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Technical and economic analyses of PV battery systems considering two different tariff policies

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ABSTRACT

Installing batteries in solar photovoltaic (PV) houses is becoming commonplace and different tariff policies give residents more options to lower their energy bills. This paper develops two rule-based control strategies to operate solar PV battery systems under fixed flat or time-of-use tariff policies, aiming to increase PV self-consumption and self-sufficiency. The battery modelling considers the charging and discharging efficiencies and the battery energy efficiency. The payback period for solar PV battery systems under the two tariff policies is also analysed considering various economic factors such as the capital cost of solar PV systems, the capital and maintenance costs of the batteries, the annual discount rate and the increases or decreases in the retail prices of grid electricity and the feed-in tariff. The analyses are conducted using actual PV energy and smart meter data from a real case study house in Geelong, Australia. Results indicate that when battery capacity is increased, PV self-consumption and self-sufficiency grow under both tariff policies, but this trend is limited by constrained PV generation due to seasonal conditions. Additionally, increasing solar PV system size for fixed battery capacity increases PV self-sufficiency, but decreases PV self-consumption. Results of economic analysis demonstrate that the payback period for a standalone solar PV system increases as its capacity grows. Moreover, the payback period for PV batteries can be slightly shorter or even longer than using solar PV systems alone under both tariff policies, which is economically unattractive. Considering the benefits that batteries can bring to residents and electricity networks, local governments need to be more proactive in providing financial subsidies for residents to install batteries.

1. Introduction

On the path to achieving the United Nations 2050 carbon neutrality goal, countries and organisations around the world need to take action to manage their greenhouse gas emissions from burning fossil fuels [1]. As a result of continuous technological advancement and decreasing cost, solar photovoltaic (PV) systems have become one of the most widely used renewable energy systems across the globe. The European Union has set itself the goal of reducing fossil fuel dependency and reaching climate neutrality by 2050 [2] and its total installed size of solar PV systems was estimated at over 158 GW in 2021 [3]. Similarly, Australia aims to reduce its greenhouse gas emissions by 26 % to 28 % from 2005 levels by 2030 and to achieve net zero emissions by 2050 [4]. Data released by the Australian Renewable Energy Agency [5] shows that over 30 % of Australian households now have rooftop solar PV systems, contributing to a total installed size of 11 GW. Continuous installation of solar PV systems in homes is anticipated to meet residential energy needs and reduce the impact on climate change.

Although solar PV systems are easily installed in homes and have low maintenance costs [6], the mismatch between peak PV generation and residential energy demand has resulted in relatively low PV self-consumption rates [7,8]. PV self-consumption measures the proportion of total solar PV generation consumed on-site [9]. On the other hand, the feed-in tariff (FIT), one of the main forces driving the expansion of solar PV installation, has been declining worldwide, resulting in prices well below the retail price of grid energy [10]. This encourages excess harvested solar energy to be consumed locally rather than being sold to the grid, which is overloaded because it is designed to supply power rather than receiving it. Using energy storage such as batteries in residential solar PV systems, excess harvested solar energy is stored during the day and consumed during peak hours or at night, leading to increased PV self-consumption rates [11].

Currently, due to the existence of different tariff policies, residents are able to choose an appropriate option based on their energy consumption in order to reduce their energy bills. In Victoria, Australia, the

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Nomenclature

AC	Alternating current
SOC	State of charge of batteries
B	Battery capacity in kWh
SOC_{max}	Maximum state of charge of batteries
C^b	Capital cost of batteries
SOC_{min}	Minimum state of charge of batteries
C^s	Capital cost of solar PV system
SS	PV self-sufficiency
C_n	Cash flow in the n^{th} year
T	Total number of time intervals in a year
DC	Direct current
d	Annual degradation rate of battery value
EE	Amount of exported energy
g	A given period, such as a year or a month
EH	Amount of house electrical load
i	Annual discount rate
EI	Amount of imported energy
n	n th year after batteries are first used
ES	Amount of harvested solar energy
o	Off-peak hours
FIT	Feed-in tariff
p	Peak hours
M	Annual maintenance cost of batteries
s	Shoulder hours
N	Payback period for batteries
t	Time interval
PV	Photovoltaic
η_b	Energy efficiency of batteries
PVC	Amount of PV energy consumed
η_c	Charging efficiency of batteries
RP	Retail price of grid electricity
η_d	Discharging efficiency of batteries
SC	PV self-consumption
Δ	Energy difference

two tariff policies that are most frequently utilised in homes are a fixed flat tariff policy and a time-of-use tariff policy. A fixed flat tariff policy can be defined as a fixed price paid for each kilowatt-hour (kWh) of electricity used that does not vary with the time of day or total electricity consumption, while a time-of-use tariff policy is flexible pricing that varies depending on the time of day, such as morning or afternoon hours. Existing studies have considered either only one tariff structure or both tariff structures when analysing the impact of battery storage on residential PV and grid energy consumption, but the energy performance in terms of PV self-consumption and self-sufficiency rate has yet to be investigated. PV self-sufficiency refers to the percentage of residential energy demand met by solar PV generation [12]. Moreover, numerous studies have utilised simulated data for PV generation and electricity demand, leading to possible discrepancies between the results of the studies and the actual situation. By developing two rule-based control strategies for PV battery systems operating under the fixed flat tariff and time-of-use tariff policies, this paper examines the feasibility of using batteries in residential solar PV systems under the current tariff structures in terms of their energy and economic performance. Compared to the existing literature, the novelty of this work is that it utilises actual hourly PV generation and electricity consumption data measured throughout the year at a case study residence. It analyses the impact of battery storage on residential PV and grid electricity consumption under the two tariff policies on a yearly, monthly and daily basis, making the results more reliable for both residents and readers. To make the analysis more trustworthy, it also analyses the economic viability of residential PV batteries based on the payback period. It considers various economic factors, such as the capital cost of solar PV systems, the capital and maintenance cost of the battery, the annual discount rate, the increase or decrease in the retail price of grid electricity and the FIT.

The rest of the paper is organised as follows. Section 2 reviews the existing literature on PV battery systems. Section 3 presents the method used for this work including two rule-based control strategies for operating PV battery systems under the two different tariff policies, the calculations of PV self-consumption and self-sufficiency, and an economic model for analysing the payback period for batteries. Section 4 describes the case study house used in this work. The technical performance of PV battery systems under the two tariff policies is presented in Section 5 and the economic performance of the PV battery systems under the two tariff policies is presented in Section 6. Section 7 draws the conclusions for this work.

2. Literature review

Recently the use of batteries in residential solar PV systems has been studied extensively, with a great deal of attention paid to the technical feasibility, optimal sizing and economic viability of PV battery systems. For example, five different rule-based energy-management strategies were developed to evaluate the technical and economic performance of batteries in microgrids under different tariff policies, taking into account PV production forecasts, battery degradation and the power-exchange limitation between micro and main grids [13]. The electricity tariffs considered in such work included fixed flat and time-of-use tariff policies, and the battery modelling considered the charging and discharging efficiency. However, the self-sufficiency of the solar PV system was ignored in the results. Based on a home energy-management system for the demand-side management of electrical loads, Duman et al. [14] proposed a model to optimise the capacity of residential PV battery systems. In addition, economic analysis was conducted to ascertain the net present value of the PV battery system. Although time-of-use and fixed flat tariff policies, as well as PV self-consumption enhancements, were considered in determining the model size, the study did not investigate the relationship between PV self-sufficiency and battery capacity, and PV generation data was generated using a simulation program rather than actual measured data. Cho and Valenzuela [15] created a scenario-based optimisation model to determine the capacity of an off-grid PV battery system by considering the variability of solar radiation and the energy consumption patterns of household appliances. As a backup energy source for the operation of an off-grid building, a diesel generator was utilised, and the investment cost of the PV batteries and the fuel cost of the generator were used as criteria to optimise the capacity of the PV batteries.

Al Khafaf et al. [16] conducted economic analysis to investigate the affordability and payback period of using batteries in residential solar PV systems. Fixed flat and time-of-use tariff structures were considered in the work. PV generation and energy consumption profiles of all studied houses used real measured data downloaded from power suppliers. The results suggested that until local governments provided additional financial incentives, considering the cost of battery degradation made the payback period for batteries economically unattractive. The authors also provided distribution network operators and policymakers with some recommendations for making batteries more affordable for residents. However, the work did not include analysis of PV self-consumption or self-sufficiency when using batteries. A mixed-integer linear programming method was proposed to size residential battery storage by considering the operational optimisation of batteries under a time-of-use tariff policy [17]. In addition, the work identified the factors that affected battery operations and compared the results with the baseline operation of battery storage based on self-consumption maximisation. The authors also explained and used a battery degradation model when calculating the battery-related costs. The findings demonstrated that installing batteries in homes was only financially advantageous with sufficient subsidy at present market prices. Optimal operation-based battery storage performed better than battery storage based on maximising self-consumption under the time-of-use tariff policy with respect to the annual expenditure, investment return and prevention of PV cut-off. However, again one of the limitations was that the PV generation data used in the work was not real measurements but downloaded from a simulation program.

In order to minimise the annual expense of electricity and batteries for a typical net zero energy home, Sharma et al. [18] proposed a method to size PV battery systems optimally. The battery charging and discharging efficiency, annual payment for battery storage and buying grid electricity, as well as the annual revenue from selling excess harvested solar energy, were investigated. The findings demonstrated that the annual cost of batteries was currently less than AUD 80/kWh and this price was decreasing rapidly each year, making installing battery storage in solar PV homes economically attractive. However, the study only considered the fixed flat tariff policy and ignored the time-of-use tariff policy. In addition, the PV generation data used in the study was downloaded from a simulation program and the electrical energy load of the house was derived from assumptions. Technical and economic analysis was conducted for a standalone home with a PV battery system and a grid-connected solar PV home with battery storage [19]. Power-management strategies for the two different design configurations were proposed, as well as genetic algorithms designed to optimise the size of the PV battery system based on the actual measured electrical load and the simulated PV generation. The authors considered both the fixed flat and time-of-use tariff policies, but did not give results for the effects of using batteries on PV self-consumption or self-sufficiency. Horan et al. [20] used real measured energy consumption and PV generation data to investigate the technical and economic performance of batteries in three residential solar PV systems. They found that a battery, regardless of size, required a significantly large solar PV system to charge during winter time. A rule-based control strategy for operating PV battery systems under the fixed flat tariff policy was proposed. However, the work did not consider the charging and discharging efficiency of batteries, PV self-consumption and self-sufficiency, or operating PV battery systems under the time-of-use tariff policy.

A summary of the selected literature on residential PV battery systems is presented in Table 1. It can be seen that previous studies neglected to model the charging or discharging efficiency of batteries, neglected to study PV battery systems under different tariff policies, did not consider the impact of using batteries on PV self-consumption and self-sufficiency or used simulated household electrical load or PV generation data. Therefore, the scope of this work is a battery storage analysis of solar PV houses under the fixed flat and time-of-use tariff policies in terms of PV self-consumption, self-sufficiency, grid energy consumption and the payback period for batteries. Two different rule-based control strategies are developed with respect to operating PV battery systems under fixed flat and time-of-use tariff policies, as well as increasing PV self-consumption and reducing energy imports from the grid. The battery modelling considers the battery charging and discharging efficiencies, the maximum and minimum state of charge of batteries and the battery energy efficiency. The real measured electric loads and PV generation data are collected from a case study house, making the analysis more realistic.

3. Method

3.1. Technical analysis of PV battery systems under two tariff policies

Fig. 1 provides a simplified diagram of a grid-connected solar PV house with batteries. The solar PV system, batteries and electricity grid are connected via an inverter that provides controls for distributing PV electricity, charging or discharging the batteries and exporting or importing energy to or from the grid. Specifically, the inverter can convert the direct current (DC) output from the batteries or solar PV to alternating current (AC) and supply it to home appliances or the grid. Also, it can convert the AC supply from the electricity grid to 48 V DC, charging the batteries. The energy from the solar PV system can be supplied to the house load, to charge the batteries or to be sold to the grid.

During the day, the batteries can be charged to store excess harvested solar energy when it is greater than the house load or can be discharged to meet the house load when there is insufficient harvested solar energy. The electricity grid is used as the energy source to supply the house load when both harvested solar energy and battery storage are unavailable. In this work, it is assumed that the battery is fully charged at the time of installation and that it has a maximum lifetime, which will be explained

Table 1
A summary of the concepts considered on PV battery systems in this work and some literature from the last six years.

References	Fixed flat tariff policy	Time-of-use tariff policy	PV self-consumption	PV self-sufficiency	Battery efficiency	Real-measured electrical load	Real-measured PV energy data
Ouédraogo et al. [13]	√	√	√		√	√	√
Duman et a. [14]	√	√	√		√		
Cho and Valenzuela [15]					√	√	
Al Khafaf et al. [16]	√	√			√	√	√
Mulleriyawage and Shen [17]		√	√		√		
Sharma et al. [18]	√				√		
Hassan and Al-Abdeli [19]	√	√			√	√	
Horan et al. [20]	√					√	√
Abou El-Ela et al. [21]					√		
Young et al. [22]	√	√			√	√	√
O'Shaughnessy et al. [23]	√	√	√				
e Silva and Hendrick [24]	√		√	√	√	√	
Mohamed et al. [25]		√	√		√		√
This work	√	√	√	√	√	√	√

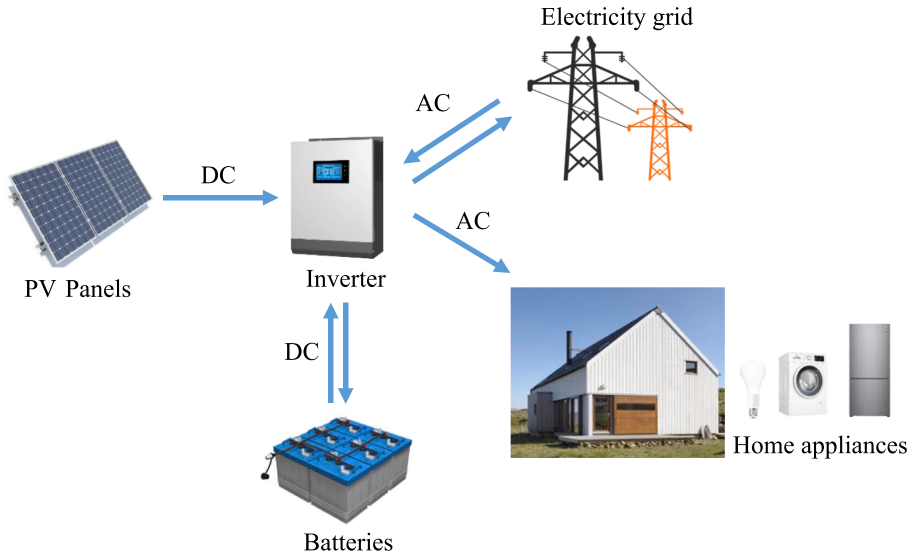


Fig. 1. Simplified diagram of a grid-connected solar PV house with batteries.

in Section 3.2 when describing the payback period for the battery. Additionally, the disposal of the battery at the end of its lifetime is assumed to be free of cost. Furthermore, in this paper we use a year as the study period and divide it into several time intervals t, which can be one hour, half an hour or quarter of an hour. In each time interval, PV or grid energy is transferred between the solar PV system, the grid, the batteries and the household appliances via the inverter.

When the harvested solar energy exceeds the electrical load of the house, the excess solar energy is used to charge the batteries and then exported to the grid after the batteries reach the maximum state of charge. Therefore, the state of charge of the batteries at the end of time interval t, SOC_t, and the amount of energy exported to the grid during time interval t, EE_t, can be expressed as:

$$SOC_t = min(SOC_{t-1} + \frac{(ES_t - EH_t) \times \eta_c}{B}, SOC_{max}) \tag{1}$$

$$EE_t = max(0, ES_t - EH_t - \frac{(SOC_t - SOC_{t-1}) \times B}{\eta_c}) \tag{2}$$

where:SOC_{t-1} is the state of charge of the batteries at the end of the previous time interval $t -1ES_t$ is the amount of harvested solar energy during time interval tEH_t is the amount of house electrical load during time interval tB is the battery capacity in kWh.η_c is the charging efficiency of the batteries, which is assumed to be 96 % in this work [14].SOC_{max} is the maximum state of charge of the batteries and is equal to 95 % in this work [18].

When the amount of harvested solar energy is smaller than the electrical load of the house, the remaining electrical load is first met by discharging the batteries and then by importing energy from the grid after the batteries reach the minimum state of charge. Thus, the state of charge of the batteries at the end of time interval t and the amount of energy imported from the grid during time interval t, EI_t, can be expressed as:

$$SOC_t = max(SOC_{min}, SOC_{t-1} - \frac{EH_t - ES_t}{B \times \eta_d \times \eta_b}) \tag{3}$$

$$EI_t = max(0, EH_t - ES_t - (SOC_{t-1} - SOC_t) \times B \times \eta_d \times \eta_b) \tag{4}$$

where:SOC_{min} is the minimum state of charge of the batteries and its value is assumed to be 10 % in this work [21].η_d is the discharging efficiency of the batteries and its value is considered to be 96 % in this work [21].η_b is the energy efficiency of the batteries, which is assumed to be 95 % in this work.

The technical parameters used to the operate batteries in the study are shown in Table 2.

Under the fixed tariff policy, the price of purchasing electricity from the grid remains constant, so whenever the solar PV system is not supplied with sufficient electricity, the house should use the batteries before importing electricity from the grid. Therefore, the batteries are discharged to meet the electrical load of the house when the harvested solar energy is insufficient. The shortfall is then met by energy imported from the grid after the batteries are discharged. When the amount of harvested solar energy is greater than the electrical load of the house, the excess harvested solar energy is first used to charge the battery and then exported to the grid after the battery is fully charged. Fig. 2 illustrates a rule-based control strategy for operating a PV battery system under the fixed flat tariff policy.

Under the time-of-use tariff policy, the retail price of grid energy is higher during peak hours than during shoulder and off-peak hours. Therefore, the energy stored in the batteries should be consumed first during peak hours when the harvested solar energy is insufficient. Then the shortfall is met by importing energy from the grid. During shoulder and off-peak hours, the price of electricity purchased from the grid is relatively low, so the house should use more grid energy and save the energy stored in the battery for the following peak hours. Therefore, when the harvested solar energy is in limited supply during shoulder and off-peak hours, batteries will not be discharged and the remaining demand for electricity will be met entirely by grid energy. Fig. 3 illustrates a rule-based control strategy for operating a PV battery system under a time-of-use tariff policy.

PV self-consumption and self-sufficiency are parameters used to describe the relationship between the amount of consumed PV energy, the total PV generation and the house's electrical demand. They can be calculated using the following equations:

Table 2
Technical parameters of Lithium-ion batteries used in this work.

Parameters	Symbols	Values
Maximum state of charge	SOC_{max}	95 %
Minimum state of charge	SOC_{min}	10 %
Charging efficiency	η_c	96 %
Discharging efficiency	η_d	96 %
Battery energy efficiency	η_b	95 %

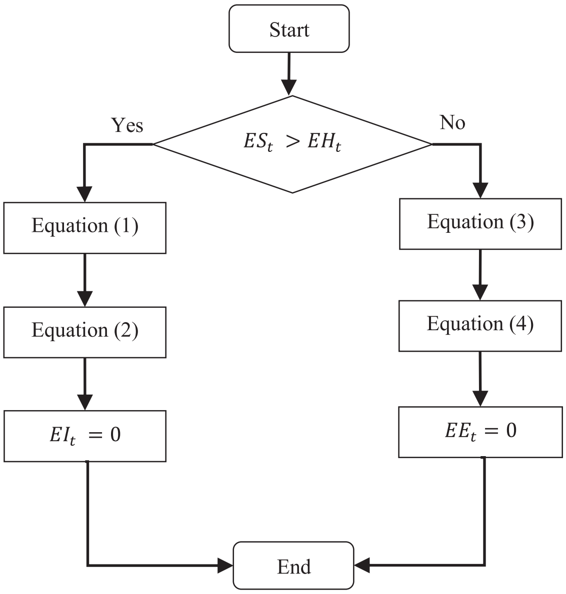


Fig. 2. Rule-based control strategies for operating PV battery system under the fixed-flat tariff policy.

$$SC_g = \frac{\sum_{t=1}^{g} PVC_t}{\sum_{t=1}^{g} ES_t} \tag{5}$$

$$SS_g = \frac{\sum_{t=1}^{g} PVC_t}{\sum_{t=1}^{g} EH_t} \tag{6}$$

where:g is a given period, such as a year or a monthPVC_t is the amount of PV energy consumed in the house during each time interval tSC_g is the PV self-consumption over a given period gSS_g is the PV self-sufficiency over a given period g

3.2. Economic analysis of PV battery systems under two tariff policies

The payback period is a recognised indicator to assess the economic performance of renewable energy systems. It represents the time period needed to recover the cost of the investment. This section presents an economic model for analysing the payback period for batteries in grid-connected solar PV houses. Nowadays, the FIT continues to decrease each year, while the retail price of grid electricity is increasing each year. In addition, electricity suppliers have started restricting excess PV-generated electricity from being sent back to the grid, so PV owners may not be able to sell electricity to the grid soon. As a result, the net cost for PV owners to purchase energy from the grid will increase each year. Installing batteries allows excess harvested solar energy to be stored during the day and consumed during peak hours, reducing the grid energy use and thus saving costs. Therefore, the cash inflows in the n th year, C_n, can be calculated based on the savings on electricity bills minus the reduction in revenue from selling excess harvested solar energy to the grid:

$$C_n = \left(\sum_{t=1}^{T} \Delta EI^{p}_{t,n} \times RP^{p}_{n} + \sum_{t=1}^{T} \Delta EI^{s}_{t,n} \times RP^{s}_{n} + \sum_{t=1}^{T} \Delta EI^{o}_{t,n} \times RP^{o}_{n}\right) - \sum_{t=1}^{T} \Delta EE_{t,n} \times FIT_n \tag{7}$$

where:T is the total number of time intervals in a year.

$\Delta EI^{p}_{t,n}$, $\Delta EI^{s}_{t,n}$ and $\Delta EI^{o}_{t,n}$ are the amounts of imported energy saved during peak, shoulder and off-peak hours in each time interval t in the n th year, respectively.

$\Delta EE_{t,n}$ is the reduced amount of exported energy in each time interval t in the n th year.

RP^{p}_{n}, RP^{s}_{n} and RP^{o}_{n} are the retail prices of grid electricity during peak, shoulder and off-peak hours in the n th year, respectively; with the fixed flat tariff policy, these three prices are the same.

FIT_n is the retail revenue from selling excess harvested solar energy to the grid in the n th year.

It is noted that C_n is a positive value, because the retail price of grid electricity is greater than the FIT. If the FIT is greater than the retail price of grid electricity, installing batteries may not be a viable option for solar PV houses because selling excess harvested solar energy is more profitable than storing it in batteries. Notably, this paper assumes that there is no limit on the amount of harvested solar energy that can be sold

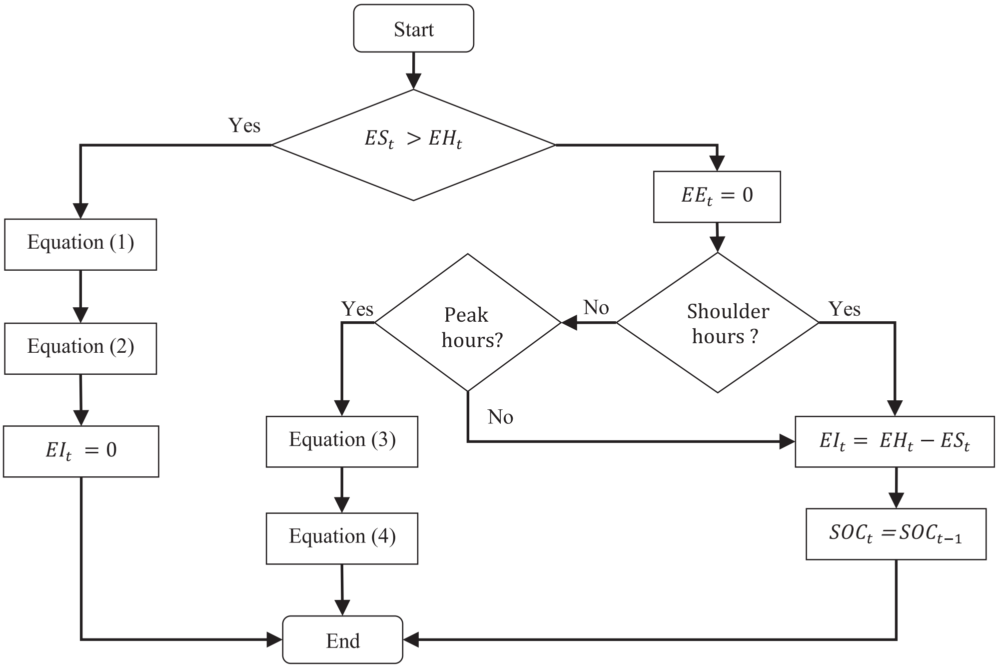


Fig. 3. Rule-based control strategies for operating PV batter system under the time-of-use tariff policy.

to the grid.

After obtaining the cash inflow C_n, the payback period for PV battery systems can be calculated based on the capital cost of the solar PV system, the capital cost of the batteries, the annual operating and maintenance costs of the batteries, the cash inflows each year and the residual value of the batteries. In this paper, the residual value of the batteries is calculated by reducing their capital cost by a fixed percentage each year. When a battery reaches its maximum lifespan its residual value is zero and the final waste disposal of batteries and solar PV systems is determined to be free of charge:

$$\sum_{n=1}^{N}\frac{C_n - M}{(1+i)^n} \le C^s + C^b \times \left(1 - \frac{1 - d \times N}{(1+i)^N}\right) < \sum_{n=1}^{N+1}\frac{C_n - M}{(1+i)^n} \tag{8}$$

where:

N is the payback period for the solar PV battery system in years and the battery is assumed to have a maximum lifespan of 20 years.

n is the n th year.

C^s is the capital cost of the solar PV system.

C^b is the capital cost of the batteries.

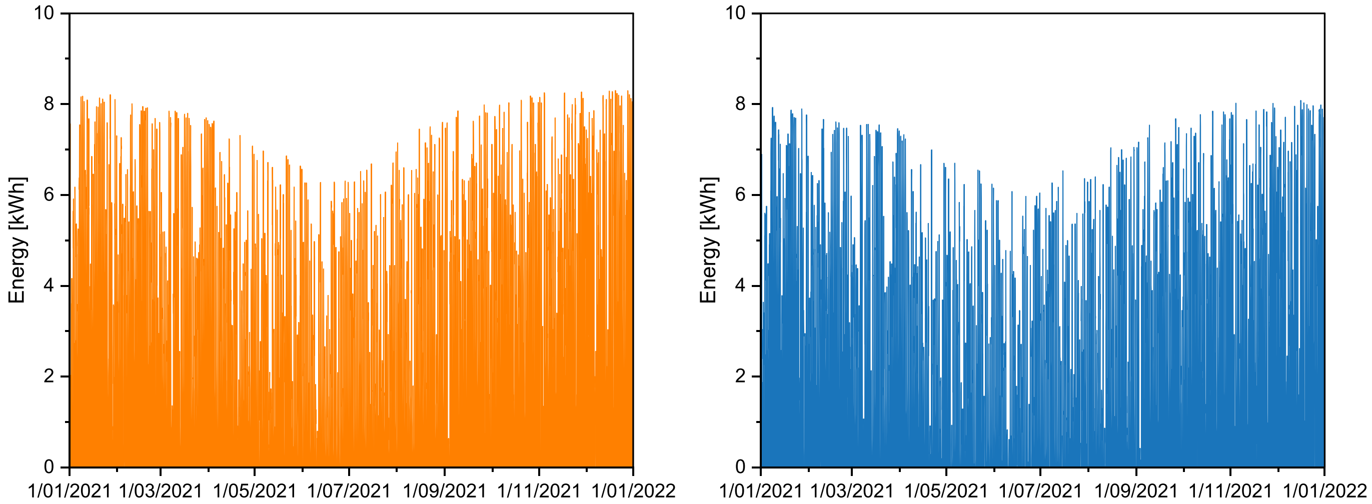
M is the annual maintenance cost of the batteries.

d is the annual degradation rate of the battery value.

i is the annual discount rate.

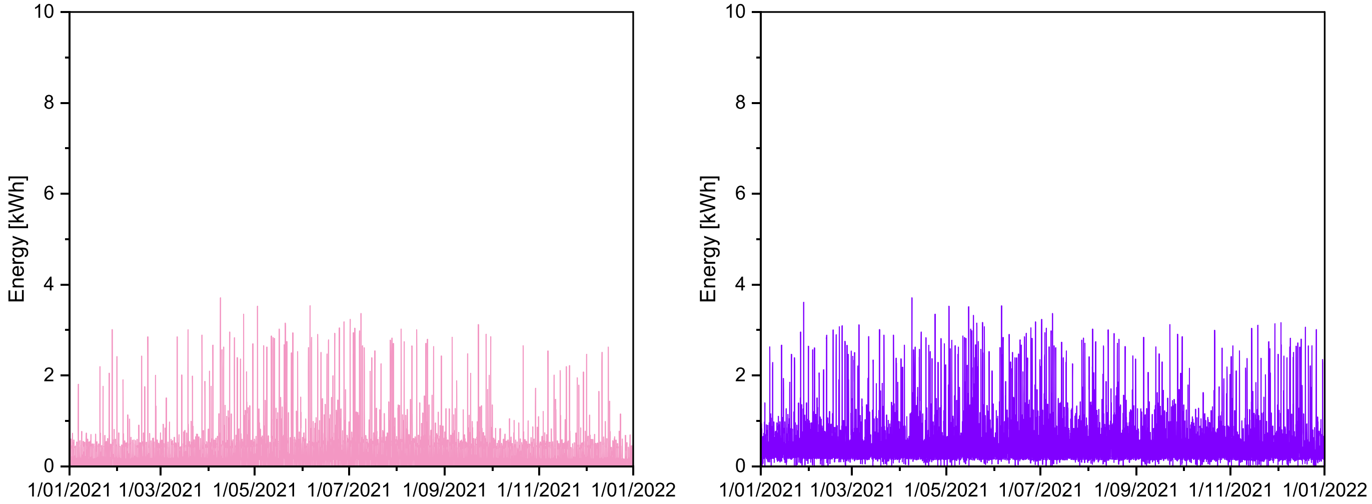
4. Case study

In this work, a house in Geelong, Australia, is used as a case study. 3 kW and 7 kW solar PV systems were installed in the house in 2014 and 2019, respectively, bringing its total PV capacity to 10 kW. Each PV panel is fitted with a micro-inverter that converts the output voltage directly to 240 V AC. Therefore, each PV panel operates independently and failure of a single PV panel will not cause system failure. In addition, a solar PV system controller measures PV power generation at 15 min intervals. In 2013, the electricity provider installed a smart meter that measures the electricity imported from and exported to the grid every half an hour. The imported and exported energy data recorded over the past two years is stored in a CSV file and can be downloaded from the electricity provider [22]. When a solar PV system is installed but no battery storage is available, the smart meter measures imported energy as house electrical load minus harvested solar energy and measures exported energy as harvested solar energy minus house electrical load. In addition, since the imported and exported energy flow through the same wire, when one is positive the other has a value of zero. The PV generation and smart meter data for the house in 2021 is used for the analysis in this work. The electrical load of the house during each time interval t was obtained by adding the harvested solar energy to the energy imported from the grid and then subtracting the energy exported to



(a) Hourly harvested solar energy

(b) Hourly energy exported to the grid



(c) Hourly energy imported from the grid

(d) Hourly house electrical load

Fig. 4. Energy summary of the house with a 10 kW solar PV system but no battery storage.

the grid. Fig. 4 shows the hourly distributions of the imported energy, exported energy, PV generation and house electrical load over the year 2021. The house had a total electrical load of 4.39 MWh in 2021, of which 2.21 MWh was met by the energy harvested from the solar PV system and the remaining 2.18 MWh was met by grid power. It is also found that a 10 kW solar PV system could harvest 14.36 MWh of electricity in 2021, while 12.15 MWh of energy was exported to the grid, resulting in a PV self-consumption rate of only 15.4 %. This can be attributed to the fact that there was a mismatch between PV generation and the electrical load of the house.

Given the relatively large capacity of the solar PV system and the fact that the FIT is decreasing annually, the homeowner has been attempting to find strategies to consume as much of the excess daily PV generation on-site as feasible. Notably, the house is well-insulated and has double-glazed windows, so no mechanical cooling device such as an air-conditioner is installed. A gas-ducted heating system provides space heating and hot water is supplied by a gas-boosted solar hot water system. Finally, the homeowner decided to purchase a plug-in hybrid vehicle in 2020 so that some of the PV energy generated during the day could be used to charge the car, thereby lowering fuel expenses and reducing carbon emissions. Fig. 5 depicts the average daily PV energy generation and average daily house electrical load for each month of 2021. Due to the variation in solar radiation, the average daily PV generation was substantially higher in summer than in other seasons. In addition, the average daily household electrical load was marginally higher in winter than at other times of the year due to the longer winter nights, which increased electricity demand. Furthermore, even with the plug-in hybrid vehicle the average daily household electricity consumption was between 10 and 15 kWh, substantially less than the average daily PV generation of a 10 kW system. Consequently, this result has increased the homeowner's interest in using batteries to enhance the PV self-consumption rate.

According to data released by the Essential Services Commission [23], a flat FIT of AUD 5.2 c/kWh applies in Victoria, Australia, from 1 July 2022 and the average downward trend for the FIT over the last three years was calculated to be 20 % based on the data provided. This work takes this value as the future downward trend for the FIT in Victoria. In addition, the Essential Services Commission [24] reported retail electricity prices in Victoria from July 2022 to June 2023. We used the electricity prices published by Powercor as the starting prices in this work. The retail price of electricity under the fixed flat tariff policy is AUD 0.23/kWh. The price under the time-of-use tariff policy is AUD 0.33/kWh during peak hours, AUD 0.28/kWh during shoulder hours and AUD 0.19/kWh during off-peak hours. In this work, the increasing rate of retail electricity prices under both tariff policies is assumed to be 5 % per annum. The annual discount rate is considered to be 3 %. Additionally, it is assumed that the costs of solar PV systems and batteries are AUD 1000/kWh and AUD 850/kWh, respectively. The annual maintenance cost of the batteries is assumed to be 2 % of their capital cost [25]. The annual degradation rate of the battery value is assumed to be 5 % of the capital cost. The values of the various parameters used in this work are summarised in Table 3.

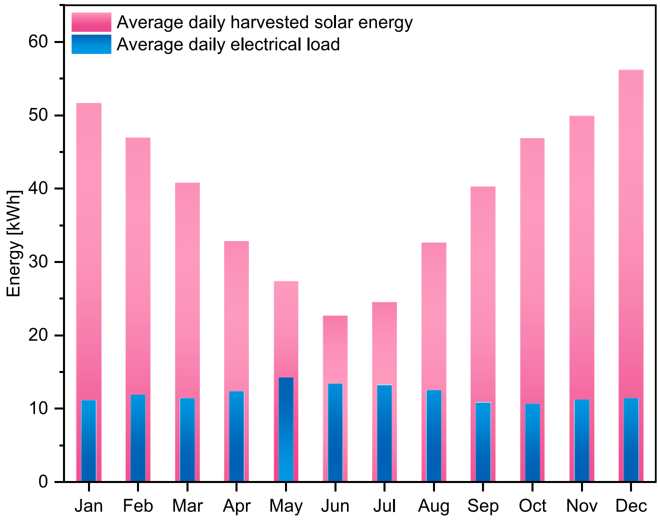


Fig. 5. Average daily harvested solar energy of the 10 kW PV system and the average daily electrical load of the house for each month in 2021.

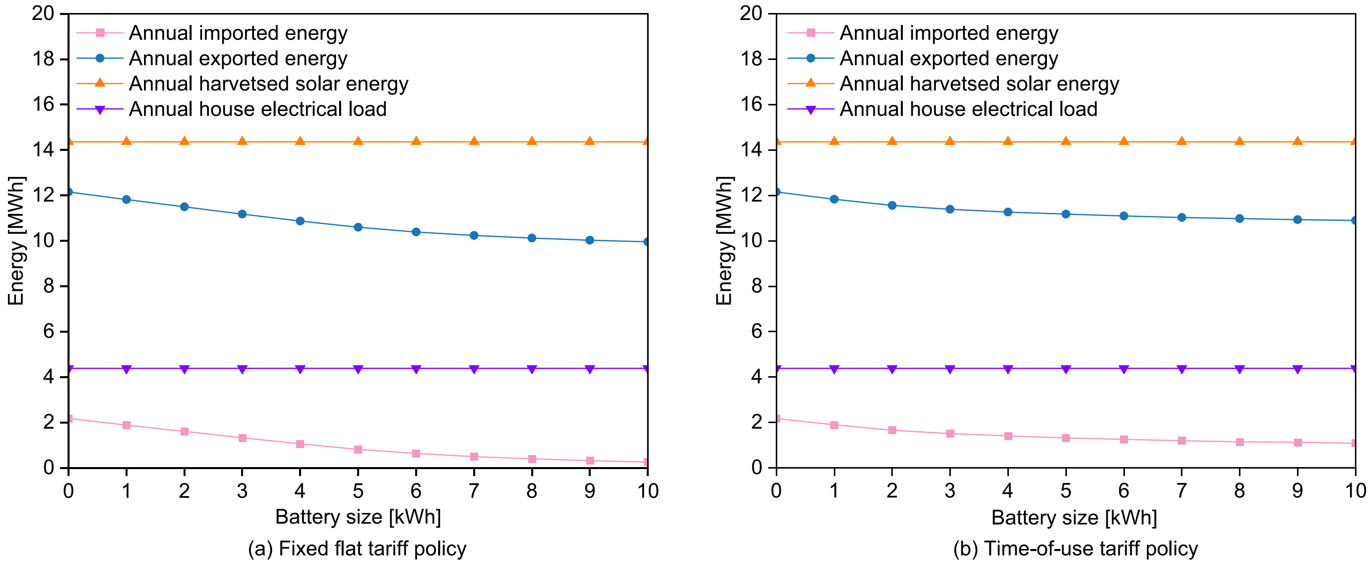
5. Technical performance of PV battery systems under two tariff policies

To analyse the effects of using battery storage on the consumption of grid electricity and harvested solar energy of the house under the fixed flat tariff and time-of-use tariff policies, the annual electrical load, annual imported and exported energy, and annual harvested solar energy of the house under the two different tariff structures were calculated and plotted, as shown in Fig. 6. The annual harvested energy of the 10 kW solar PV system and the electrical load of the house are constant values. It can be seen that the annual imported and exported energy of the house decreased as the battery capacity increased and the difference between these two parameters was the same since it is equal to the difference between the annual harvested solar energy and the electrical load of the house. Additionally, it can be found from the two graphs in Fig. 6 that as the battery capacity increased, the annual imported and exported energy decreased faster under the fixed-flat tariff than under the time-of-use tariff policy. This is because under the fixed flat tariff policy, the energy stored in the batteries was consumed at any time when not enough solar energy was harvested, while under the time-of-use tariff policy, the batteries were discharged only during peak hours (3:00 pm – 9:00 pm) to meet household demand when there was insufficient harvested solar energy and during shoulder and off-peak hours the household load was met entirely by purchasing electricity from the grid. Therefore, it can be argued that using battery storage in a grid-connected solar PV house can have a great impact on reducing the annual grid energy consumption of the house and increasing the consumption of harvested solar energy. Moreover, the use of battery storage under the fixed flat tariff policy has a greater impact on PV and grid energy consumption than under the time-of-use tariff policy.

To further investigate the impact of battery storage on the consumption of grid electricity and harvested solar energy, the annual imported and exported energy during peak and off-peak hours for the two different tariff policies was collected and plotted, as illustrated in Fig. 7. Fig. 7(a) and (b) show that during peak hours, the annual imported energy decreased for both tariff policies when the size of batteries

Table 3
Input data of various parameters for the year 2022.

Parameters	Values
Fix flat tariff	AUD 0.23/kWh
Changing rate in fixed flat tariff	5 % per annum
Time-of-use tariff	
Peak hours (3:00 pm – 9:00 pm, everyday)	AUD 0.33/kWh
Off peak hours (10:00 am – 3:00 pm, everyday)	AUD 0.19/kWh
Shoulders hours (all other times)	AUD 0.28/kWh
Changing rate in time-of-use tariff	5 % per annum
FIT	AUD 0.052/kWh
Changing rate in FIT	− 20 % per annum
Annual discount rate	3 %
PV capital cost	AUD 1000/kWh
Battery capital cost	AUD 850/kWh
Annual maintenance cost of batteries	2 % of battery capital cost
Battery lifespan	20 years
Annual degradation rate of the battery value	5 % of battery capital cost per annum



(a) Fixed flat tariff policy

(b) Time-of-use tariff policy

Fig. 6. House energy summary as a function of battery size for the fixed flat and time-of-use tariff policies.

increased, while the annual exported energy remained almost constant. It is also noteworthy that during peak hours, the annual imported and exported energy values were nearly the same for the two different tariff policies. This can be explained by the fact that the principle of using the batteries during peak hours was the same for the two different tariff policies, i.e., the home load was first met by the harvested solar energy, then by the energy stored in the batteries when the harvested solar energy was insufficient and finally by energy from the grid after the batteries were fully discharged.

On the other hand, as shown in Fig. 7(c) and (d) there was a significant difference in the annual imported and exported energy under the two tariff policies during shoulder and off-peak hours as the battery capacity increased. The reason for this is that during shoulder and off-peak hours, when the harvested solar energy was insufficient to meet the house's electrical requirement grid energy was consumed under the time-of-use tariff policy, whereas under the fixed flat tariff policy the batteries were discharged resulting in less grid energy consumption. In addition, it is for this reason that less excess harvested solar energy was needed to charge the batteries during shoulder hours under the time-of-use tariff policy, resulting in more energy being exported to the grid. Another interesting point from Fig. 7 is that the annual imported energy during off-peak hours was less than 10 kWh for the two tariff policies. This can be attributed to the fact that solar radiation is generally abundant during off-peak hours (10:00 am – 3:00 pm) and enough solar energy could be collected for household consumption, resulting in very little grid energy use but a significant amount of exported energy, as shown in Fig. 7(f). In summary, using batteries can effectively reduce the consumption of grid electricity and harvested solar energy. For the two rule-based battery control strategies proposed in this paper, the difference in the impact of the batteries on energy consumption mainly occurred during shoulder hours.

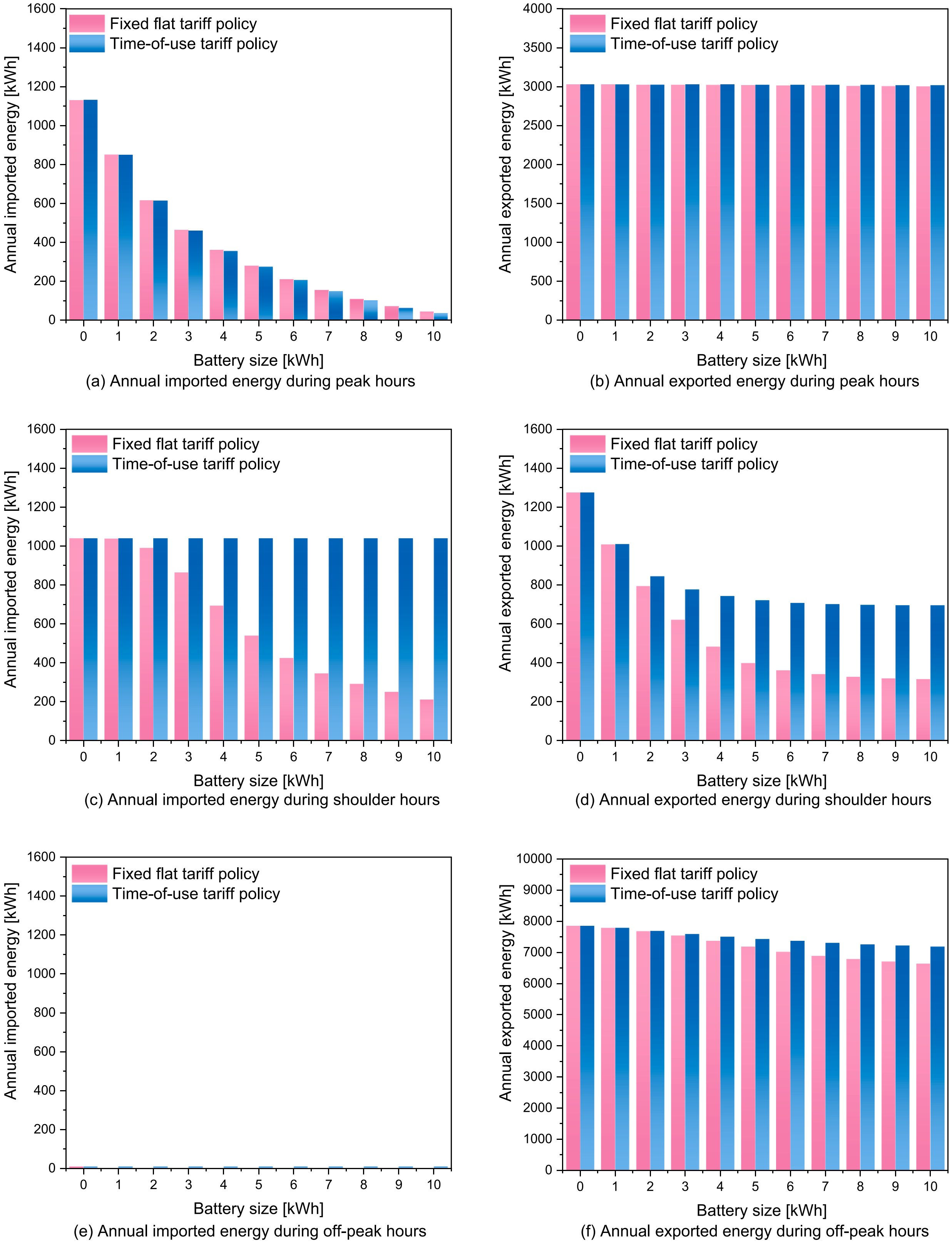
The annual self-consumption and self-sufficiency rates for the four different sizes of solar PV systems with varying battery sizes were calculated using Equations 8 and 9. The results are plotted in Figs. 8 and 9 to show the effects of PV and battery size on the annual PV self-consumption and self-sufficiency. The four different solar PV systems harvested different amounts of annual solar energy, increasing in proportion to their size. It can be found from the graphs that the PV self-consumption and self-sufficiency under the two tariff policies increased as the battery size increased, but these trends were limited because the amount of PV-generated electricity was related to seasonal conditions. Specifically, during the summer months PV generation was sufficient and excess PV energy could be used to charge the battery. However, in winter, when PV generation was constrained, the daily PV generation was not enough to meet the daily house load, so the batteries could not be charged effectively. It can also be observed from the graphs that when increasing the size of the batteries, the household had higher PV self-consumption and self-sufficiency under the fixed flat tariff policy than under the time-of-use tariff policy. This is due to the different principles for using batteries under the two different tariff policies. The strategy of not using battery-stored electricity under the time-of-use tariff policy during shoulder and off-peak hours resulted in more grid electricity consumption compared to the fixed flat tariff policy.

Additionally, it can be seen that for a fixed battery size, increasing the size of the solar PV system led to an increase in PV self-sufficiency but a decrease in PV self-consumption. This is because when the battery size was fixed, an increase in solar PV system size allowed more PV energy to be generated to meet the electrical energy demand of the house, but the amount of excess PV energy during the day that was not consumed and exported to the grid was greater than the increase for meeting the electrical demand of the house, resulting in decreased PV self-consumption. Therefore, it can be concluded that PV size and battery size influence PV self-consumption and self-sufficiency. The characteristics of both solar PV and home energy demand should be considered when installing PV and battery systems in order to determine the optimal size for both systems.

The annual PV self-consumption and self-sufficiency were discovered to vary with PV size and battery size. We plotted monthly self-consumption and self-sufficiency for the 10 kW solar PV system under the fixed flat and time-of-use tariff policies in Figs. 10 and 11 to better understand how monthly PV energy consumption fluctuated when utilising different sizes of batteries. It can be discovered from the graphs that increasing the size of the batteries led to increases in PV self-consumption and self-sufficiency, and these two parameters had higher values under the fixed flat tariff policy than under the time-of-use tariff policy. In addition, compared to other times of the year, the household was shown to have higher PV self-consumption and lower PV self-sufficiency in winter.

As seen in Fig. 4, this was due to the high demand for electricity in the home during winter, when PV generation is generally low. Even while the house load in winter consumed most of the PV generation, making the self-consumption rate high, it was still small compared to the amount of electricity required by the house, making the self-sufficiency rate in winter relatively low.

These facts are also supported by the results shown in Fig. 12, which depicts the energy imported per day in a year as a function of battery size



(a) Annual imported energy during peak hours

(b) Annual exported energy during peak hours

(c) Annual imported energy during shoulder hours

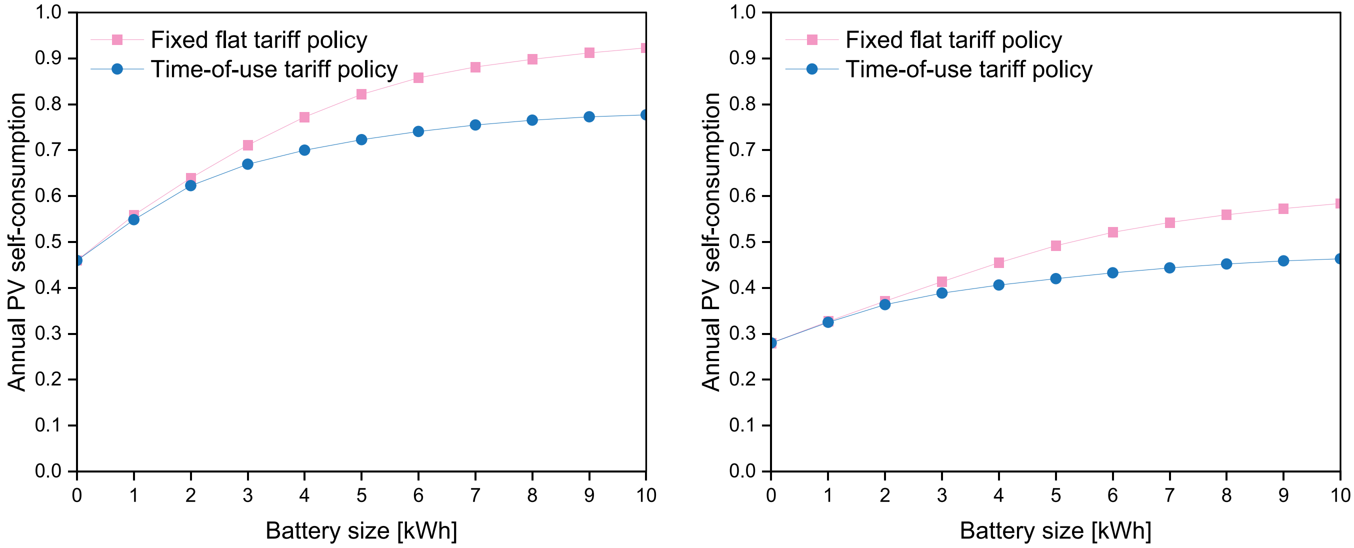
(d) Annual exported energy during shoulder hours

(e) Annual imported energy during off-peak hours

(f) Annual exported energy during off-peak hours

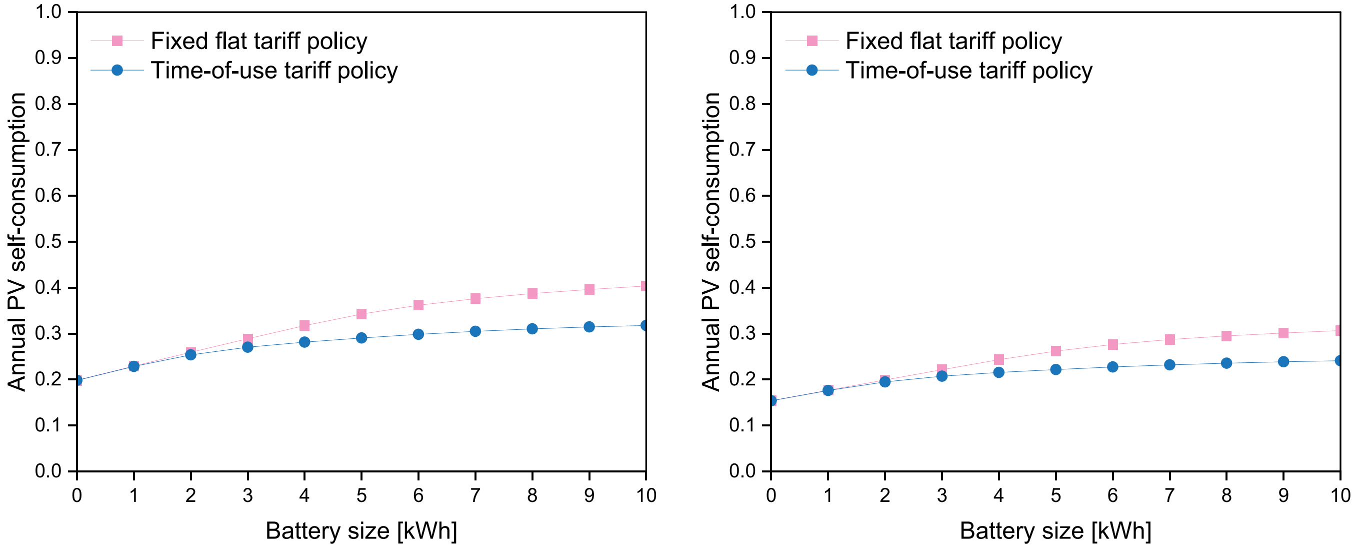
Fig. 7. Annual imported and exported energy as a function of battery size for the two different tariff policies during peak and off-peak hours.

for a house with a 10 kW solar PV system under the two tariff policies. It can be seen from the graphs that increasing the battery size greatly reduced the amount of grid energy consumption. However, the majority of the decline occurred from spring to autumn. Because solar PV generation during winter is constrained by shorter days, lower solar altitudes and higher night-time energy consumption, the home had to purchase energy from the grid to satisfy its demand. This resulted in 0.16 MWh of the 0.2 MW being drawn from the grid between May and August under the fixed flat tariff policy when a 10 kWh battery was used. Additionally, under the time-of-use tariff policy, 0.44 MWh of the



(a) 2.5 kW PV system

(b) 5 kW PV system



(c) 7.5 kW PV system

(d) 10 kW PV system

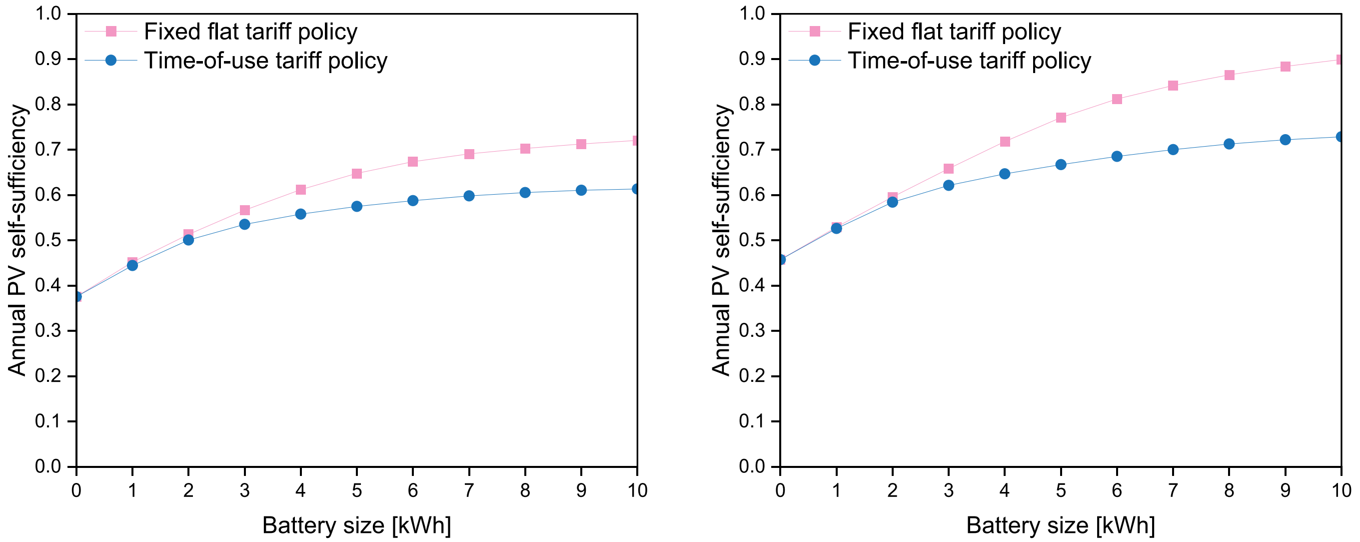
Fig. 8. Annual PV self-consumption as functions of PV and battery sizes for the fixed flat and time-of-use tariff policies.

1.07 MWh of grid energy was drawn between May and August. Here, we find that the annual grid energy consumption of the house under the time-of-use tariff policy was higher than its consumption under the fixed flat tariff policy. This is because the batteries under the fixed tariff policy discharged when there was insufficient PV generation to meet the home's demand. Under the time-of-use tariff policy, grid electricity is more expensive during peak hours (3:00 pm – 9:00 pm) than at other times. For cost-saving reasons, the batteries were only discharged during peak hours when there was not enough PV generation, leading to an increase in grid electricity consumption.

6. Economic performance of using PV battery systems under two tariff policies

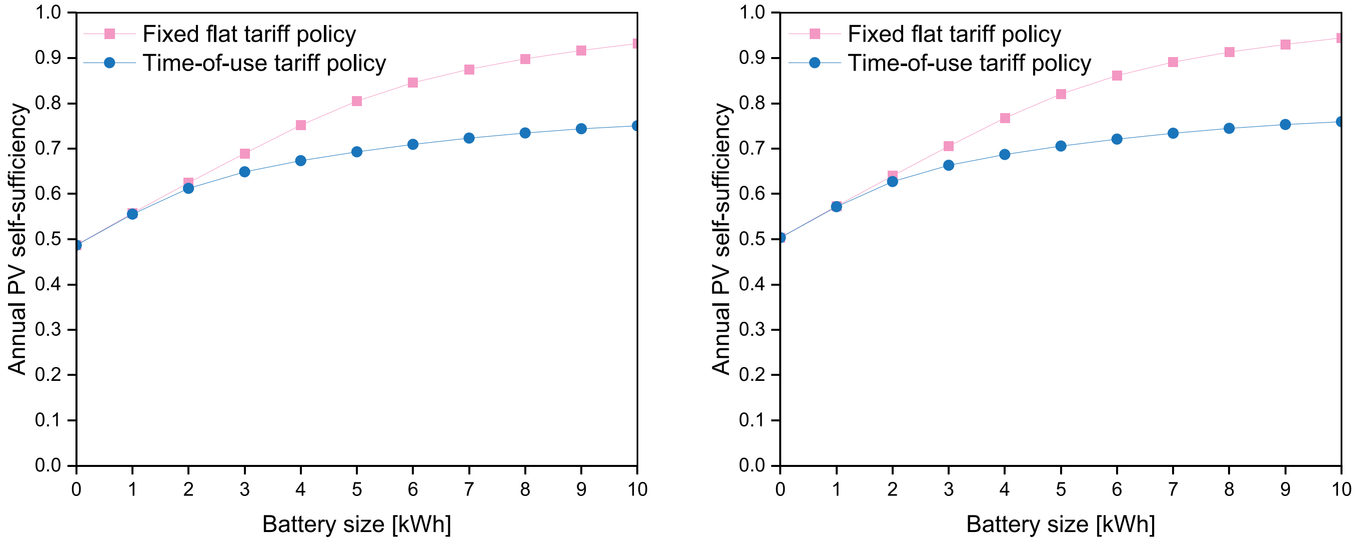
This section investigates the payback period for PV batteries under the fixed flat and time-of-use tariff policies. The payback period for PV batteries is analysed based on several parameters, including the retail price of the grid electricity and its changing rate, FIT and its changing rate, the capital and annual maintenance cost of the batteries, the capital cost of the solar PV system and the annual discount rate. Additionally, it is assumed that the annual electrical load of the house will be constant and equal to the values in 2021. The payback periods for a 10 kW solar PV system with different sizes of batteries under the fixed flat and time-of-use tariff policies are shown in Table 4. As shown in the table, the payback periods for a 10 kW solar PV system without batteries are 17 and 16 years under the two tariff policies, respectively. Furthermore, the payback period for batteries with the 10 kW solar PV system under the fixed flat tariff policy exceeds 20 years. This is greater than the payback periods without the use of batteries and beyond the batteries' maximum expected life. In this situation, the cost of using PV batteries will not be recovered by the end of the batteries' life, showing that there is no reason to utilise batteries under present economic assumptions. In comparison, it can be observed that the payback period for batteries with a capacity of less than 4 kWh with a 10 kW solar PV system under the time-of-use tariff policy is slightly shorter than that for only a 10 kW solar PV system. When the capacity of the battery surpasses 4 kWh, the payback period exceeds 20 years. As a result, the findings of this research do not show the necessity or benefit of employing batteries in solar PV homes under current economic conditions.

Given the comparably substantial capacity of 10 kW solar PV systems, which typically exceeds the capacity of solar PV systems commonly installed in residential buildings, we additionally calculated



(a) 2.5 kW PV system

(b) 5 kW PV system



(c) 7.5 kW PV system

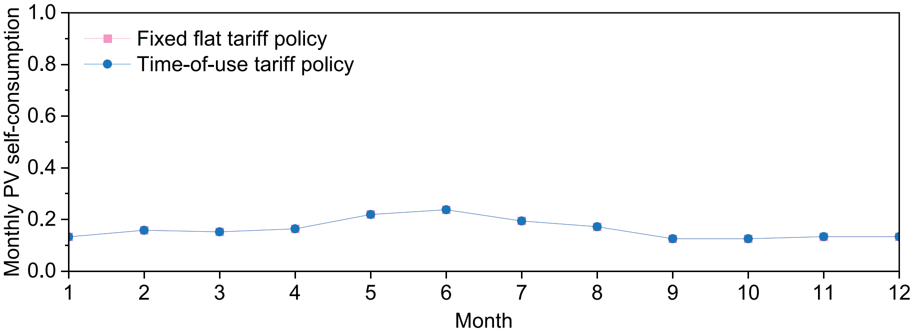
(d) 10 kW PV system

Fig. 9. Annual PV self-sufficiency as functions of PV and battery sizes for the fixed flat and time-of-use tariff policies.

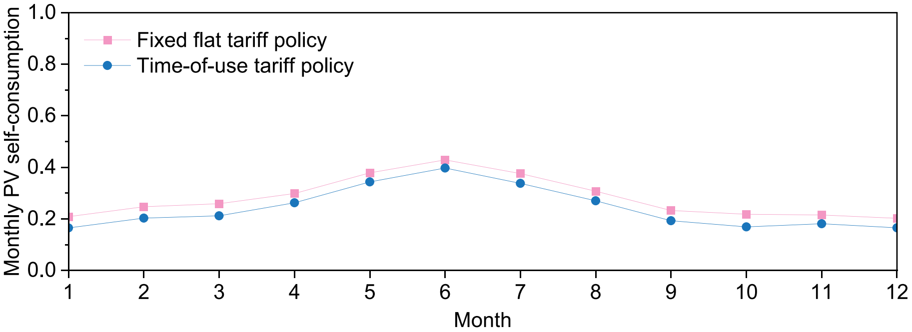
the payback periods for 7.5 kW, 5 kW and 2.5 kW solar PV systems equipped with various battery capacities in the same dwelling and the results are summarised in Tables 5 and 6. This aims to provide users and readers with more specific and tailored recommendations for using batteries in PV homes. The annual energy generation of the 7.5 kW, 5 kW and 2.5 kW solar PV systems was proportionally reduced relative to the energy generation pattern of the 10 kW solar PV system. It can be seen that the payback period for a 7.5 kW solar PV system is 14 and 13 years under the fixed flat tariff policy and the time-of-use tariff policy, respectively. It is interesting to note that the same payback period can be obtained using batteries with a capacity of less than 7 kWh under a fixed price tariff policy. Similarly, under the time-of-use tariff policy the payback period for batteries in combination with a 7.5 kW solar PV system is slightly shorter than in the case of not using batteries. This trend continues until the battery capacity exceeds 3 kWh. With both tariff policies, when the battery capacity exceeds 6 kWh the payback period is longer than without batteries, indicating the non-essentiality of using batteries in solar PV homes.

Table 6 presents comparable outcomes in relation to the payback period for implementing a 5 kW solar PV system alongside different battery capacities under the fixed flat and time-of-use tariff policies. The utilisation of batteries with a capacity below 6 kWh yields a payback period equivalent to that of a standalone solar PV system under the fixed flat tariff policy. Similarly, employing batteries with a capacity over 3 kWh results in a less favourable payback period than with a 5 kW solar PV system operating independently under the time-of-use tariff policy.

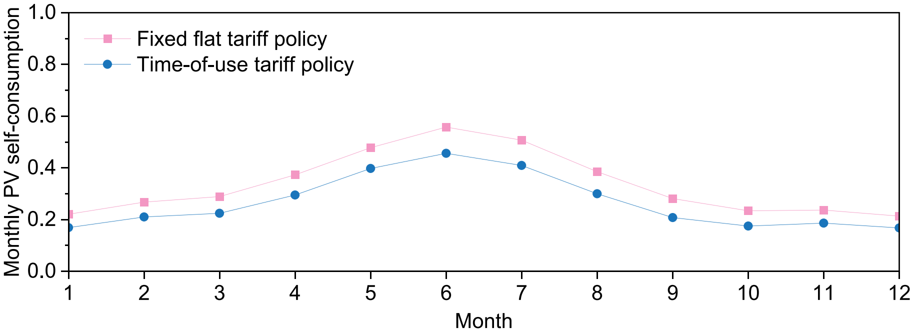
Upon examining the data presented in Tables 4 to 6, a clear correlation emerges between the standalone capacity of the solar PV system and its payback period. Specifically, there is a positive and linear relationship, indicating that as the capacity of the solar PV system decreases, the payback period also decreases. Further examination of the data in the three tables reveals that utilising batteries can give a slightly shorter or even a longer payback period than not using batteries under both tariff policies. The critical reasons for this include the unique energy consumption patterns of the household, the constant changes in grid energy pricing and the FIT, and the relatively high capital and operating costs of PV batteries. For example, under the time-of-use tariff policy and a PV size of 10 kW, the house would consume 1049 kWh of grid electricity during off-peak and shoulder hours, independent of the battery capacity. Although current off-peak and shoulder tariffs (AUD 0.19/kWh and AUD 0.28/kWh, respectively) are lower than the peak tariff (AUD 0.33/kWh), they continue to increase at 5 % annually, the rate



(a) 0 kWh battery



(b) 5 kWh battery



(c) 10 kWh battery

Fig. 10. Monthly PV self-consumption of a 10 kW solar PV system as a function of battery sizes for the fixed flat and time-of-use tariff policies.

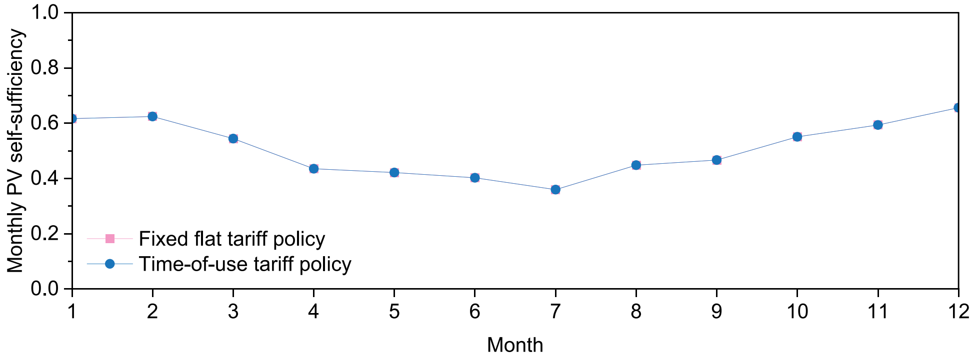
also applied to the fixed tariff policy. However, the present FIT is only AUD 0.052/kWh and declining at 20 % each year. As a result, the difference between the annual revenue from selling excess electricity to the grid and the annual cost of purchasing electricity from the grid decreases yearly.

Based on the findings derived from our technical analysis, the incorporation of batteries within solar PV systems yields a substantial reduction in the household's reliance on grid electricity, irrespective of the tariff policy. As an illustration, incorporating a 5 kWh battery into a 10 kW solar PV system leads to a decrease in annual grid energy consumption of 62 % under the fixed flat tariff policy and 39 % under the time-of-use tariff policy. While the decrease in grid energy consumption resulting from implementing the time-of-use tariff policy is comparatively modest compared to that of the fixed–fixed tariff policy, it is important to note that all reductions are concentrated within peak hours. This targeted reduction in energy demand during peak periods alleviates the strain on the electricity supply to the distribution grid, particularly when extended to the community level. Nevertheless, the results of the economic analysis indicate that the payback period for a 5 kWh battery under both tariff policies is over 20 years when the PV capacity is 10 kW and exceeds the payback period for using PV alone. Consequently, these results indicate that incorporating batteries is not a financially appealing option.

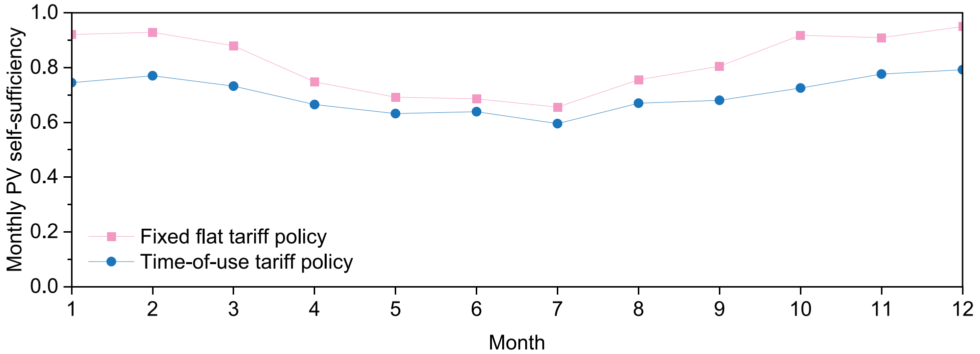
At present, a number of policies have been implemented by the Victorian government to encourage residents to install batteries. For instance, a subsidy of up to AUD 2590 can be requested for the installation of batteries in a residence [26]. Considering the benefits of using PV batteries for both residents and the electricity grid, local government policies should be more proactive and continue until battery technology has matured and the payback period reaches approximately five years. A variety of incentives could be considered, including reducing the annual maintenance cost of batteries and increasing subsidies for battery use for residents willing to install high-capacity batteries.

7. Conclusion

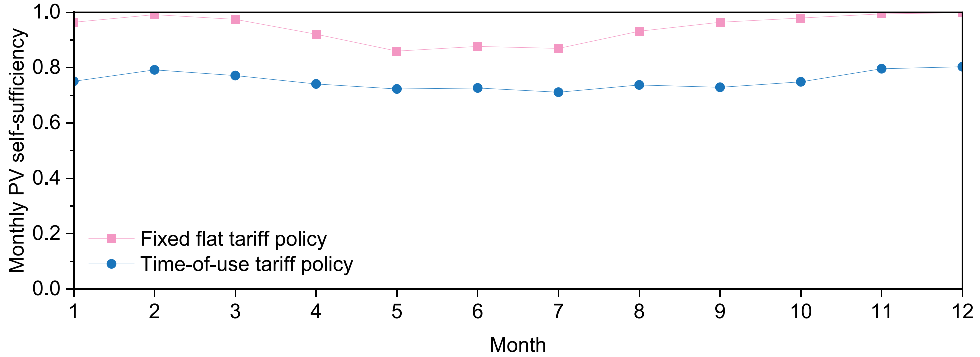
To increase the self-consumption and self-sufficiency of residential solar PV systems and reduce the grid energy imports to homes, two different rule-based control strategies to operate solar PV battery systems under the fixed flat tariff and time-of-use tariff policies are proposed in this paper. The main difference between the two control strategies is that under the time-of-use tariff policy, the batteries are discharged only during peak hours (3:00 pm – 9:00 pm) to meet household demand when the harvested solar energy is insufficient and the household load is met entirely by purchasing power from the grid during off-peak hours (10:00 am – 3:00 pm) and shoulder hours (all



(a) 0 kWh battery



(b) 5 kWh battery



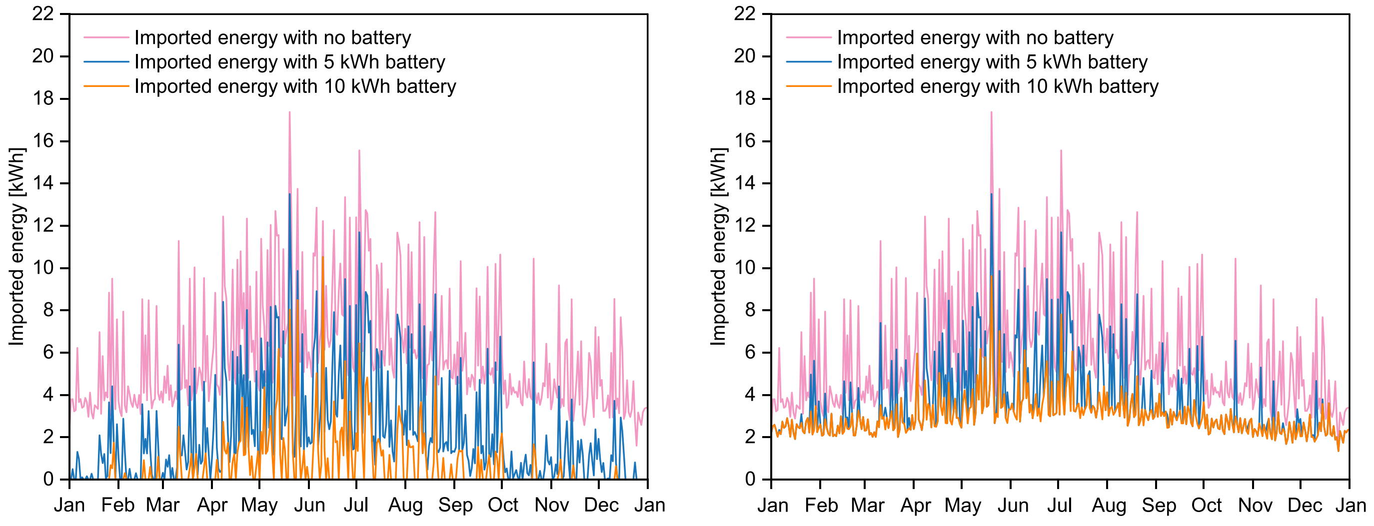
(c) 10 kWh battery

Fig. 11. Monthly PV self-sufficiency of a 10 kW solar PV system as a function of battery sizes for the fixed flat and time-of-use tariff policies.

other times), while under the fixed flat tariff policy, the energy stored in the batteries is consumed at any time when the harvested solar energy is insufficient. Then, the two proposed control strategies are applied to a typical case study house with real measured generation data for a 10 kW rooftop solar PV system and its smart meter data. In addition, an economic model analysing the payback period for PV batteries is presented considering the retail price of grid electricity and its changing rate, the FIT and its changing rate, the capital cost of solar PV systems, the capital and annual maintenance costs of batteries, and the annual discount rate.

It has been discovered that due to the same principle for using battery-stored energy, the annual imported and exported energy are nearly the same under the two tariff policies during peak hours. In addition, as battery capacity grows, differing strategies for using batteries during shoulder and off-peak hours present considerable variation in the annual import and export of electricity under the two tariff policies. Furthermore, when battery capacity is increased, PV self-consumption and self-sufficiency grow under both tariff policies, but the trend is limited by the fact that PV generation is seasonally dependent. Moreover, when battery capacity increases, households' PV self-consumption and self-sufficiency under the fixed flat tariff policy exceed their values under the time-of-use tariff policy.

According to previous definitions, PV self-consumption measures the proportion of total solar PV generation consumed on-site, while PV self-sufficiency measures the percentage of house load met by solar PV generation. Another noteworthy point in this study is that PV self-consumption and self-sufficiency can both be increased by storing excess solar energy in a battery and using it when there is electrical demand. However, the increases in these two parameters are always based on satisfying the existing electrical load of the house, which is assumed to be a constant value in this paper. Therefore, in order to further increase PV self-consumption and self-sufficiency, we can increase the electrical load of the home so that the solar PV generation meets a more significant proportion of its energy demand. Specifically, given the relatively large capacity of the 10 kW solar PV system in the case study house, the building service systems used for heating and domestic hot water can be transitioned from gas-fired equipment to heat pumps with water storage tanks. This increased electrical load of the home enhances the potential to consume more solar PV generated energy and excess solar energy harvested during the day can be stored in batteries as electricity or in water storage tanks as thermal energy,



(a) Fixed flat tariff policy

(b) Time-of-use tariff policy

Fig. 12. Distribution of imported energy for a house with a 10 kW solar PV system and different battery sizes under the fixed flat and time-of-use tariff policies.

Table 4
The payback period for using a 10 kW solar PV system with different sizes of batteries under the fixed flat and the time-of-use tariff policies.

PV size (kW)	Battery size (kWh)	Payback period of PV batteries (year)	
		Fixed flat tariff policy	Time-of-use tariff policy
10	0	17	16
10	1	>20	15
10	2	>20	15
10	3	>20	15
10	4	>20	15
10	5	>20	>20
10	6	>20	>20
10	7	>20	>20
10	8	>20	>20
10	9	>20	>20
10	10	>20	>20

Table 5
The payback period for using a 7.5 kW solar PV system with different sizes of batteries under the fixed flat and the time-of-use tariff policies.

PV size (kW)	Battery size (kWh)	Payback period of PV batteries (year)	
		Fixed flat tariff policy	Time-of-use tariff policy
7.5	0	14	13
7.5	1	14	12
7.5	2	14	12
7.5	3	14	12
7.5	4	14	13
7.5	5	14	13
7.5	6	14	14
7.5	7	15	15
7.5	8	>20	>20
7.5	9	>20	>20
7.5	10	>20	>20

Table 6
The payback period for using a 5 kW solar PV system with different sizes of batteries under the fixed flat and the time-of-use tariff policies.

PV size (kW)	Battery size (kWh)	Payback period of PV batteries (year)	
		Fixed flat tariff policy	Time-of-use tariff policy
5	0	11	10
5	1	11	10
5	2	11	10
5	3	11	10
5	4	11	11
5	5	11	11
5	6	12	11
5	7	12	12
5	8	13	13
5	9	14	14
5	10	15	15

further increasing PV self-consumption and self-sufficiency.

Findings from the economic analysis indicate that the payback period for a standalone solar PV system increases as its capacity grows. Moreover, under both tariff policies using batteries can result in a slightly shorter or even a longer payback period than not using batteries. This is due to the distinct energy consumption patterns of the household, the constant fluctuations of utility energy prices and the FIT, and the relatively high capital and operating costs of PV batteries. Given the current long payback period for PV batteries along with the benefits they can bring to residents and the electricity network, local governments also need to be more proactive in providing financial subsidies for residents to install batteries.

One of the limitations of this work is that the economic and energy performance of solar PV battery systems is only analysed in a single house under a single climatic condition. The proposed rule-based control strategies can be applied worldwide in any residential solar PV battery system as long as data on electric loads and PV generation is available. Therefore, future research could examine the economic and energy performance of using batteries in residential solar PV systems using actual measured PV generation and electrical demand data from multiple houses in different climate zones. Furthermore, this study examines the economic performance of utilising PV batteries solely based on payback period outcomes, so future research could employ additional economic models to assess the economic viability of residential solar PV battery systems.

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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