VPP integrates five distinct participants: three residential users with solar photovoltaic (PV) systems, electric vehicles (EVs), and residential batteries; and two commercial entities comprising a community battery energy storage system (CBESS) and a commercial complex with large-scale solar PV plant. A decentralized energy management system, powered by blockchain smart contracts, is developed to immutably store energy data and transaction records in a decentralized manner, ensuring data integrity and security. This system ensures transparent and equitable energy trading among participants. Comparative simulations reveal that the VPP model increases participant profits by up to 76% and reduces grid energy consumption by 22% with peak import reduction by 38%. Based on an Australian case study, the proposed approach demonstrates practical viability for VPP operators and offers promising potential for integration with distribution networks.

1 Introduction

Western Australia is experiencing rapid growth in distributed energy resources (DERs), driven by strong consumer adoption and supportive government initiatives. As of 2025, approximately 40% of residential customers in Western Australia have installed rooftop solar photovoltaic (PV) systems, making it one of the highest adoption rates globally [1-2]. In Western Australia, the government is introducing a residential battery rebate scheme starting July 2025 to accelerate battery adoption. To be eligible, households must install Virtual Power Plant (VPP)-ready batteries and participate in a VPP, supporting broader grid integration and energy resilience goals. The government is introducing a residential battery rebate scheme starting July 2025 to accelerate battery adoption. To be eligible, households must install VPP-ready batteries and participate in a VPP, supporting broader grid integration and energy resilience goals [3-4].

The increasing adoption of DERs, such as solar PV and battery storage, has catalyzed the development of VPPs, which aggregate and coordinate DERs to optimize grid interaction and energy management. While traditional VPPs rely on centralized control systems, recent advancements in blockchain technology offer decentralized alternatives that improve transparency, trust, and operational efficiency among participants [5-6]. Recent advancements in blockchain and machine learning technologies are transforming the coordination of residential and commercial participants within VPPs. These technologies enable decentralized, intelligent energy management systems that optimize energy trading, reduce grid dependency, and maximize participant profits. Blockchain ensures transparency and trust in peer-to-peer (P2P) energy transactions, while machine learning enhances forecasting, load balancing, and decision-making processes [7-8]. Together, they support the evolution of VPPs from centralized control models to more adaptive, distributed frameworks capable of integrating diverse DERs effectively [9-10].

While VPPs have emerged as a promising solution for integrating DERs, most existing research focuses on either centralized control systems or limited blockchain applications. For instance, Yang et al. developed a blockchain-based energy management platform for residential DERs, emphasizing decentralized optimization but without integrating commercial-scale assets or tariff-based trading schemes [6]. Similarly, Li et al. proposed a blockchain-assisted VPP framework for operating reserve markets, focusing primarily on reserve capacity evaluation rather than holistic energy dispatch and profit maximization [11]. In contrast, this research introduces a comprehensive blockchain-based VPP model that coordinates both residential and commercial participants, integrates time-of-use (ToU) and feed-in tariff (FiT) mechanisms, and demonstrates significant economic and operational benefits through simulation. This dual-layered approach—combining decentralized control with tariff-based optimization—offers a more scalable and equitable framework for VPP. The main contributions of this paper are:

- Design of a blockchain-enabled decentralized energy management system that coordinates heterogeneous DERs across residential and commercial sectors.

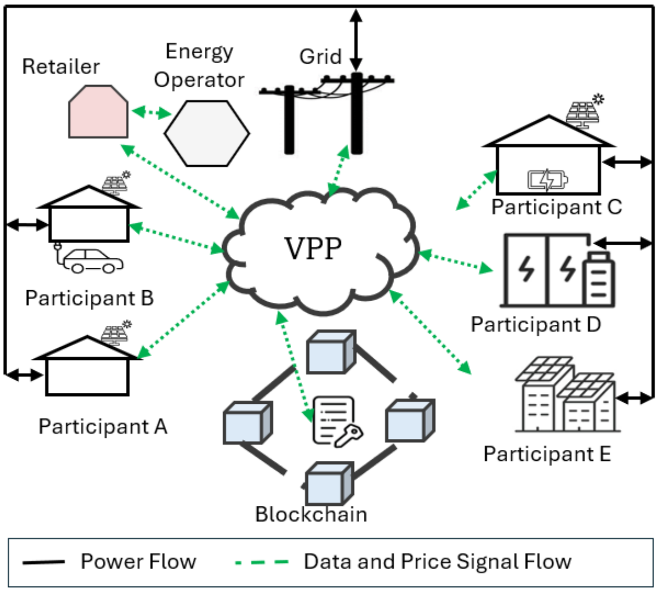

Fig. 1 System model for proposed VPP

- Integration of ToU and FiT schemes into the VPP model to enable transparent and economically optimized energy trading.
- Simulation-based validation showing a 76% increase in participant profit and a 22% reduction in grid energy consumption and 38% reduction in peak grid import.
- Application to an Australian case study, demonstrating practical feasibility and future potential for integration with distribution networks.

The remainder of this paper is structured as follows: Section 2 and 3 outlines the system model and blockchain integration with the VPP, respectively. Problem statement and mathematical model is formulated in Section 4. Section 5 presents the simulation setup and discusses the simulation results. Finally, Conclusion and future works are presented in Section 6.

2 System Model

The proposed VPP model comprises five distinct participants, categorized into residential and commercial sectors. The residential segment includes three types of customers:

- Solar PV-only households equipped with 6.6 kW rooftop solar systems.
- EV-owning households that also have solar PV systems and utilize a 20-kWh battery integrated into their electric vehicles. These batteries serve dual purposes: charging for mobility and contributing to VPP operations.
- Mixed residential participants with both solar PV of 6.6 kW and 10-kWh residential battery for energy storage and VPP participation, capable of flexible energy dispatch.

The commercial segment consists of:

- A Community Battery Energy Storage System (CBESS) of 600 kWh designed to support neighbourhood-level energy balancing contributing significant energy to VPP.
- A large-scale commercial complex with 80 kW solar PV plant contributing significant energy to the VPP.

All participants are coordinated by a VPP provider, who has operational control over the battery systems as shown in Fig. 1. The provider can dispatch stored energy from participant batteries and CBESS for grid support or commercial transactions on request. Two discharge pathways are available:

- To retailers at a tariff rate of \$0.70 per kWh.
- To large commercial consumers at a premium rate of \$1.50 per kWh.

Participants benefit economically through:

- Self-consumption of solar PV-generated energy.
- EV charging using stored or solar energy.
- Revenue sharing when their batteries are utilized by the VPP provider for external energy dispatch.

This model ensures optimized energy utilization, reduced grid dependency, and equitable profit distribution among participants, forming a scalable and transparent framework for VPP.

3 Blockchain Integration with the VPP

In the proposed VPP framework, blockchain technology serves as the backbone for secure, transparent, and decentralized energy management. Each residential and commercial participant is registered on a blockchain network, enabling tamper-proof recording of energy generation, consumption, battery status, and transaction history. Blockchain can be used for energy usage tracking, allowing participants to monitor their solar generation, EV charging, and battery contributions.

To ensure data privacy and operational transparency, smart contracts securely manage participant data, including energy profiles and financial transactions. Each participant is granted access to a user-facing application, which provides real-time visibility into:

- Their energy usage and generation.
- Battery status and dispatch history.
- Earnings from self-consumption, EV charging, and VPP participation.

This blockchain-enabled architecture not only enhances trust among stakeholders but also ensures scalable and equitable energy coordination, making it a robust solution for future decentralized energy systems [12].

4 Problem Formulation

The concept of virtual VPP pool is used to optimize the DER resources. The VPP pool acts as a shared energy hub for all participants and ensures fair energy sharing and cost allocation. Participants with solar PV and BESS contributes excess energy and stored energy in the VPP pool. The VPP pool optimally distributes the energy to meet participant's internal load, charge BESS, sell to the retailer, external load or grid for profit maximization.

The VPP optimizes energy flows for five participants ($\boldsymbol{P} = \{\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}, \boldsymbol{d}, \boldsymbol{e}\}$) over 24 hours ($\boldsymbol{T} = \{\boldsymbol{0}, \dots, \boldsymbol{23}\}$) using a shared VPP pool to maximize profit. Participants with solar PV ($\boldsymbol{G} = \{\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}, \boldsymbol{e}\}$) and BESS ($\boldsymbol{B} = \{\boldsymbol{b}, \boldsymbol{c}, \boldsymbol{d}\}$) contribute excess solar and BESS energy to the pool, which supplies internal loads, charges BESS, or sells to the retailer, external load, or grid. Participant $\boldsymbol{d}$ is a community BESS (CBESS), and $\boldsymbol{e}$ has a large commercial load. Pool based VPP model ensures energy balance, fair cost allocation, and exclusive battery charging or discharging.

4.1 Parameters

The list of input data required to define the VPP model are as follow:

$Y(p,t), L(p,t)$	Solar PV generation, Load demand in kW of participant $p \in P$ in time t
$Y^{min}(p,t)$, $Y^{max}(p,t)$	Minimum and maximum PV capacity in kW for participant $p \in P$ in time t
$X^{rate}(p)$	BESS rated capacity in kWh for participant $p \in B$
$X^{min}(p,t)$, $X^{max}(p,t)$	Maximum BESS charging for participant $p \in B$
$SoC^{mn}(p)$, $SoC^{mx}(p), SoC^{o}(p)$	Minimum, maximum and initial SoC of BESS for participant $p \in B$
$SoC(p,t)$	SoC of BESS for participant $p \in B$ in time t
η_c, η_d	BESS charging and discharging efficiency
$\mu^{ToU}(t), \mu^{FiT}(t)$, $\mu^{ch}(t)$	ToU, FiT and charging rates in \$/kWh
$\mu^{R}(t), \mu^{c}(t)$	Retailer and External load rates in \$/kWh
$R^{max}(t), C^{max}(t)$	Maximum retailer and external load in \$/kWh

4.2 Decision Variables

List of decision variables that used for optimization are as follow:

$Y^{a}(p,t), X^{ch}(p,t)$, $\boldsymbol{X^{dis}(p,t)}$	Solar PV to self-load, self-BESS charge and discharge in kWh for participant $\boldsymbol{p} \in \boldsymbol{P}$ in time $\boldsymbol{t}$
$Z^{pool-pv}(p,t)$, $Z^{pool-BESS}(p,t)$, $\boldsymbol{Z^{ch-pool}(p,t)}$	Solar PV to Pool, BESS to pool; pool to BESS in kWh for participant $\boldsymbol{p} \in \boldsymbol{P}$ in time $\boldsymbol{t}$
$Z^{imp}(p,t), Z^{exp}(p,t)$, $\boldsymbol{Z^{int-pool}(p,t)}$	Grid import, export and internal load from pool in kWh for participant $\boldsymbol{p} \in \boldsymbol{P}$ in time $\boldsymbol{t}$
$\boldsymbol{S(p,t)}$	Battery charge in kWh for $\boldsymbol{p} \in \boldsymbol{B}$ for time $\boldsymbol{t}$
$\boldsymbol{R(t), C(t)}$	Retailer and external load in kWh in time $\boldsymbol{t}$
$\boldsymbol{\delta(p,t)}$	Binary variable (1 for charging and 0 for discharging) for participant $\boldsymbol{p} \in \boldsymbol{P}$ in time $\boldsymbol{t}$
$Y^{a}(p,t), X^{ch}(p,t)$, $\boldsymbol{X^{dis}(p,t)}$	Solar PV to self-load, self-BESS charge and discharge in kWh for participant $\boldsymbol{p} \in \boldsymbol{P}$ in time $\boldsymbol{t}$

4.3 Objective Function

The main objective of the model is to maximize the total profit of each participant over a period $\boldsymbol{T}$ expressed by Eq. (1)

$$OF = max(\sum_{t}^{T} Revenue(t) - Cost\ (t) \tag{1}$$

Where:

$$Revenue(t) = \mu^{R}(t) \times R(t) + \mu^{C}(t) \times C(t) + \mu^{FiT}(t) \times Z^{exp}(t) \tag{2}$$

$$Cost(t) = \sum_{p \in P}(\mu^{ToU}(t) \times Z^{imp}(p,t) + \mu^{ch}(t) \times Z^{ech-pool}(p,t) \tag{3}$$

4.4 Constraints

Objective function is subjected to the following constraints:

4.4.1 Energy Balance in the VPP pool:

$$\sum_{p \in P} \left(Z^{pool-PV}(p,t) + Z^{pool-BESS}(p,t) + Z^{imp}(p,t) \right) = \sum_{p \in P} \left((Z^{int-pool}(p,t) + Z^{ch-pool}(p,t) \right) + R(t) + C(t) + Z^{exp}(t) \tag{4}$$

4.4.2 BESS constraints:

$$0 \le X^{c}(p,t) \le \delta(t) \times X^{c\_max}(p,t) \tag{5}$$

$$0 \le X^{d}(p,t) \le X^{d\_max}(B,t) \times \big(1 - \delta(t)\big) \tag{6}$$

$$SoC(p,t) = SoC^{o}(p) + \Big(\eta_C\big(X^{c}(p,t) + Z^{ch-pool}(p,t)\big) - \Big(\frac{X^{d}(p,t) + Z^{pool-BESS}(p,t)}{\eta_D}\Big) \text{ for } t=0 \tag{7}$$

$$SoC(p,t) = SoC(p,t-1) + \Big(\eta_C\big(X^{c}(p,t) + Z^{ch-pool}(p,t)\big) - \Big(\frac{X^{d}(p,t) + Z^{pool-BESS}(p,t)}{\eta_D}\Big) \text{ for } t \ge 1 \tag{8}$$

4.4.3 Generation, Load and External Demand Constraints:

$$Z^{int-pool}(p,t) = L(p,t) - Y^{a}(p,t) - X^{d}(p,t) \tag{9}$$

$$0 \le R(t) \le R^{max}(t) \tag{10}$$

$$0 \le C(t) \le C^{max}(t) \tag{11}$$

$$Y^{min}(p,t) \le Y^{a}(p,t) \le Y^{max}(p,t) \tag{12}$$

5 Simulation and Results

The proposed VPP simulation optimizes energy for five participants ($P = \{a, b, c, d, e\}$) over 24 hours. Participant a has a 6.6 kW solar PV and 2.5 kW load; b has a 6.6 kW solar PV, 2.5 kW load, and 10kW, 20 kWh BESS; c has a 6.6 kW PV, 2.5 kW load, and 5kW, 10 kWh BESS; d is a 300 kW, 600 kWh CBESS; and e is a commercial complex with a 50 kW load and 80 kW solar PV. The VPP pool manages energy flows to meet loads, charge/discharge BESS, or sell to retailers at \$0.70/kWh and an external load at premium rate of \$1.50/kWh. $SoC^{o} = 50\%$, $SoC^{min}(p,t) = 10\%$, $SoC^{max}(p,t) = 100\%$. Different tariff structure used during simulation is given in Table 1.

The mixed-integer linear programming (MILP) model is formulated and solved using Gurobipy's branch-and-cut algorithm on a PC with an AMD Ryzen 7 7730U CPU (2.00 GHz), 16 GB RAM, and Windows 11 (64-bit). A smart contract is written in Solidity and deployed on Ganache. Ganache is a tool that simulates an Ethereum blockchain locally to create a private Ethereum network for testing and development of smart contract.

Table 1 Tariff rate for different type of users [13-14]

Period	FiT	ToU (Midday Saver)	ToU (EV Home Plan)
0 AM - 6 AM	0.02	0.231	0.189
6 AM - 9 AM	0.02	0.231	0.231
9 AM - 3 PM	0.02	0.084	0.084
3 PM - 9 PM	0.1	0.525	0.525
9 PM - 11 PM	0.02	0.231	0.231
11 PM - 0 AM	0.02	0.231	0.189

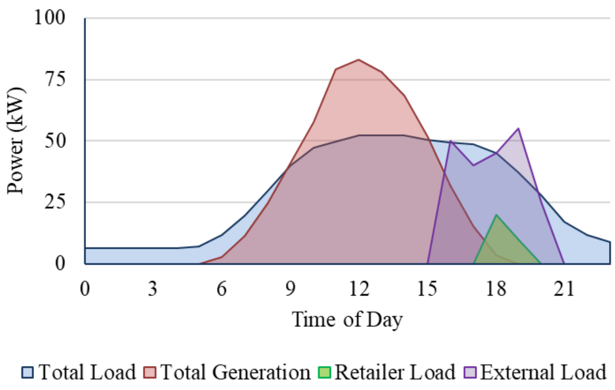

Fig. 2 Load and Generation profile managed by VPP

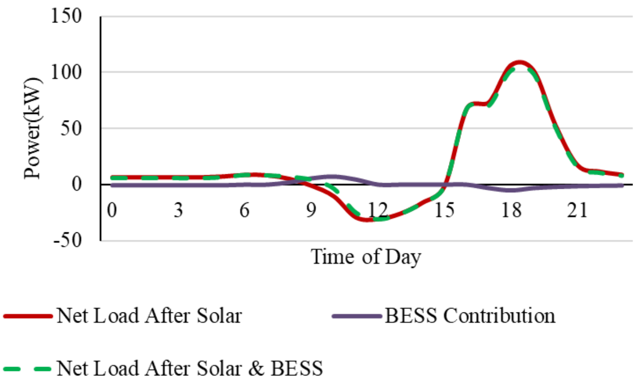

Fig. 3 Grid Interaction in BAU without VPP

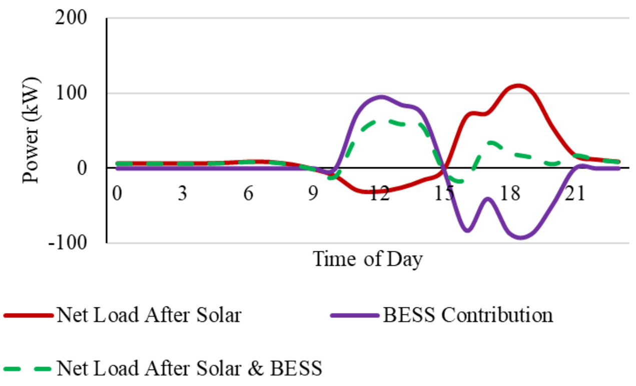

Fig. 4 Grid Interaction with VPP

5.1 Load and generation profile

VPP optimizes the total load, solar generation, BESS dispatch, retailer demand and external commercial load to maximize the profit for each participant. Fig. 2 illustrates the total residential load, solar generation, retailer's load and external commercial load for a day. Solar generation peaks at 12:00. Retailer load and external commercial load are there in the evening time during peak time.

5.2 Grid Interaction Comparison: With vs. Without VPP Service

The VPP optimizes the charging and discharging of BESS to maximize consumption within VPP and minimize grid import to reduce the cost of energy. VPP also schedules BESS dispatch to address retailer's demand and external commercial load to maximize profit. Fig. 3 shows the grid import and export for No-VPP case. Since, there is no optimization, CBESS is not being used. So, the surplus energy available during mid-day (103 kWh of surplus energy available from 10:00 to 15:00) is exported to the grid at FiT rate and deficit energy at the evening time is imported from the grid. Fig. 4 shows the grid import and export when VPP in implemented to coordinate the available resource. CBESS is charged during mid-day and it is being used at the evening time to reduce grid import.

Table 2 shows the cost and revenue comparison for five participants in no-VPP and VPP scenarios. The simulation results of profit analysis for the VPP model are summarized below:

- Residential Solar PV: $2.6
- Residential EV: $2.7
- Commercial CBESS: $38.3
- Commercial Complex with Solar PV: $25.2

These results reflect the combined profits from self-consumption of solar energy, EV charging (where applicable), and battery dispatch by the VPP provider to either retailers or large commercial consumers. Commercial participants generate significantly higher profits due to their large-scale PV and battery capacities, and higher VPP dispatch tariffs. Residential participants benefit more from self-consumption and EV charging, with limited surplus energy available for VPP dispatch.

5.3 *Profit Comparison: With vs. Without VPP Service*

VPP optimizes the utilization of BESS to charge during surplus solar energy and discharge during peak demand or high-price periods to maximize system-wide profit. Fig. 5 shows the cost vs benefit for participants A, B, C, D, and E over a day under no-VPP and VPP scenarios. The VPP reduces cost for participants (A, and E) and increases the profit for battery-equipped participants (B, C, and D) with 34% overall profit increase compared to the no-VPP case. This improvement stems from the VPP pool's efficient coordination of all participants' solar and battery contributions, with the CBESS (D) leveraging its large 600 kWh capacity to maximize high-value exports.

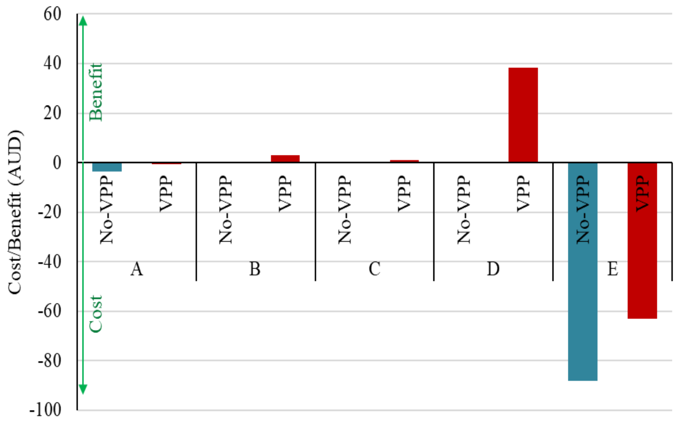

Fig. 5 Cost vs Benefit for each participant with VPP and without VPP

Table 2 Cost vs Benefit (AUD) comparison with VPP and without VPP

	A	B	C	D	E
No-VPP	-3.6	0.3	0.4	0	-88.2
VPP	-0.5	3	0.9	38.3	-63

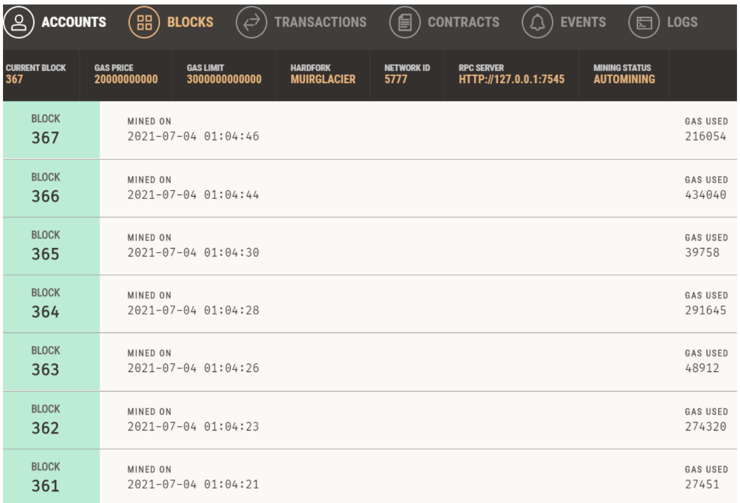

Fig. 6 Screenshot of Smart Contact being deployed and Block formation

5.4 *Blockchain implementation*

Smart Contract is developed for registering the participants, recoding the hourly data and recording hourly cost and revenue for each participant. Smart contract is developed using Solidity programming language for implementing in Ethereum Virtual Machine (EVM) compatible blockchain and deployed in local Ethereum blockchain created using Ganache GUI tool as shown in Fig. 6. Participants can track their energy usage using a user-facing application, which provides real-time visibility and the source of energy.

Each residential and commercial participant is registered on a blockchain network using the *registerParticipant* function of the smart contract, deployed on Ganache. The *recordHourlyData* function immutably stores hourly load, solar generation, BESS SoC, VPP pool sharing, grid import/export and profit for five participants, enabling tamper-proof tracking of energy usage, BESS charging, and battery contributions in VPP. The *getHourlyData* and *getParticipantList* functions allow transparent data retrieval, ensuring real-time visibility and the source of energy.

6 Conclusion

This study introduces a blockchain-based VPP model that effectively coordinates residential and commercial DERs to maximize profit and reduce grid dependency. The proposed VPP optimizes the system that enables participants to benefit by maximizing self-consumption, battery dispatch and grid interaction. Simulation results confirm a profit increase of up to 76% across all participant types, demonstrating the model's economic viability and scalability. The proposed model reduces grid energy consumption by 22% with peak import reduction by 38%. Energy data and transaction record are stored on blockchain for transparency and better visibility. The proposed framework offers a practical solution for future decentralized energy systems, particularly within the evolving Australian energy landscape.

Future work could focus on incorporating dynamic pricing models, real-time grid signals, and demand response strategies to further enhance the flexibility and responsiveness of the VPP. Additionally, integrating battery degradation costs, user behaviour modelling, and advanced forecasting using AI could improve the accuracy and economic optimization of the system. Expanding the model to include peer-to-peer trading and interoperability with other energy markets would also support broader scalability and adoption.

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8 References

[1]. Government of Western Australia, "DER Roadmap," WA.gov.au, Jul. 2024. [Online]. Available: https://www.wa.gov.au/system/files/2024-07/248948epwaderrroadmap26_july.pdf. [Accessed: 11-Jun-2025].

[2]. L. Ali, M. I. Azim, J. Peters, V. Bhandari, A. Menon, V. Tiwari, and J. Green, "BESS-facilitated local energy market: A case study on typical Australian consumers," in Proc. 43rd IAEE Int. Conference, Mapping the Energy Future – Voyage in Uncharted Territory, July 31–Aug. 3, 2022, International Association for Energy Economics.

[3]. D. Wang, Z. Wang, and X. Lian, "Research on distributed energy consensus mechanism based on blockchain in virtual power plant," Sensors, vol. 22, no. 5, p. 1783, 2022, doi: 10.3390/s22051783.

[4]. L. Ali, J. Peters, M. I. Azim, E. Pashajavid, V. Bhandari, A. Menon, V. Tiwari, A. Ghosh, and J. Green, "How P2P trading helps an electricity retailer exposed to volatile spot prices: A case study," in Proc. 2022 IEEE Sustainable Power and Energy Conf. (iSPEC), pp. 1–5, IEEE, 2022.

[5]. T. Fu et al., "De-Re-Coupling Scheme-based Model Predictive Control of a Three-phase High-Frequency Link Matrix Converter," 2022 IEEE Sustainable Power and Energy Conference (iSPEC), Perth, Australia, 2022, pp. 1-5, doi: 10.1109/iSPEC54162.2022.10032976

[6]. Q. Yang, H. Wang, T. Wang, S. Zhang, X. Wu, and H. Wang, "Blockchain-based decentralized energy management platform for residential distributed energy resources in a virtual power plant," Applied Energy, vol. 294, p. 117026, 2021.

[7]. L. Ali, M. I. Azim, J. Peters, N. B. Ojha, M. G. Simoes and S. M. Muyeen, "Integrating Gen3 Blockchain Into a Transactive Energy Market for DERs Orchestration," in IEEE Transactions on Industry Applications, vol. 61, no. 3, pp. 5103-5115, May-June 2025, doi: 10.1109/TIA.2025.3541604.

[8]. L. Ali, V. Bhandari, J. Peters, and J. Green, "How local energy markets benefit distribution utilities," Powerledger, Whitepaper Rev. 1, 2023, pp. 1–34, DOI: 10.13140/RG.2.2.23163.69925.

[9]. S. Sierla, M. Pourakbari-Kasmaei, and V. Vyatkin, "A taxonomy of machine learning applications for virtual power plants and home/building energy management systems," Automation in Construction, vol. 136, p. 104174, 2022.

[10]. L. Ali, M. I. Azim, J. Peters, and E. Pashajavid, "Expediting battery investment returns for residential customers utilising spot price-aware local energy exchanges," Energy, vol. 306, 2024, Art. no. 132458. doi: 10.1016/j.energy.2024.132458.

[11]. H. Li, H. Hui, and H. Zhang, "Blockchain-assisted virtual power plant framework for providing operating reserve with various distributed energy resources," iEnergy, vol. 2, no. 2, pp. 133–142, 2023.

[12]. L. Ali, M. I. Azim, J. Peters, N. B. Ojha, V. Bhandari, A. Menon, V. Tiwari, J. Green, S. M. Muyeen, and M. G. Simoes, "Blockchain-integrated local energy market and P2P trading benefits for participants and stakeholders," in Proc. 2023 IEEE Green Technologies Conf. (GreenTech), 2023, pp. 191–195.

[13]. Synergy, "Electric Vehicle Add-On," Synergy, [Online]. Available: https://www.synergy.net.au/Your-home/Energy-plans/Electric-Vehicle-Add-On. [Accessed: 11-Jun-2025].

[14]. F. R. Tatari et al., "A Game Theory Based Optimal Planning for a Hybrid Energy System Considering Time of Use Tariffs," 2022 4th Global Power, Energy and Communication Conference (GPECOM), Nevsehir, Turkey, 2022, pp. 552-557.