

Technical and economic analyses of grid-connected residential PV considering batteries and peer-to-peer energy sharing

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ABSTRACT

The widespread installation of solar photovoltaic (PV) promotes using batteries and peer-to-peer (P2P) energy sharing, where prosumers sell excess PV energy to their peers. Therefore, this paper develops four mathematical energy trading models using transient system simulation for grid-connected residential PV, considering batteries and P2P energy sharing: Peer-to-grid (P2G); P2G with batteries; P2P; and P2P with batteries. These four models are proposed in order to evaluate the impacts of batteries and P2P energy sharing on reducing grid energy consumption and increasing PV energy utilisation by prosumers. An Australian house with 10 kW PV in Geelong, Victoria, is used as a prosumer, and we have collected hourly data on the solar PV generation and electrical load of the house over a year. Three consumers are assumed to be in the analyses, and their electrical loads are developed based on the prosumer's load profile. Results indicate that while batteries and P2P energy sharing can effectively increase PV energy utilisation and reduce grid energy imports for the prosumer, batteries hinder the level at which the consumers can decrease their grid energy consumption because of the operational strategy of charging batteries before P2P energy sharing. The economic analysis demonstrates that P2P energy sharing creates a positive net present value (NPV) for the prosumer over 20 years under the current economic conditions, and the highest cumulated NPV reaches AUD 4929 at the battery capacity of 10 kWh. The minimum payback period that the prosumer can attain with PV-batteries is 12 years, at which point the battery has a capacity of 7.5 kWh. Also, the sensitivity analysis verifies that the payback periods of PV and batteries become more desirable when some influencing factors, such as initial equipment purchase costs, P2P energy sharing prices, and annual discount rates, become more favourable to users.

Nomenclature

AUD	Australian dollar	E_{PX}	Exported energy of prosumer
FiT	Feed-in tariff	E_{PV}	PV generation of prosumer
N	Payback period	E_{PVP}	Amount of PV energy delivered to prosumer's electrical load
NPV	Net present value	E_{P2P}^i	Amount of PV energy shared with i^{th} consumer
P2P	Peer-to-peer	P_{P2P}	P2P energy sharing price
P2G	Peer-to-grid	R_{P2P}	Revenues received by the prosumer from P2P energy sharing
PV	Photovoltaic	R_{FIT}	Revenues received by the prosumer from PV energy exports

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RT	Retail price of grid electricity	SOC_{max}	Maximum state of charge of batteries
B	Battery capacity	SOC_{min}	Minimum state of charge of batteries
C_B	Total cost of batteries	d	Annual discount rate
C_{PV}	Total cost of solar PV	g	Given period
C_B^{ipc}	Initial purchase cost of batteries	i	Consumer number
C_{PV}^{ipc}	Initial purchase cost of solar PV	m	Number of years
C_{P-RT}	Costs of purchasing grid electricity for the prosumer	n	Number of consumers
C_{C-RT}	Costs of purchasing grid electricity for consumers	t	Time interval

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E_{B+}	Energy for charging batteries	$r_{o\&m}$	Annual operational and maintenance rate of solar PV and batteries
E_{B-}	Energy from discharging batteries	r_{dep}	Annual depreciation rate of solar PV and batteries
E_{CI}^i	Imported energy of i^{th} consumer	r_{FIT}	Annual decrease rate of FiT
E_{CL}^i	Electrical load of i^{th} consumer	r_{RT}	Annual increase rate of RT
E_{LB}	Energy losses from battery charge or discharge	r_{P2P}	Annual increase rate of P2P energy sharing price
E_{LI}	Energy loss of inverter to convert direct current to alternating current	η_{B+}	Charging efficiency of batteries
E_{PI}	Imported energy of prosumer	η_{B-}	Discharging efficiency of batteries
E_{PL}	Electrical load of prosumer	η_C	Converting efficiency of inverter

1. Introduction

Many countries worldwide agree that using renewable energy is a viable way to displace fossil fuels, reduce carbon emissions, and achieve carbon neutrality on a global scale [1,2]. Renewable energy systems can be classified into two categories based on their size: Large-scale renewable energy systems, such as wind and solar farms and hydroelectric power stations [3]; and small-scale renewable energy systems, such as rooftop solar photovoltaic (PV) systems [4,5]. Small-scale renewable energy systems are more suitable for installation in residential communities, small businesses, and households because they have lower investment costs than large-scale renewable energy systems and can be located “behind the meter” in proximity to energy consumption and can, therefore, benefit from reduced energy losses in delivering energy to the location of consumption [1,6]. Australia has the greatest solar irradiance of all continents globally, granting it a distinct advantage in advancing its solar PV industry. It has been reported that by December 2023, Australia had a total of more than 3.69 million PV installations, with a collective capacity exceeding 34 GW [7], and that more than 30 % of Australian houses have been fitted with solar PV systems [8]. Consequently, residential solar PV is anticipated to continue contributing significantly to the reduction of fossil fuel consumption and carbon emissions in the Australian residential sector.

Traditionally, most consumers purchase grid-delivered energy at retail prices provided by a retailer. Having a grid-connected residential PV system, known as peer-to-grid (P2G) integration, provides prosumers with the opportunity to displace some of their grid consumption and even export PV generation to the grid at certain prices agreed with retailers, also referred to as feed-in tariffs (FiTs) [9,10]. However, due to the increasing amount of PV energy exports, the grid, which is primarily built to distribute power rather than receive it, becomes overloaded [11]. In order to tackle this concern, retailers have initiated a phased reduction in FiT to encourage PV owners to utilise surplus PV energy locally whenever feasible, as opposed to exporting it to the grid [12,13].

Meanwhile, initiatives are being made to introduce local energy storage (e.g., batteries) to prosumers, with the aim of increasing localised PV energy consumption [14,15]. Batteries can be employed to store surplus PV energy generated during the day for use at night and during periods of high demand [16]. This can not only increase the utilisation of locally generated PV energy but also reduce the energy expenses for prosumers, especially in cases where time-of-use tariffs exist [17,18]. Prior research has confirmed the remarkable capability of batteries to address the challenges of grid stability caused by the intermittent and fluctuating nature of PV power generation [19]; however, the use of batteries in PV homes is still hindered by the substantial investment cost [4,20]. Therefore, it is crucial to identify solutions that will further increase PV self-consumption and mitigate the problem of grid overload while affirming the roles of batteries in achieving this objective.

Another approach presently accessible to increase residential PV self-

consumption is peer-to-peer (P2P) energy sharing. Under this energy sharing model, prosumers and consumers can engage in direct energy transactions with each other by taking into account the energy sharing prices and their own energy requirements [21]. Prior research has discovered numerous benefits associated with P2P energy sharing. First, by balancing local energy supply and demand, local P2P energy sharing can reduce the export of renewable generation to the grid, thereby improving grid stability [22,23]. Second, P2P energy sharing empowers prosumers and consumers to manage their energy sharing independently, free of third-party interference in pricing negotiations and energy distribution [24]. Third, P2P energy sharing enables prosumers to achieve greater profits than by exporting PV energy to the grid, while simultaneously allowing consumers to incur lower costs compared to purchasing power from the grid, as P2P energy sharing prices currently fall between the FiTs and retail prices of grid electricity [25,26].

Therefore, given the current widespread acceptance and popularity of batteries and P2P energy sharing in residential PV systems, this paper designs four mathematical energy trading models associated with PV, including P2G, P2G with batteries, P2P, and P2P with batteries, details of which will be explained in Section 4.1. This is done to investigate the technical and economic performances of prosumers and consumers under these models. Compared to the existing literature, the novelty of this work is its thorough examination of the technical and economic performance of prosumers and consumers across various energy trading models. Unlike prior works that typically focus on the annual energy performance of residents, the technical analysis of this work will examine the grid and PV energy utilisation of prosumers and consumers on an annual, monthly, and daily basis. Furthermore, this work addresses a literature gap by analysing the net present value (NPV) and payback periods of PV batteries, a topic often overlooked in existing literature. The inclusion of a sensitivity analysis exploring the impact of various influencing factors, such as PV cost, battery cost, annual discount rate, and P2P energy price, on the economic performance of PV-batteries across different energy models further strengthens the originality and practical relevance of this work.

The rest of the paper is organised as follows. Section 2 reviews the existing literature on the application of batteries and P2P energy in residential PV systems, and the research gap and aims are also highlighted in this section. Section 3 outlines four energy trading models for residential PV systems and their operating principles. The methods used for analysing the technical and economic performance of the four energy trading models are explained in Section 4, and this section also explains the data collection process. The technical and economic performance of the four energy trading models is presented in Section 5. Section 6 presents the discussion, and Section 7 draws the conclusions for this work.

2. Literature review

This section reviews the existing literature on the application of batteries and P2P energy sharing in grid-connected residential solar PV systems. The research gaps and aims are presented at the end of this section.

The implementation of batteries in residential solar PV systems has become a widely researched topic in the literature and many scholars have investigated the technical and economic performance of PV-batteries. For instance, Abou El-Ela et al. [27] proposed an equilibrium optimisation algorithm to achieve the optimal integration of PV systems with batteries in distribution networks. The model incorporates considerations of energy costs and the investments and operation costs of PV and batteries. Han et al. [13] evaluated the economic and technical effectiveness of PV-batteries for different residential groups. The authors discovered that due to the combined impact of policy changes and economic conditions, the payback period for PV-batteries fluctuates significantly, and the economic feasibility of investing in PV-batteries is higher for residential customer groups with higher annual irradiation

and electricity demand. However, several economic factors, such as FiTs and their annual change rates, were not considered in the economic analysis of this study.

Schleifer et al. [28] investigated the relationship between the evolution of the bulk power system and the energy and capacity value of PV-batteries over time. Wu et al. [18] proposed a mixed-integer nonlinear programming model to minimise the lifecycle cost of PV-batteries, and the impact of battery degradation and tariffs on PV self-consumption and optimal battery capacities was evaluated. The authors determined that the overall lifecycle cost and optimal battery capacity are significantly affected by the FiTs and PV degradation; however, the annual change rates of the retail price of grid electricity and FiTs were not identified in the analyses of the study. Cho and Valenzuela [19] determined the capacity of residential off-grid PV-batteries taking into account the solar radiation uncertainty and hourly energy consumption patterns, and using the minimum investment cost and fuel cost as criteria; nevertheless, the study overlooked the annual operational and maintenance costs of batteries, which might substantially influence the economic outcomes of the research. Sadeghibakhtiar et al. [29] developed a hybrid system of PV, wind, and batteries that was used to supply electricity to a residential building, and the authors calculated the optimal size of the hybrid system by focusing on PV panel sizes, battery capacity, etc. The above-reviewed studies have successfully demonstrated the applicability of batteries in increasing PV energy consumption in buildings; however, their economic analyses of PV-batteries did not consider some of the necessary economic factors, rendering their findings less comprehensive.

Research on P2P energy sharing is also very important. Chen et al. [30] developed a P2P energy sharing model for minimising the power losses of prosumers and increasing local energy sharing among prosumers and consumers. While the study explored the impact of P2P energy sharing on the energy efficiency of PV communities, it did not examine its economic viability. Du vignau et al. [31] proposed a cost-optimisation model for P2P energy sharing in PV communities, aiming to explore how the scale of P2P communities influences the cost performance of sharing energy between prosumers and consumers; nevertheless, the impact of P2P energy sharing on the payback period of PV systems was missing in the work. Combining batteries with P2P energy sharing for PV communities has also become a promising research topic. Zhao et al. [32] introduced an energy-management strategy that incorporates demand-side management into P2P energy sharing. The primary goal was to ensure reduced PV energy expenses for all participants in energy sharing by implementing uniform pricing and energy allocation mechanisms based on the supply–demand ratio. Nevertheless, this study failed to investigate the intrinsic correlation between batteries and P2P energy sharing in terms of their impact on the energy performance of prosumers and consumers, and the payback period of using PV-batteries in the P2P model was not explored as well.

A P2P energy sharing strategy for power management of a battery-equipped PV community was proposed to minimise grid electricity consumption and increase the lifespan of batteries [33]. The authors assessed the energy performance of PV communities under three models: P2G; P2P; and P2P with batteries. However, they did not consider the P2G model with batteries, which may have limited the opportunity to determine the energy impact of choosing to share energy or not when using batteries of the same capacity. Pricing mechanisms have been another important topic in the P2P energy sharing PV community. For instance, Wang et al. [34] formulated a supply function bidding mechanism to determine the optimal strategies for sharing energy between prosumers and consumers, such as optimal social welfare and fair benefit distribution to participants. This study primarily focused on cost analysis of energy sharing; however, it overlooked certain findings related to the energy aspect, such as PV self-consumption.

An extensive analysis of current research has revealed a lack of studies examining the combined technical and economic performance of integrating both batteries and P2P energy sharing with residential solar

PV systems. Furthermore, the existing literature lacks clarity on the advantages of utilising batteries and P2P energy sharing as opposed to the P2G energy trading model. Moreover, the correlation between the utilisation of batteries and P2P energy sharing in residential PV systems remains ambiguous. Finally, some economic factors, such as FiTs, their annual changing rates, and the annual operational and maintenance costs of batteries, were not considered in the economic analyses of the reviewed studies, potentially making their results less reflective of real-world conditions. Therefore, this paper will analyse the technical and economic performance of prosumers and consumers under the four mathematical energy trading models. It will focus on the grid and PV energy utilisation on a daily, monthly and annual basis, as well as the cumulative net present value and the payback period for using PV-batteries under different energy models.

3. Descriptions of four mathematical energy trading models

Fig. 1 illustrates the four mathematical energy trading models of grid-connected PV systems, including P2G, P2G with batteries, P2P and P2P with batteries. The main difference among these four models is whether or not the prosumer possesses batteries and whether or not the prosumer is willing to lead and participate in P2P energy sharing with neighbouring consumers. These four energy models follow the sequence of energy flows, and Sections 4 to 6 will present the methods of applying these models to a case study house with actual measurements of electrical data and the results for their energy generation, use, and sharing. The specific operating strategies of these four energy models are described below.

In the P2G energy trading model, the prosumer satisfies its energy demand through PV and grid energy, as illustrated in Fig. 1(a), while consumers can only purchase energy from the electricity grid for their consumption. Specifically, when the prosumer's PV generation exceeds its electrical load, the surplus PV energy is sold to the electricity grid at a predetermined price set in the FiT schemes. If the prosumer's PV generation is lower than its electrical load, the shortfall of electricity will be purchased from the electricity grid at retail prices. In contrast, consumers lacking PV systems and P2P energy sharing satisfy their electrical demand through the direct purchase of electricity from the grid at retail prices. In the model of P2G with batteries, as shown in Fig. 1(b), the prosumer will store the surplus PV energy in batteries for consumption during periods of high electrical demand or when PV generation is insufficient. Also, any surplus PV energy that remains after the batteries are fully charged is sold to the grid at the FiTs. Similar to the P2G model, consumers under the model of P2G with batteries are restricted from purchasing electricity from the grid to satisfy their demand, owing to the absence of PV systems and P2P energy sharing.

The P2P energy sharing model, presented in Fig. 1(c), is developed to enhance the utilisation of the prosumer's PV energy. Compared to the P2G model described in Fig. 1(a), the principle of the P2P model is that any surplus PV energy that exceeds the prosumer's electrical need is first shared with nearby consumers at an agreed-upon price. Any remaining surplus PV energy is subsequently exported to the electricity grid. If the prosumer's surplus PV energy is insufficient to meet the electrical demands of consumers, the shortfall will be compensated for by importing electricity from the grid. When both batteries and P2P energy sharing are considered (see Fig. 1(d)), the prosumer's PV energy is initially utilised to meet its electricity needs, subsequently utilised to charge batteries, then sold to neighbouring consumers, and ultimately exported to the grid. The energy stored in batteries is exclusively utilised by the prosumer in situations where the PV generation is inadequate. If there is a shortfall in the supply of PV energy to the prosumer and consumers, it will be covered by purchasing electricity from the grid.

4. Method

Four different mathematical energy trading models for grid-

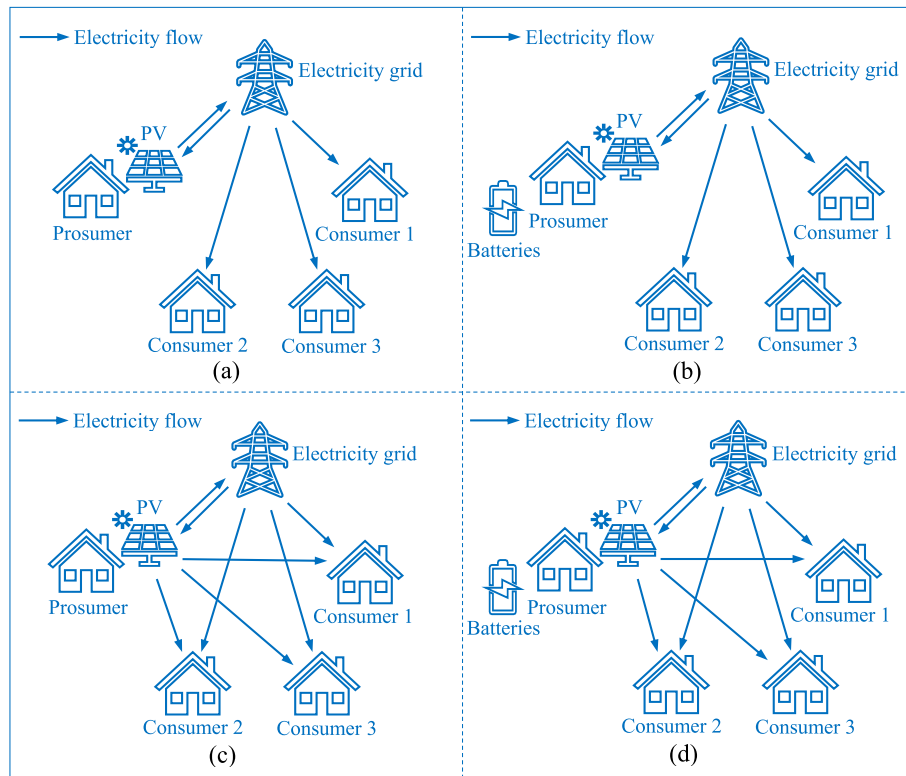


Fig. 1. Simplified diagrams of four mathematical energy trading models for grid-connected residential PV: (a) P2G; (b) P2G with batteries; (c) P2P; (d) P2P with batteries.

connected residential PV considering batteries and P2P energy sharing have been explained in Section 3. This section first outlines the mathematical algorithms used to analyse the technical aspects of the four energy models. It then discusses the methodologies employed to assess the economic performance of the four energy trading models, i.e., the prosumer and consumers' net present value (NPV) over specific years after engaging with batteries and P2P energy sharing.

4.1. Technical analysis of four mathematical energy trading models

The quantitative equilibrium of energy supply and demand between the prosumer and consumers is shown in the following equation.

$$\sum_{t=1}^g E_{PV} + \sum_{t=1}^g E_{PI} + \sum_{i=1}^n \left(\sum_{t=1}^g E_{CI}^i \right) + \sum_{t=1}^g E_{B-} = \sum_{t=1}^g E_{PL} + \sum_{i=1}^n \left(\sum_{t=1}^g E_{CL}^i \right) + \sum_{t=1}^g E_{B+} + \sum_{t=1}^g E_{LI} + \sum_{t=1}^g E_{LB} + \sum_{t=1}^g E_{PX} \quad (1)$$

Where:

g is a given period, such as an hour, a day, a month, or a year, and t is the time interval. E_{PV} is the PV generation of the prosumer and E_{PI} is the imported energy of the prosumer. E_{CI}^i is the imported energy of the i^{th} consumer and n is the total number of consumers. E_{B+} and E_{B-} are the energy for or from charging or discharging batteries. E_{PL} and E_{CL}^i are the electrical loads of the prosumer and the i^{th} consumer. E_{LI} is the energy loss of the inverter to convert direct current to alternating current. E_{LB} is the energy loss resulting from charging and discharging batteries. E_{PX} represents the exported energy of the prosumer.

For the prosumer only, the energy supply and demand satisfy the following equation:

$$\sum_{t=1}^g E_{PV} + \sum_{t=1}^g E_{PI} + \sum_{t=1}^g E_{B-} = \sum_{t=1}^g E_{PL} + \sum_{t=1}^g E_{B+} + \sum_{t=1}^g E_{LI} + \sum_{t=1}^g E_{LB} + \sum_{i=1}^n \left(\sum_{t=1}^g E_{P2P}^i \right) + \sum_{t=1}^g E_{PX} \quad (2)$$

Where:

E_{P2P}^i represents the amount of PV energy that the prosumer shares with the i^{th} consumer and it equals zero in the models of P2G and P2G with batteries. E_{B+} , E_{B-} , and E_{LB} will be equal to zero in the P2G and P2P models.

When batteries are employed by the prosumer, the state of charge of the batteries is described based on Equation (3):

$$SOC_t = \begin{cases} \text{Min} \left(SOC_{t-1} + \frac{\left(E_{PV} - \frac{E_{PL}}{\eta_C} \right) \times \eta_{B+}}{B}, SOC_{max} \right), \text{Chargebatteries} \\ \text{Max} \left(SOC_{min}, SOC_{t-1} - \frac{(E_{PL} - E_{PV} \times \eta_C) \times \eta_{B-}}{B} \right), \text{Dischargebatteries} \end{cases} \quad (3)$$

Where:

SOC_t is the state of charge of the batteries at the end of the time interval t . η_C is the converting efficiency of the inverter. η_{B+} and η_{B-} are the charging and discharging efficiencies of the batteries, respectively. SOC_{max} and SOC_{min} are the maximum and minimum states of charge of the batteries. B is the capacity of the batteries in kWh.

Similarly, E_{B-} is zero when batteries are not considered and E_{P2P} is zero when P2P energy sharing is not considered for the prosumer's PV. Furthermore, this paper focuses on the utilisation of lithium-ion batteries due to their recognised safety, extended lifespan, exceptional

thermal stability, and compatibility with residential buildings [35]. It is assumed that 5 kWh lithium-ion batteries are to be used in the analyses. The state of charge of lithium-ion batteries can vary from 0 % to 100 %, as per Zhang et al. [36]. However, in this study, the minimum state of charge is set at 20 % to safeguard the battery's lifespan and to account for the potential degradation of its performance during operation. The maximum state of charge is assumed to be 100 % to demonstrate the exceptional efficiency of lithium-ion batteries. Also, the maximum charging and discharging power of the batteries is assumed to be 5 kW. Also, the impact of battery capacity on PV and grid electricity consumption will be evaluated in Section 5.1 of this paper. The specifications regarding the inverter and batteries are described in Table 1.

For consumers, the energy supply and demand satisfy Equation (4):

$$\sum_{i=1}^n \left(\sum_{t=1}^g E_{P2P}^i \right) + \sum_{i=1}^n \left(\sum_{t=1}^g E_{CI}^i \right) = \sum_{i=1}^n \left(\sum_{t=1}^g E_{CL}^i \right) \quad (4)$$

PV self-consumption and self-sufficiency are two parameters used to determine the percentage of PV energy that is consumed locally [37] and the percentage of PV energy that is contributed to the total electrical demand [38]. These two parameters are utilised in this paper to evaluate the correlation between residential electricity demand and local PV generation and consumption. They can be calculated using Equations (5) and (6).

$$SC = \frac{\sum_{t=1}^g E_{PVP} + \sum_{t=1}^g E_{B+} + \sum_{t=1}^g \left(\sum_{i=1}^n E_{P2P} \right)}{\sum_{t=1}^g E_{PV}} \quad (5)$$

Where:

E_{PVP} is the amount of PV energy consumed by the prosumer's electrical load directly. E_{B+} is zero when batteries are not considered and E_{P2P} is zero when P2P is not considered for the prosumer's PV.

$$SS = \frac{\sum_{t=1}^g E_{PVP} + \sum_{t=1}^g E_{B-} + \sum_{t=1}^g \left(\sum_{i=1}^n E_{P2P} \right)}{\sum_{t=1}^g \left(\sum_{i=1}^n E_{CL}^i \right) + \sum_{t=1}^g E_{PL}} \quad (6)$$

4.2. Economic analysis of four mathematical energy trading models

In order to promote engagement in P2P energy sharing among prosumers and consumers, the cost of energy exchanged between peers should fall within the range specified by the retail price of grid electricity and FiTs. Therefore, the P2P energy pricing can be expressed as follows:

$$FiT \leq P_{P2P} \leq RT \quad (7)$$

Where:

P_{P2P} is the P2P energy sharing price, which is used to calculate the revenue received by prosumers and the cost borne by consumers as a result of P2P energy sharing. RT is the retail price of grid electricity.

NPV is an economic indicator that calculates the difference between the present values of cash inflows and outflows. The cash inflows of the prosumer could include the revenues received from selling excess PV

energy to the electricity grid and from the P2P energy sharing, while its cash outflows could include the cost associated with using solar PV and batteries and the cost of purchasing grid electricity. For consumers, cash outflows could include the cost of P2P energy sharing and purchasing grid electricity. The NPV of the prosumer and consumers under the four different energy trading models can be calculated using the following equations.

$$C_{PV}^m = C_{PV}^{ipc} + \sum_{t=1}^m \frac{C_{PV}^{ipc} \times r_{o\&m}}{(1+d)^t} - \frac{C_{PV}^{ipc} \times (1-r_{dep})^m}{(1+d)^m} \quad (8)$$

$$C_B^m = C_B^{ipc} + \sum_{t=1}^m \frac{C_B^{ipc} \times r_{o\&m}}{(1+d)^t} - \frac{C_B^{ipc} \times (1-r_{dep})^m}{(1+d)^m} \quad (9)$$

$$C_{P_RT}^m = \sum_{t=1}^m \frac{RT \times (1+r_{RT})^t}{(1+d)^t} \times E_{PI} \quad (10)$$

$$C_{C_RT}^m = \sum_{t=1}^m \frac{RT \times (1+r_{RT})^t}{(1+d)^t} \times E_{CI} \quad (11)$$

$$R_{FIT}^m = \sum_{t=1}^m \frac{FiT \times (1-r_{FIT})^t}{(1+d)^t} \times E_{PX} \quad (12)$$

$$R_{P2P}^m = \sum_{i=1}^n \left(\sum_{t=1}^m E_{P2P}^i \times \frac{P2P \times (1+r_{P2P})^t}{(1+d)^t} \right) \quad (13)$$

$$NPV_{Pro}^m = R_{P2P}^m + R_{FIT}^m - C_{PV}^m - C_B^m - C_{P_RT}^m \quad (14)$$

$$NPV_{Cons}^m = 0 - \sum_{i=1}^n \left(C_{C_RT}^m \right) - R_{P2P}^m \quad (15)$$

Where:

C_{PV} and C_B are the total cost of solar PV and batteries, respectively. C_{PV}^{ipc} and C_B^{ipc} are the initial purchase cost of solar PV and batteries, respectively. $r_{o\&m}$ is the annual operational and maintenance rate of solar PV and batteries, r_{dep} is the annual depreciation rate of solar PV and batteries, and d is the annual discount rate. m is the number of years. C_{P_RT} and C_{C_RT} are the costs of purchasing grid electricity for the prosumer and consumers, respectively. R_{P2P} and R_{FIT} are the revenues received by the prosumer from P2P energy sharing and selling PV energy to the grid, respectively. r_{FIT} is the annual decrease rate of the FiT and r_{P2P} is the annual increase rate of the P2P energy sharing price. r_{RT} is the annual increase rate of the retail price of grid electricity. i is the consumer number.

The payback period indicates the duration required to recover the investment cost of the equipment. For the prosumer under different energy trading models, the payback period (N) of using solar PV and batteries can be calculated as follows:

$$R_{FIT}^{N-1} + R_{P2P}^{N-1} - C_{P_RT}^{N-1} \leq C_{PV}^N + C_B^N < R_{FIT}^N + R_{P2P}^N - C_{P_RT}^N \quad (16)$$

The values of the various parameters used in the economic analysis are summarised in Table 2. To effectively motivate both prosumers and consumers to engage in the P2P energy sharing scheme, the pricing mechanism must be structured to provide clear economic advantages over traditional energy transactions. A commonly accepted and rational strategy is to establish the P2P energy sharing price between the FiT, i.e., the compensation rate for prosumers exporting excess PV energy to the grid, and the retail price of grid electricity, which consumers incur when purchasing energy from the energy providers. This price range guarantees reciprocal advantage: prosumers receive more earnings than through PV energy exports, while consumers incur lower costs than conventional grid electricity purchases.

Table 1

Technical parameters of the inverter and lithium-ion batteries used in this paper.

Parameter	Symbol	Value
Converting efficiency of the inverter	η_C	85 %
Maximum state of charge of batteries	SOC_{max}	100 %
Minimum state of charge of batteries	SOC_{min}	20 %
Charging or discharging efficiency of batteries	η_{B+}/η_{B-}	90 %
Maximum charging power		5 kW
Maximum discharging power		5 kW

Table 2
Values of various parameters used in the economic analyses in this work.

Parameter	Value
Initial purchase cost of solar PV	AUD 800/kW
Initial purchase cost of batteries	AUD 450/kWh
Annual operational and maintenance cost of solar PV and batteries	2 % of the initial purchase cost
Lifespan of solar PV and batteries	20 years
Annual depreciation value of solar PV and batteries	2 % of the initial purchase cost
Increase rate of retail price of grid electricity	3 % per annum
Decrease rate of FiT	3 % per annum
Starting P2P energy sharing price	Between the starting FiT and the starting retail price of grid electricity
Increase rate of P2P energy sharing price	4 % per annum
Annual discount rate	3 %

4.3. PV generation and electrical load profiles

This study focuses on a typical house located in Geelong, Australia, which is considered the prosumer. The house is outfitted with a 10 kW solar PV system that is connected to the electricity grid. The amount of power generated by the PV system and the electrical load of the house were monitored throughout the year 2021. The hourly generation of the 10 kW PV system is simulated and verified using actual measurements. It can be found from Fig. 2(a) that the total electrical load of the house in 2021 is 4393 kWh and the total energy generated by the simulated 10 kW solar PV system in that year is 14,985 kWh, of which only 2192 kWh of PV energy is supplied to the electrical demand of the house, while the rest is exported to the grid. It is worth noting that PV generation is comparatively lower during the middle of the year than at other times. This discrepancy could potentially be attributed to the winter season spanning June to August, which is characterised by reduced solar altitudes and shorter daylight hours, both of which have a negative impact on PV generation. Furthermore, the 2025 grid retail price and FiT for Geelong, where the residence is situated, are AUD 0.277/kWh and AUD 0.049/kWh, respectively. These two values will serve as the starting retail price of grid energy and the starting FiT for conducting NPV and payback period analyses in this study.

This study assumes the participation of three customers in the P2P energy sharing scheme, determined by the housing ratio of the community to which the case study house prosumer belongs. Their electricity load profiles are constructed similarly, utilising the electrical load of the prosumer as a benchmark. This approach is reliable for estimating the electricity demand of consumers in the absence of direct load data, as it is able to maintain consistency and realism in the consumption behaviour modelled by generating load analogously from the prosumer’s existing load data. Specifically, this method incorporates controlled variability e.g., 80 %, 100 %, 120 % of the prosumer’s electrical load through proportional scaling to reflect differences in usage

without introducing arbitrary or unrelated data, which guarantees that the P2P energy sharing is based on plausible behavioural patterns and accommodate the diversity of participants. The average daily electrical loads of the three consumers and the prosumer are displayed in Fig. 2(a). It can be calculated that the three consumers have annual electrical loads of 3273 kWh, 3269 kWh, and 3334 kWh. Furthermore, the hourly power summary for the prosumer and the three consumers during the first week of winter is depicted in Fig. 2(b). It is evident that in most cases, the PV generation surpasses the electrical demand during the day. However, when the PV generation ceases at night, both the prosumer and consumers still have substantial electrical demands and require an energy supply.

5. Results

5.1. Technical performance of four mathematical energy trading models

To elucidate the effects of batteries and P2P energy sharing on the energy usage of the prosumer and three consumers, we conducted annual simulations of the four energy models and compiled the corresponding annual energy results in Fig. 3. As can be seen from the figure, in the P2G model, all 9876 kWh of the electrical demand of the three consumers needs to be supplied by the grid. Also, the prosumer is required to import 2201 kWh of grid electricity annually, with PV power fulfilling the remaining electrical load of 2192 kWh. A substantial quantity of PV energy, specifically 12,793 kWh, is exported to the grid, resulting in annual PV self-consumption and self-sufficiency rates of only 14.6 % and 15.4 %, respectively. In the P2G model with batteries, the prosumer experiences a decrease in annual energy imports and exports,

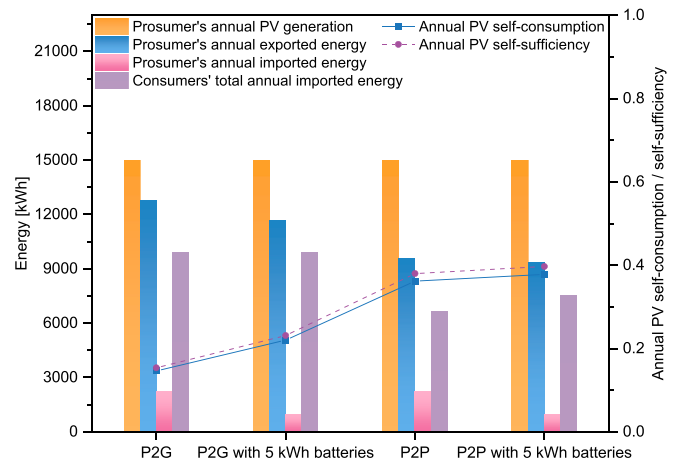


Fig. 3. Annual energy summary of four energy models.

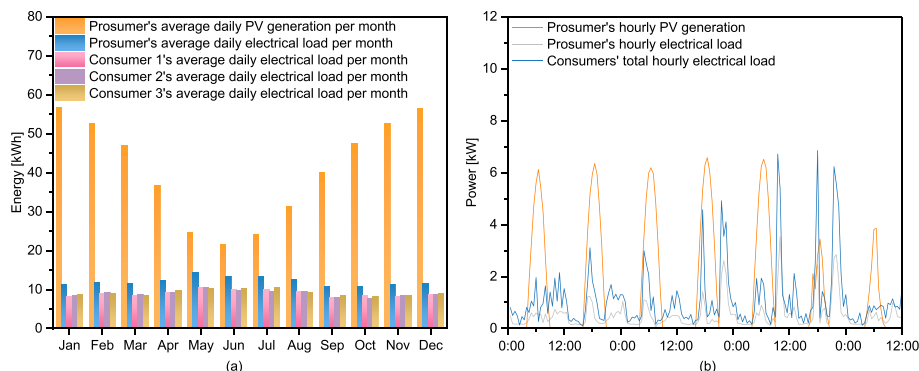


Fig. 2. (a) Monthly energy summary of prosumer and three consumers; and (b) hourly energy summary of prosumer and three consumers during first week of winter.

while the annual PV self-consumption and self-sufficiency rates climb to 22.0 % and 23.1 %, respectively. This is because the 5 kWh batteries store a portion of the surplus PV energy for subsequent consumption, which reduces the grid electricity demand.

Due to the absence of energy sharing in this model, the overall electricity demand of the three customers on the grid remains unchanged. When it comes to the P2P model, the sharing of PV energy among peers decreases the annual grid energy imports to 6647 kWh for the three consumers. Additionally, it greatly reduces the prosumer's annual energy export to 9564 kWh. As a result, there is a substantial increase in PV self-consumption to 36.2 % and in self-sufficiency to 38.0 %. When 5 kWh batteries are further incorporated into the P2P model, the prosumer's annual energy import remains 975 kWh, equivalent to the value in the P2G model with batteries. However, the three consumers' annual energy import increases to 7510 kWh, surpassing the result in the P2P model. This is due to the operating principles of the P2P model with batteries. Specifically, as stated in Section 3, the surplus PV energy generated by the prosumer is prioritised for battery charging, followed by sharing with the consumers, and any residual excess PV power is then exported to the grid. When comparing the P2P model with batteries to the P2P model, the amount of PV energy shared by the prosumer to the consumers is consequently reduced. Therefore, it can be argued that both batteries and P2P energy sharing have impacts on the annual PV and grid electricity usage of the prosumer and consumers to a certain degree.

To further investigate the disparities in PV and grid energy consumption between the prosumer and consumers in accordance with the four energy models, monthly energy consumption data for each model was collected and is presented in Figs. 4 and 5, respectively. It is evident from Fig. 4(b) that the amount of grid energy imported by the prosumer is greater during the winter seasons. This disparity can be attributed to two factors: First, the prosumer has greater electrical loads during the winter, as indicated in Fig. 4(b); and second, the length of daylight and solar intensity during the other seasons surpass those of the winter season, resulting in significant seasonal variations in PV generation, as shown in Fig. 4(a). According to the data presented in Fig. 4(b), incorporating 5 kWh batteries into the P2G or P2P model significantly reduces the imported energy of the prosumer from October to February and also results in a substantial decrease in its reliance on the electricity grid during the winter months. It is also discovered that the monthly imported energy curves of the prosumer under the P2G and P2P models overlap. This is because the P2P energy sharing only occurs when there is surplus PV energy after meeting the electrical load of the prosumer and after batteries are charged, which does not affect the amount of grid energy that the prosumer purchases from the grid when compared to the P2G model with batteries.

Nevertheless, it can be seen from Fig. 4(a) that the amount of exported energy for the prosumer is reduced in the P2P model from the value in the P2G model as the excess PV energy is shared between the prosumer and consumers. The reduction is more pronounced during the

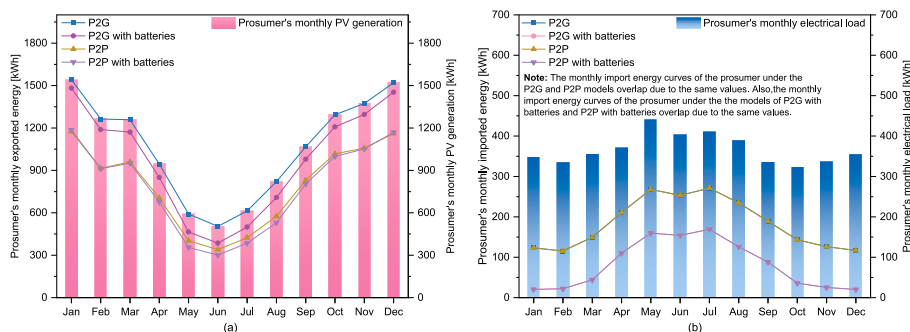


Fig. 4. Monthly energy summary of prosumer under four energy models: (a) Prosumer's monthly exported energy under four energy models and its monthly PV generation, and (b) prosumer's monthly imported energy under four energy models and its monthly electrical load.

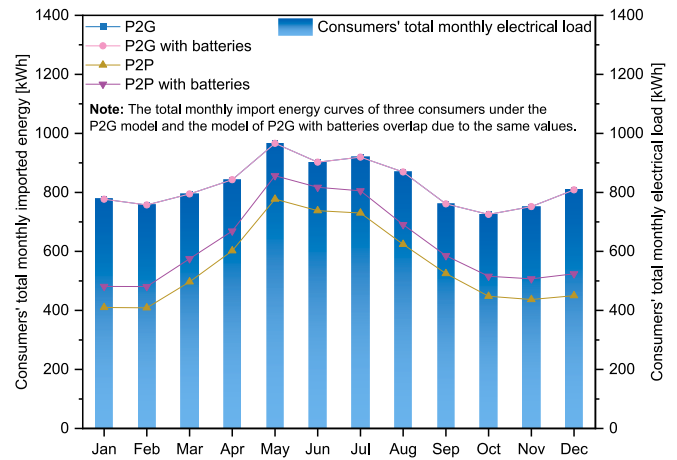


Fig. 5. Monthly energy summary of three consumers under four energy models.

summer compared to other seasons and this decrease in exported energy remains in the P2P model with 5 kWh batteries. Therefore, it can be inferred that the utilisation of batteries and P2P energy sharing can effectively enhance the PV energy consumption of the prosumer, thereby alleviating the burden on the electricity grid caused by PV energy exports; nevertheless, the effectiveness of these measures is influenced by the prosumer's electrical load and PV generation profiles.

The effect of batteries and P2P energy sharing on the grid energy usage of the consumers is evident in Fig. 5, which displays the consumers' monthly electrical loads and imported energy consumption. It can be observed from Fig. 5 that when neither batteries nor P2P energy sharing is considered in the model, the electrical loads of the three consumers need to be met entirely through grid energy imports. In comparison, when P2P energy sharing is activated, a portion of the electricity needed by the three consumers is offset by the shared PV energy from the prosumer, which mirrors the decrease in exported energy by the prosumer as indicated in Fig. 4(a). However, it is important to realise that P2P energy sharing can only partially address the consumers' energy consumption, even if the prosumer's PV system has a capacity as high as 10 kWh and its daily power generation remains significant. This is because PV generation only occurs during daylight hours. As depicted in Fig. 2(b), when PV generation approaches zero after sunset, the consumers continue to have substantial energy demands; in such cases, grid electricity becomes essential. When the prosumer utilises 5 kWh batteries in conjunction with P2P energy sharing, the amount of grid energy supplied to the consumers increases compared to when only P2P energy sharing is enabled, as depicted in Fig. 5. This is because charging of batteries takes precedence over P2P energy sharing and battery energy storage is only distributed to the prosumer, not the consumers. Thus, it can be concluded that P2P energy

sharing decreases the amount of grid electricity consumed by the consumers, while charging batteries for the prosumer undermines the benefits that P2P energy sharing brings to the consumers.

To gain a clear picture of how PV and grid energy are consumed by the prosumer and consumers, we collected the energy generation, storage, and consumption data of the prosumer and consumers under the four energy models on the two days with the highest and lowest PV power in the year and plotted the results in Figs. 6 and 7, respectively. Upon comparing Fig. 6(a) and (b), it becomes evident that 5 kWh batteries adequately fulfil the energy requirements of the prosumer after daylight hours. The prosumer experiences a decline in energy exports from 7:00 to 9:00 as a result of battery charging. As illustrated in Fig. 6(c), in the case of energy sharing between peers, the PV energy supplied by the prosumer completely fulfils the consumers' electricity requirements from 8:00 to 18:00, resulting in a decrease in energy export from the prosumer to the grid. Integrating batteries into the P2P model, as can be seen in Fig. 6(d), eliminates all grid energy consumption by the prosumer while maintaining daytime energy sharing with the consumers. Therefore, it can be concluded that the integration of batteries and P2P energy sharing can significantly reduce the grid energy consumption of both the prosumer and consumers, particularly when there is sufficient PV energy available throughout the day.

Situations vary when PV generation is at its minimum on certain days throughout the year. As illustrated in Fig. 7(a) and (b), the inability to efficiently charge batteries in the P2G model during the day is attributable to the negligible PV generation. The prosumer and consumers alike need substantial quantities of grid energy to meet their energy demands. Similarly, the limited PV generation prevents P2P energy sharing from providing significant benefits to the consumers in terms of diminishing their grid energy needs (see Fig. 7(c)). The outcomes depicted in Fig. 7(d) are identical to those shown in Fig. 7(b), given that PV generation is negligible and batteries are charged only using the prosumer's PV generation and before P2P energy sharing with the consumers. In summary, it is clear that the quantity of PV energy produced significantly influences the benefits that P2P energy sharing and

batteries can offer to both the prosumer and consumers.

It has been discovered above that batteries exhibit a vital impact on both the PV and grid energy consumption of users. The capacity of the batteries utilised in prior analyses was kept at 5 kWh. In order to ascertain the influence of battery capacity variation on the energy consumption of both the prosumer and consumers, we conducted simulations while proportionally varying the battery capacities in the P2G and P2P models, and the results are summarised in Tables 3 and 4, respectively. The prosumer's annual imported and exported energy decreases progressively as battery capacity increases, as shown in Table 3. This is because as battery capacity increases, more PV energy is stored to satisfy the electrical demand of the prosumer, thereby enhancing their annual PV self-consumption and self-sufficiency. Additionally, it is observed that when the battery capacity surpasses 12.5 kWh, the rate of decline in the prosumer's annual energy imports reduces, resulting in a gradual redundancy of battery capacity. This results from the high electrical demand on the prosumer during the extended winter nights, as illustrated in Fig. 2(b), and the diminished efficiency of PV power generation in winter due to the lower solar altitude. As a result, the constant increase of battery capacity cannot ensure an ongoing state of charge, indicating the battery's capability to satisfy the producer's power demands, particularly at night, diminishes. Furthermore, the increase in battery capacity does not have any influence on the consumers' utilisation of grid energy because, under the model of P2G with batteries, the consumers' electrical energy requirements are solely fulfilled by the grid. Overall, these results indicate that increasing the battery capacity will yield a favourable effect on the rise in PV energy consumption and the decline in grid electricity demand for the prosumer. Nevertheless, the determination of battery size needs to be relative to specific electricity demand and PV generation profiles to prevent excess capacity.

Table 4 demonstrates a clear relationship between battery capacity and the annual energy summary of the prosumer and consumers under the P2P model with batteries. Specifically, as battery capacity grows, the prosumer sees a decrease in energy imports, while the consumers see

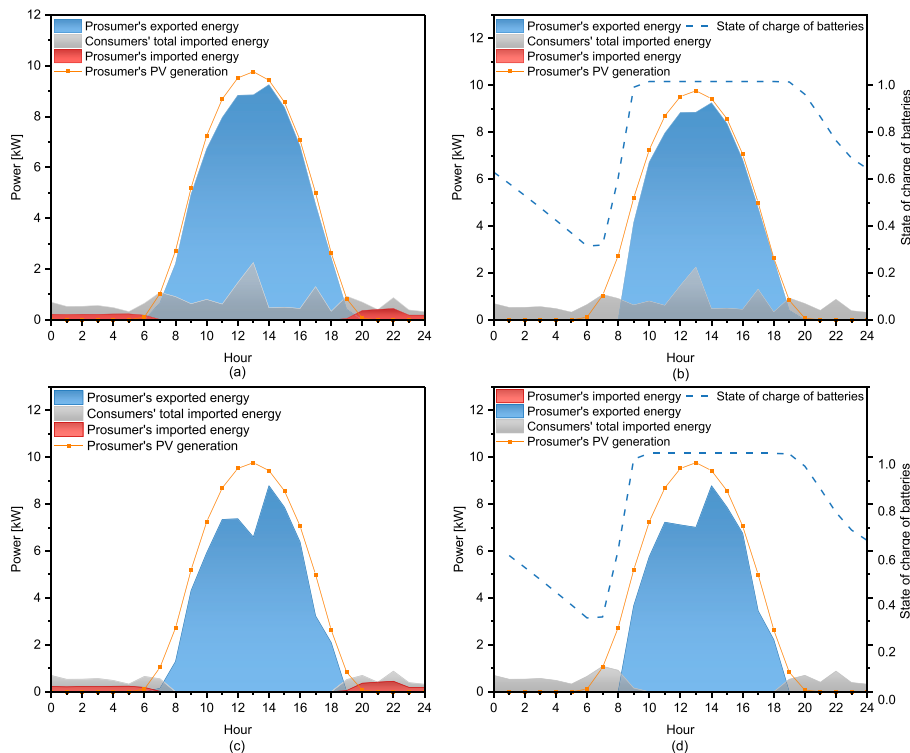


Fig. 6. Hourly power summary of prosumer and three consumers on day with highest PV generation and under four energy models: (a) P2G; (b) P2G with 5 kWh batteries; (c) P2P; (d) P2P with 5 kWh batteries.

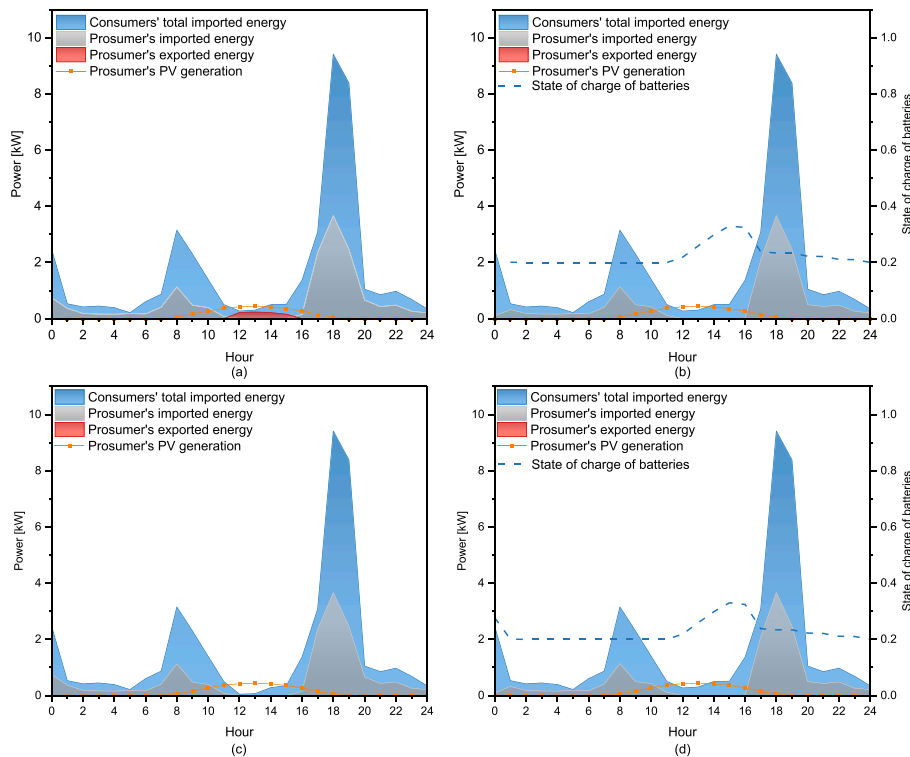


Fig. 7. Hourly power summary of prosumer and three consumers on day with lowest PV generation and under four energy models: (a) P2G; (b) P2G with 5 kWh batteries; (c) P2P; (d) P2P with 5 kWh batteries.

Table 3

Annual energy summary of the prosumer and three consumers as a function of battery capacity under the model of P2G with batteries.

Battery capacity (kWh)	Prosumer's annual PV generation (kWh)	Prosumer's annual imported energy (kWh)	Prosumer's annual exported energy (kWh)	Consumers' annual imported energy (kWh)	Annual PV self-consumption	Annual PV self-sufficiency
0	14985	2201	12793	9876	14.6 %	15.4 %
2.5	14985	1567	12465	9876	16.8 %	17.7 %
5	14985	975	11688	9876	22.0 %	23.1 %
7.5	14985	569	11155	9876	25.6 %	26.8 %
10	14985	350	10866	9876	27.5 %	28.9 %
12.5	14985	225	10700	9876	28.6 %	30.0 %
15	14985	142	10588	9876	29.3 %	30.8 %
17.5	14985	95	10524	9876	29.8 %	31.3 %
20	14985	68	10486	9876	30.0 %	31.5 %

Table 4

Annual energy summary of the prosumer and three consumers as a function of battery capacity under the model of P2P with batteries.

Battery capacity (kWh)	Prosumer's annual PV generation (kWh)	Prosumer's annual imported energy (kWh)	Prosumer's annual exported energy (kWh)	Consumers' annual imported energy (kWh)	Annual PV self-consumption	Annual PV self-sufficiency
0	14985	2201	9564	6647	36.2 %	38.0 %
2.5	14985	1567	9796	7207	34.6 %	36.4 %
5	14985	975	9321	7510	37.8 %	39.7 %
7.5	14985	569	8937	7659	40.4 %	42.4 %
10	14985	350	8729	7739	41.7 %	43.8 %
12.5	14985	225	8606	7783	42.6 %	44.7 %
15	14985	142	8526	7814	43.1 %	45.3 %
17.5	14985	95	8475	7828	43.4 %	45.6 %
20	14985	68	8448	7837	43.6 %	45.8 %

increases in energy imports. This can be attributed to the fact that the distribution of surplus PV energy to the consumers only takes place once the prosumer's batteries have been fully charged. Consequently, a rise in battery capacity leads to a decrease in the quantity of surplus PV energy that is distributed to the consumers. Additionally, it can be observed that the annual self-consumption and self-sufficiency with a battery capacity of 2.5 kWh are lower than the values without the battery, which

indicates that the use of a 2.5 kWh battery paired with P2P energy sharing diminishes the benefits of grid energy consumption to the prosumer and consumers when only P2P energy sharing is used. The limited capacity of the 2.5 kWh battery requires frequent recharging throughout the day, thereby losing the ideal opportunities for the prosumer to distribute surplus PV energy to consumers at peak demand, leading to increased energy exports from the prosumer. The results are further

supported by the increase in the prosumer’s annual exported energy and consumers’ annual imported energy when battery capacity increases from 0 kWh to 2.5 kWh, as illustrated in Table 4.

Furthermore, similar to the findings presented in Table 3, the growth rates in annual PV self-consumption and self-sufficiency decelerate after the battery capacity reaches 12.5 kWh. To summarise, these findings indicate that both batteries and P2P energy sharing can benefit users by increasing the utilisation of PV energy and reducing reliance on the grid. However, when determining the optimal mode of operation for residential PV systems, it is crucial to consider potential conflicts between batteries and P2P energy sharing that may arise due to energy utilisation prioritisation.

5.2. Economic performance of four mathematical energy trading models

In order to assess the economic performance of both the prosumer and consumers in the four energy models, we calculated the NPV for the prosumer and consumers in the P2G and P2P models with different battery capacities over a 20-year period. The results of these calculations are shown in Figs. 8 and 9, respectively. It is evident from Fig. 8(a) that the prosumer is unable to generate any profit, irrespective of the battery size. The high initial purchase cost and the operational and maintenance costs of the solar PV and batteries are the primary reasons for this. The minor revenue generated by the sale of excess PV energy to the grid, which results from the continuous decrease in the FiT, is insufficient to offset these costs. Nevertheless, upon further examination of the results in Fig. 8(a), the prosumer can, in comparison, incur the least annual expenditure with 10 kWh batteries. This leads to a cumulative NPV of AUD -3364 over a 20-year period, and the cumulative NPVs for the prosumer remain negative and decline gradually when the battery capacity exceeds 10 kWh. The consumers’ annual energy expenses appear unaffected by the increase in the battery capacity of the prosumer, as the consumers exclusively purchase electricity from the grid under the P2G model, and the cumulative electricity expenditure for the three consumers amounts to AUD 54,714 over a 20-year period (see Fig. 8(b)). Consequently, batteries have the potential to reduce grid energy consumption for the prosumer in the P2G model. Nevertheless, it is imperative to evaluate current and prospective economic conditions and determine the optimal battery capacity to prevent excessive

expenditures associated with battery use.

Fig. 9 shows the cumulative NPVs of the prosumer and consumers in the P2P model with different battery capacities and at a starting energy sharing price of AUD 0.20/kWh. The cumulative NPV of the prosumer remains positive in 20 years for all the battery capacities, as shown in Fig. 9(a), and the highest cumulative NPV of the prosumer reaches AUD 4929 at the battery capacity of 10 kWh. This is a significant improvement over the findings for the P2G model with batteries, in which the prosumer exhibits a negative cumulative NPV at the end of 20 years for all the battery capacities. This is primarily because the starting P2P energy sharing price of AUD 0.20 with an annual increase rate of 4 % is significantly greater than the FiT of AUD 0.049 with an annual decrease rate of 3 %; the prosumer can earn more benefits from sharing excess PV energy with consumers than from selling it to the electricity grid. Additionally, the cumulative NPV for the prosumer decreases as the battery capacity exceeds 10 kWh. This is because an increase in battery capacity results in a decrease in the quantity of energy shared with the consumers and an increase in the battery operation and maintenance cost, which in turn reduces the overall benefits. Furthermore, as illustrated in Fig. 9(b), the cumulative energy cost to consumers barely fluctuate as the battery capacity increases. The proximity of P2P energy sharing prices to retail price of the grid electricity results in minimal difference in consumers’ expenditure between purchasing electricity from the grid and from the prosumer. To summarise, P2P energy sharing can be advantageous for the prosumer and consumers if the energy sharing price is higher than the FiT but lower than the retail price of grid electricity; however, an increase in battery capacity can diminish the financial benefits for the prosumer and consumers.

To further explore the economic benefits of using batteries and participating in P2P energy sharing, we calculated the payback period for the prosumer using different sizes of batteries in P2P and P2G models, respectively, and summarised the results in Table 5. The table indicates that the payback period for the prosumer utilising PV-batteries within the P2G model exceeds 20 years, irrespective of battery capacity, and it exceeds the operational lifespan of both the solar PV systems and the batteries. This indicates that, under current economic conditions, characterised by an annual reduction in the FiT and an annual increase in the retail price of grid electricity, the substantial initial, operational, and maintenance expenses associated with PV and batteries cannot be

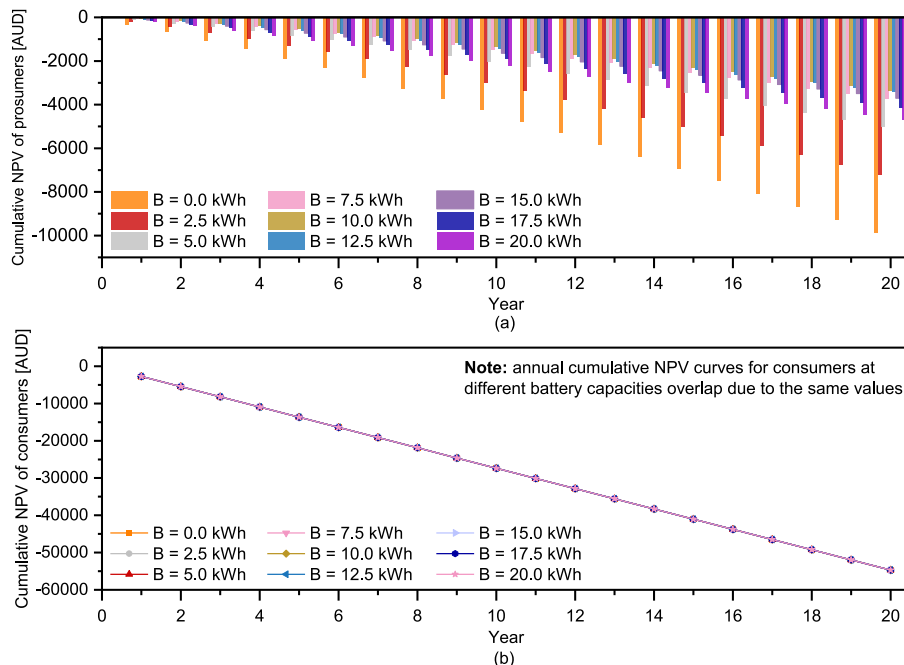


Fig. 8. Cumulative NPVs of (a) Prosumer; and (b) three consumers in P2G model at different battery capacities over a 20-year period.

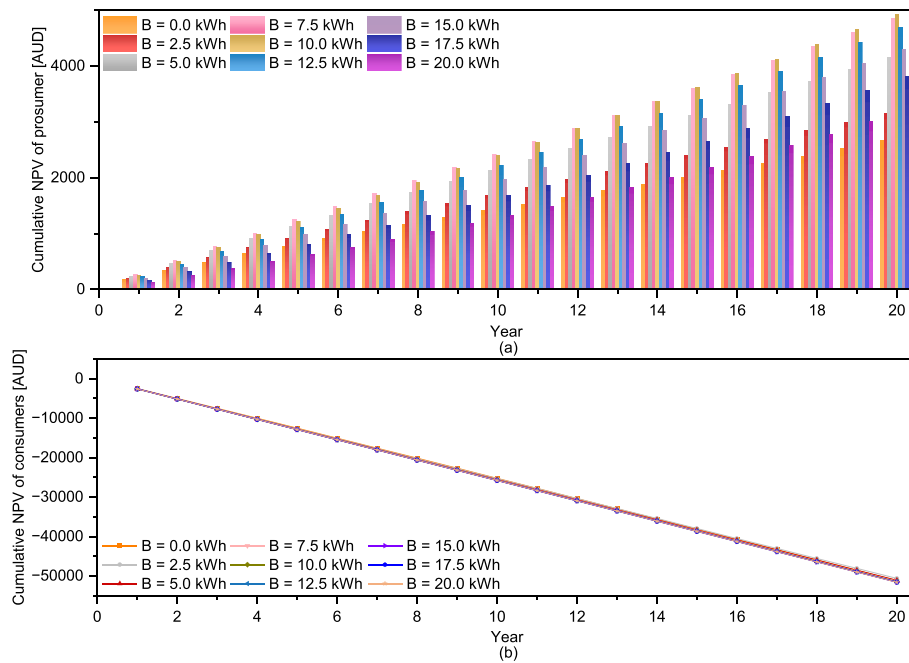


Fig. 9. Cumulative NPVs of (a) Prosumer; and (b) three consumers under P2P model with different battery capacity and at the starting P2P energy sharing price of AUD 0.20/kWh over a 20-year period.

Table 5

Payback periods of the 10 kW PV with different capacities of batteries under the P2G and P2P models and at the starting P2P energy sharing price of AUD 0.2/kWh.

Battery capacity (kWh)	Payback period (year) of PV-batteries under the P2G model	Payback period (year) of PV-batteries under the P2P model
0	>20	>20
2.5	>20	19
5	>20	13
7.5	>20	12
10	>20	15
12.5	>20	20
15	>20	>20
17.5	>20	>20
20	>20	>20

recovered only through the sale of PV energy to the grid. In comparison, engagement in P2P energy sharing enables the prosumer to generate additional revenue by selling excess PV energy to consumers, therefore decreasing the payback period for PV-batteries, and a minimum payback period of 12 years is achieved when the battery capacity is 7.5 kWh. Nevertheless, the payback period of PV-batteries is shorter than its lifespan only if the battery capacity is less than 12.5 kWh, as illustrated in the table. When the battery capacity is zero, the payback period of PV alone still exceeds its lifespan. This is due to various factors: Firstly, the high cost of PV systems is not offset by the benefits of PV energy exports and P2P energy sharing. Secondly, while battery utilisation diminishes the costs of grid energy imports, the escalating capacity of batteries leads to initial, operating, and maintenance costs that exceed the savings from reduced electricity purchases from the grid. Consequently, it can be stated that the prosumer can derive significant advantages from P2P energy sharing and the utilisation of batteries. However, the battery capacity must be fairly evaluated in order to maximise the benefits.

To assess the effect of various influencing factors on the economic performance of PV-batteries within the P2G and P2P models, we adjusted the values of many influencing factors. Subsequently, we computed the payback periods for the 10 kW PV system with varying battery capacities under the P2G and P2P models and compiled the findings in Tables 6 and 7. Table 6 illustrates that the expenses

Table 6

Payback period of the 10 kW PV system with different capacities of batteries at different values of influencing factors in P2G model.

No.	Influencing factors			Battery capacity (kWh)	Payback period (year) of PV-batteries
	Initial purchase cost of solar PV (AUD/kW)	Initial purchase cost of batteries (AUD/kW)	Annual discount rate		
1	800	-	3 %	0	>20
2	800	-	2.5 %	0	>20
3	700	-	3 %	0	>20
4	700	-	2.5 %	0	>20
5	600	-	3 %	0	>20
6	600	-	2.5 %	0	>20
7	800	450	3 %	5	>20
8	800	450	2.5 %	5	>20
9	700	450	3 %	5	>20
10	700	450	2.5 %	5	>20
11	600	450	3 %	5	>20
12	600	450	2.5 %	5	>20
13	800	400	3 %	5	>20
14	800	400	2.5 %	5	>20
15	700	400	3 %	5	>20
16	700	400	2.5 %	5	>20
17	600	400	3 %	5	>20
18	600	400	2.5 %	5	>20

associated with a 10 kW PV system, whether utilised independently or in conjunction with a 5 kWh battery, cannot be recovered over the equipment's lifespan of 20 years under various economic conditions. The primary cause of this situation is that the existing low FiT provides the prosumer with negligible income, which is the sole revenue producers obtain without participating in the P2P energy sharing scheme, and which evidently fails to compensate for the substantial expenses of operating equipment and purchasing electricity from the grid.

The situation changed significantly when P2P energy sharing was enabled for the prosumer. As illustrated in the first, third and fifth sets of results in Table 7, a decrease in the initial purchase cost of PV systems from AUD 800/kWh to AUD 750/kWh and a reduction in the annual discount rate from 3 % to 2.5 %, results in a payback period of 13 years and 12 years, respectively, for the 10 kW of PV system. Similar results

Table 7
Payback period of the 10 kW PV system with different capacities of batteries at different values of influencing factors in P2P model.

No.	Influencing factors				Battery capacity (kWh)	Payback period (year) of PV-batteries
	Initial purchase cost of solar PV (AUD/kW)	Initial purchase cost of batteries (AUD/kW)	Annual discount rate	Starting P2P energy sharing price (AUD/kWh)		
1	800	–	3 %	0.2	0	>20
2	800	–	3 %	0.15	0	>20
3	750	–	3 %	0.2	0	13
4	750	–	3 %	0.15	0	>20
5	800	–	2.5 %	0.2	0	12
6	800	–	2.5 %	0.15	0	>20
7	750	–	2.5 %	0.2	0	0
8	750	–	2.5 %	0.15	0	>20
9	800	450	3 %	0.2	7.5	12
10	800	450	3 %	0.15	7.5	>20
11	800	400	3 %	0.2	7.5	9
12	800	400	3 %	0.15	7.5	>20
13	750	450	3 %	0.2	7.5	8
14	750	450	3 %	0.15	7.5	>20
15	750	400	3 %	0.2	7.5	3
16	750	400	3 %	0.15	7.5	>20
17	800	450	2.5 %	0.2	7.5	4
18	800	450	2.5 %	0.15	7.5	>20
19	800	400	2.5 %	0.2	7.5	0
20	800	400	2.5 %	0.15	7.5	>20
21	750	450	2.5 %	0.2	7.5	0
22	750	450	2.5 %	0.15	7.5	18
23	750	400	2.5 %	0.2	7.5	0
24	750	400	2.5 %	0.15	7.5	13

are observed when batteries are employed. The payback period of PV-batteries can be considerably impacted by reducing the initial purchase of batteries, as evidenced by the ninth and the eleventh sets of results and the thirteenth and the fifteenth sets of results in Table 7. Additionally, Table 7 illustrates the great advantages that P2P energy sharing can provide to the prosumer. For instance, the cost of utilising 10 kW of PV and 7.5 kWh of batteries is essentially unrecoverable over their lifespan when the starting P2P energy sharing price is reduced from AUD 0.2/kWh to AUD 0.15/kWh. As the last four sets of results show, the cost associated with the 10 kW of PV and 7.5 kWh of batteries will not be effectively recovered unless both the initial purchase cost and the annual depreciation rate values of PV and batteries are reduced. Therefore, it can be inferred that the economics of using PV and batteries depend on numerous influencing factors, highlighting the need to assess the current economic situation before participating in P2P energy sharing scheme and using PV and batteries.

6. Discussion

This study has examined the technical and economic performance of the prosumer and consumers across four energy models. The results indicate that P2P energy sharing is highly capable of reducing the consumers' grid energy use and, as a result, lowering their electricity costs during daylight hours. These results align with the findings of Jin et al. [33], who concluded that incorporating P2P energy sharing significantly decreased the grid energy usage of participants between 7:00 and 19:00, compared to a scenario without P2P energy sharing. Furthermore, this study has discovered that under the P2P model with batteries, the utilisation of batteries decreases the quantity of excess PV energy that the prosumer distributes to the consumers via P2P energy sharing. This is in opposition to the results reported by Sahebi et al. [10], who suggested that the integration of batteries into a local PV community through a P2P energy sharing model could yield notable benefits for prosumers and consumers, including decreased costs and energy

consumption on the electricity grid. The reason for this discrepancy lies in the different battery-operation strategies between these two works. In the study by Sahebi et al. [10], the batteries were interconnected and their stored energy could be distributed among peers. However, in our case, we focus on the fact that batteries are exclusively utilised by the prosumer and must be fully charged before the prosumer can share any surplus PV energy with the consumers.

In addition, a study by Guo et al. [26] found that consumers experience substantial advantages when they engage in peer-to-peer (P2P) energy sharing; nevertheless, the authors also claimed that the utilisation of batteries does not yield additional advantages for consumers, which is not entirely in accordance with our results. The findings presented in Tables 5 and 7 of our work show that using batteries could reduce the payback period of PV batteries to a certain degree, depending on the battery capacity. The main reason behind this difference is that Guo et al. [26] failed to account for the ongoing rise in the retail price of grid electricity, which could result in a continued high cost of grid electricity consumption in the absence of battery use. Having batteries could ensure the amount of grid electricity consumption is reduced over the years for prosumers, thus yielding further financial benefits.

This study is contrasted with the study [23] that addresses both P2P energy sharing and batteries, primarily focusing on minimising battery investment costs and electricity purchase expenses. Employing solar PV and batteries is crucial for attaining energy independence in residential buildings [19]; thus, the economic assessment must be more realistic and concentrate on key factors, such as the life cycle costs of the equipment and the evolving economic conditions. Therefore, the paper further enhances the economic analysis by including the initial purchase cost of PV systems and batteries, operational and maintenance expenses, and annual depreciation costs. This paper also performs a sensitivity analysis to illustrate the effects of variations in multiple influencing factors on the payback period of PV batteries within the P2G and P2P models, aiming to offer a more thorough understanding of the economic advantages for prosumers and consumers utilising batteries and engaging in the P2P energy sharing initiative.

The findings of this study also indicate that even in the P2P model with batteries, the prosumer still exports a substantial amount of PV energy to the grid. For instance, Table 4 demonstrates that when the battery capacity reaches 20 kWh, the annual exported energy amounts to 8, 448 kWh. This results in annual PV self-consumption of 43.6 %, indicating that less than half of the PV energy generated is consumed by the prosumer and consumers. Hence, additional methods can be implemented in the PV community to enhance the utilisation of PV power. One such strategy involves incorporating heat pumps and water storage tanks into residential PV systems. This allows surplus PV energy, rather than being exported, to be utilised to generate heating and cooling energy for space heating, space cooling, and domestic hot water use [8,39]. Furthermore, the affordability of thermal energy storage offers a significant advantage to users in terms of cost savings when compared to the more expensive battery storage [40,41].

7. Conclusion

This study has explored the technical and economic performance of four mathematical energy trading modes in residential solar PV systems, including P2G, P2G with batteries, P2P, and P2P with batteries. The results showed that when neither batteries nor P2P energy sharing was considered, the prosumer exported 14,985 kWh of PV energy to the grid, while the three consumers purchased 9876 kWh of grid electricity for their consumption. When 5 kWh batteries were used by the prosumer, their annual PV self-consumption and self-sufficiency increased to 22.0 % and 23.1 %, respectively. In the P2P model, the three consumers' grid electricity consumption was reduced to 6647 kWh owing to the energy sharing among the prosumer and consumers. When the prosumer had 5 kWh batteries in the P2P model, the total grid electricity consumption of the three consumers increased to 7510 kWh. This is because battery

charging occurred prior to energy sharing, resulting in a reduced amount of energy available for sharing. Furthermore, it was shown that the rates of increase in annual PV self-consumption and self-sufficiency diminished once the battery capacity surpassed 12.5 kWh. This indicates that the larger battery storage could not be effectively utilised and became redundant.

The economic findings indicated that under the P2G model with batteries, the prosumer is unable to generate any profits regardless of the battery capacity due to the high initial purchase, the operational and maintenance cost of PV and batteries, and the annual energy costs for consumers seem unaffected by the prosumer's battery capacity under the P2G model, with the total cost spent for the three consumers reaching AUD 54,714 over 20 years. When it comes to the P2P model with batteries, the prosumer can yield benefits at all the battery capacities and the P2P energy sharing price of AUD 0.2/kWh. The highest cumulative NPV of AUD 4929 is achieved for the prosumer at the battery capacity of 10 kWh. Also, due to receiving less energy from the prosumer after batteries are used, the cumulative energy cost to the consumers rises steadily as battery capacity increases. The results of the payback period analysis show that in the P2G model, the cost of using PV-batteries cannot be recovered over the life of the equipment under the economic conditions shown in Table 2, whereas in the P2P model, the lowest payback period occurs for 10 kW PV and 7.5 kWh batteries under the same economic conditions and is 12 years. A sensitivity analysis shows that many influencing factors, such as PV cost, battery cost, annual discount rate and the P2P energy sharing price, can have a significant impact on the payback period of PV batteries but only under the P2P model.

This research provides a valuable guide for residents who plan to participate in community energy sharing and install PV systems and batteries. Nevertheless, the electrical load profiles of the three consumers were derived analogously from the electrical data of the prosumer, which may have been somewhat idealistic. This may have resulted in time and power constraints in terms of energy trading, as only one prosumer was considered to provide energy sharing for consumers. Consequently, future research should include additional prosumers or consumers with actual electrical data, both with and without batteries, to determine their energy costs and their PV and grid energy consumption. Moreover, the technical and economic analysis of this research was based on a single case study house in Australia, which restricted the global application of the results. Therefore, future research may investigate the influence of a variety of housing types in different regions with varying climatic conditions and electricity market environments on the technical and economic performance of prosumers and consumers. This will enhance the practical applicability and generalisability of the four energy trading models.

CRedit authorship contribution statement

Zheng Wang: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Mark Luther:** Supervision. **Peter Horan:** Supervision. **Jane Matthews:** Supervision. **Chunlu Liu:** Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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