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Energy Management Systems for Grid-Connected Houses with Solar PV and Battery by Considering Flat and Time-of-Use Electricity Rates

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Abstract: This paper develops new practical rule-based energy management systems (EMSs) for typical grid-connected houses with solar photovoltaic (PV) and battery by considering different rates for purchasing and selling electricity. The EMSs are developed to supply the household's loads and reduce operating costs of the system based on different options of flat and time-of-use (ToU) rates for buying and selling electricity prices. Four different options are evaluated and compared in this study: (1) Flat-Flat, (2) ToU-Flat, (3) Flat-ToU, and (4) ToU-ToU. The operation cost is calculated based on the electricity exchange with the main grid, the equivalent cost of PV generation, as well as the degradation cost of battery storage. The operation of the grid-connected house with rooftop solar PV and battery is evaluated for a sunny week in summer and a cloudy week in winter to investigate the proper performance for high and low generations of PV. While the developed rule-based EMS are generic and can be applied for any case studies, a grid-connected house in Australia is examined. For this purpose, real data of solar radiation, air temperature, electricity consumption, and electricity rates are used. It is found that the ToU-Flat option has the lowest operating cost for the customers.

Keywords: Australia; battery energy storage; electricity cost analysis; flat electricity rate; grid-connected household; home energy management system; rooftop solar PV; time of use tariffs



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1. Introduction

1.1. Background and Motivation

Renewable energies, especially solar energy, have been rapidly developed globally in the past decade. Air pollution reduction and the falling cost of solar photovoltaic (PV) technologies are the main reasons for its high integration in power systems [1,2]. The global average price of a solar PV module has been dropped by 92% between 2000 and 2019 [3]. Rooftop solar PV is the most suitable type of renewable energy source for installation on the premises of residential households [4]. It is estimated that the global capacity of residential solar PV in 2024 will be more than twice of that in 2018 [3].

In addition to the international scope, renewable energy in Australia has received a significant amount of attention. Renewable energy reports show that wind, hydro, and small-scale PV are the top three renewable resources, accounting for 35.4%, 25.7% and 22.3% of energy production in Australia in 2019, respectively [5]. The total annual electricity generation by renewable energy has reached 24% of the electricity consumption in the country [5]. In addition, the installation of small-scale rooftop solar PV in 2019 reached 2.2 GW, which exceeds the previous record of 1.6 GW in 2018 [5].

With such a high penetration of renewable energy resources in the world, several problems have been revealed including variability and intermittency [6,7]. Installing a hybrid grid-connected renewable energy system (RES) with the integration of energy storage systems is an efficient solution to overcome these drawbacks [8,9]. Therefore, a reasonable control of the energy resources and storage system faces new challenges which are of a high complexity. To address this issue, an effective energy management system (EMS) is an essential feature for RES to be of the highest economic benefit for consumers [10].

Currently in South Australia (SA), an area with a high penetration of solar PV, the feed-in-tariff (FiT) is almost three times lower than the retail price (RP) [11]. This reduces the household's revenue when excess solar PV energy is sold to the grid [12]. On the other hand, an RES may not result in an electricity cost reduction if not operated properly [13]. Besides, different electricity tariffs such as flat rates and ToU rates provide a variety of options for consumers, thereby affecting the performance of the installed RES [14,15]. Conventional EMSs are mostly developed based on one specific electricity rate, which lacks a reference value under the current electricity pricing programs. The ToU scheme enables the consumers to reduce electricity bills by appropriately managing energy usage. Hence, the EMSs attract more attention to achieve the best performance with the highest benefits. Increasing the penetration level of solar PV and battery energy storage, as well as different prices for exchange electricity tariffs are the motivations for the researchers to develop new EMSs.

1.2. Literature Review and Research Gaps

A literature review focuses on the design of EMS for economic benefits of grid-connected houses under flat and ToU electricity pricing programs. Yuce, et al. [16] presented a hybrid power management system based on Artificial Neural Networks and Genetic Algorithm. The proposed system maximised the use of the PV and wind turbine, and reduced the energy imported from the grid. However, the storage system was ignored. García, et al. [17] proposed an off-grid hybrid energy system composed of wind turbine, PV, and energy storage system. A fuzzy logic control (FLC) method was chosen for the EMS algorithm. The proposed EMS with FLC ensured a 13% cost reduction and a longer system lifetime. However, the system was stand-alone, which constrained its development based on electricity tariffs.

In [18], a hybrid grid-connected RES containing PV, battery, and supercapacitor was proposed. The proposed scheme changed the modes of RES during different renewable energy and load level. The storage system ensured the reliability of the system, however, ToU rates were not considered in that system. Abushnaf, et al. [19] introduced an EMS to control the residential energy usage with the ToU rates. The results showed that the designed EMS could minimize the user electricity cost. However, the battery degradation cost was not considered. By overlooking the effect of degradation, the simulation may achieve inaccurate results.

Zhang and Tang [20] conducted a study on the optimal scheduling of a grid-connected EMS. The proposed system optimised the energy schedule between solar PV, battery, and the utility grid. The ToU and step tariffs were considered, and a genetic algorithm was employed as the optimisation method. The study showed that the proposed genetic algorithm-based EMS can achieve a decent performance and satisfy the system requirements. However, the battery degradation costs, and the generation costs of the renewable components were overlooked. In [21], the EMS problem of a grid-connected home was formulated as an optimisation problem. The house was integrated with wind turbine, solar PV, and battery. However, the study neglected battery's degradation cost and only considered one electricity tariff.

A grid-connected energy system with PV and battery was proposed in [22] for a case study in Sweden. The study employed the rule-based method to control the energy flow of the system. A genetic algorithm was introduced to optimise the size of the battery.

The results showed that a hybrid renewable energy system was more attractive than a conventional system after price reduction of the battery. The same PV-battery system was examined for residential households in Australia [23,24]. However, battery degradation and ToU rates were not considered in those studies. In [25], a rule-based EMS was evaluated for residential grid-connected homes with PV-battery system in The Netherlands and USA. However, the EMS was so general, and it was based on a net metering scheme. In some studies [26–28], a predictive part has been added in the EMS design to forecast the load consumption of PV generation. Lack of predictiveness is one of the limitations of the current study. However, it should be noted that predictive optimization systems achieve proper results if and only if accurate prediction is available. In real world scenarios, a bad prediction may be very pricey for the quality of the control and overall power usage/cost.

Table 1 lists a summary of drawbacks of the existing studies based on EMS model, equivalent PV cost, battery degradation cost, grid constraint, and electricity tariff. As illustrated in the table, rule-based EMS models are mostly used in the existing studies. The main issue with optimisation-based EMS model is its practicality. The optimization-based models do not provide any information on how the proposed optimized EMS is implemented in practice. The degradation cost of battery was not addressed in most of the existing studies. Only one electricity tariff was evaluated in the existing studies and no comparison was provided for different electricity tariffs. In addition, the grid constraint was rarely addressed.

Table 1. Summary of drawbacks of the existing studies.

Reference	EMS Model	Equivalent PV Cost	Battery Degradation Cost	Grid Constraint	Electricity Tariff	Predictive	Country
[16]	Optimisation	✓	×	×	Flat	×	United Kingdom
[17]	Optimisation	✓	×	×	–	×	Spain
[18]	Rule-based	×	×	✓	Flat	×	India
[19]	Rule-based	×	×	×	ToU	×	Australia
[20]	Optimisation	×	×	×	ToU	×	China
[21]	Optimisation	×	×	×	ToU	×	Turkey
[22]	Rule-based	✓	×	×	ToU	×	Sweden
[23]	Rule-based	×	×	✓	Flat	×	Australia
[24]	Rule-based	✓	×	✓	Flat	×	Australia
[25]	Rule-based	✓	×	×	ToU	×	The Netherlands United States
[26]	Rule-based	✓	×	×	ToU	✓	Southeast Asian Countries
[27]	Optimisation	×	×	×	-	✓	Italy
[28]	Optimisation and Rule-based	×	✓	×	ToU	✓	UK
This study	Rule-based	✓	✓	✓	Flat and ToU	×	Australia

1.3. Contribution

The motivation of this work is to address a timely topic of practicing engineering problem for a real case study. The key contribution of this paper is to develop four new practical rule-based home EMSs for grid-connected households with solar PV and battery by considering different rates for purchasing and selling electricity. To the best of the authors' knowledge, this is the first study that proposes and compares different rule-based EMSs for flat and ToU electricity tariffs. An important feature of the developed rule-based

EMSs is their practicality which means that they can be easily employed for the customers. The EMSs are developed based on different options of flat and ToU (peak, off-peak, and shoulder) electricity rates for buying and selling prices, i.e., RP and FiT. Hence, four different options are investigated in this study: (1) flat-flat, (2) ToU-flat, (3) flat-ToU, and (4) ToU-ToU. These EMSs are used to control the power flow of the system among PV, battery, grid, and load based on the electricity rate of RP and FiT by considering the grid constraint. As a scientific contribution, the proposed EMSs updated the power flow not only based on the PV generation, but also based on the electricity price. The main aim is to reduce the operation cost of electricity for a typical house with optimal capacities of PV and BESS. The operation cost is calculated based on the cost of electricity exchange within grid, the equivalent cost of PV generation, and the cost of battery degradation. The operation of the grid-connected house with rooftop PV and battery is evaluated for a sunny week in summer and a cloudy week in winter. The operation analysis involves the power operation and cost calculation. The developed rule-based EMSs are generic and can be applied for any case study. A grid-connected house in South Australia is considered to examine the proposed EMSs of this study. For this purpose, real data of solar radiation, air temperature, and electricity consumption are used for a week in summer and a week in winter. The electricity rates and components prices are selected according to the current market prices in South Australia.

2. Energy Management Systems

The EMSs are designed for a typical grid-connected house with rooftop solar PV and battery energy storage. Figure 1 demonstrates the system configuration of the grid-connected home with the EMS. It is assumed that rooftop solar PV and battery storage are installed in the premises of the household. The generated power of the PV can be used for load supply, battery charging, and selling electricity to the grid. The installed battery can only be charged by the solar PV. Hence, there is a power connection between the installed PV and the battery. The solar PV can charge the battery, if required, with this connection. As illustrated, the EMS receives the signals from the load consumption, PV generation, available charge/discharge energy of battery, and the electricity price. Then, the EMS controls the power flow between the components. The capacities of PV and battery are selected based on our previous study for optimal sizing of a typical grid-connected house [23].

In this study, rule-based EMSs are developed due to practicality, simplicity, user-friendliness, low computational requirement, and ease of implementation in practice. In these methods, all considered rules are explicit for the customers and designers. It is notable that the rules are designed based on the experiences of the expert on the operation of the solar PV and battery systems. This is another feature of rule-based EMSs that give the designer sufficient flexibility to update the rules.

In this study, different EMSs are developed for four options based on electricity prices for buying and selling. Table 2 shows these four different options in terms of electricity buying and selling tariffs.

Table 3 presents the rates and periods for the Flat and ToU electricity price data of the case study in South Australia. The flat rate of electricity selling is almost one third of the electricity buying [23]. The ToU rate is changed based on three periods of the day: off-peak, shoulder, and peak periods [4]. The peak period is between 6 pm and 11 pm, the off-peak period starts from 11 pm to 8 am, and the shoulder period starts from 8 am to 6 pm. Table 3 lists the electricity buying and selling prices under flat and ToU rates.

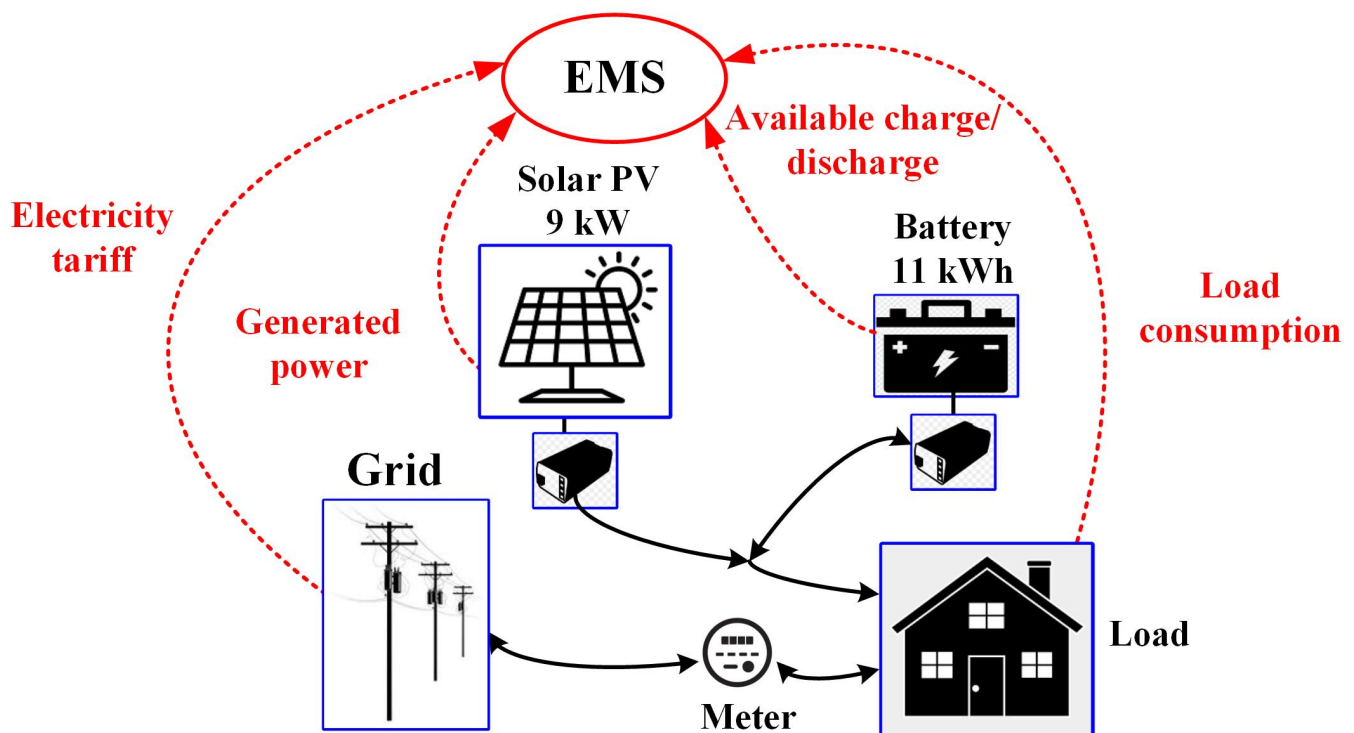


Figure 1. System configuration of the grid-connected home with PV-battery and the EMS.

Table 2. The four options based on electricity tariffs for electricity buying and selling.

	Flat Rate Buying	ToU Rates Buying
Flat rate selling	Option 1 (Flat-Flat)	Option 2 (ToU-Flat)
ToU rates selling	Option 3 (Flat-ToU)	Option 4 (ToU-ToU)

Table 3. Electricity rates for the case study in South Australia to validate the proposed EMSs [4,23].

Electricity Exchange	Buying (¢/kWh)	Selling (¢/kWh)	Period (hr)	Reference
Flat rates	48.00	17.00	All day hours	[23]
ToU rates during Peak	58.01	18.00	6 pm to 11 pm	[4]
ToU rates during Shoulder	39.93	10.00	8 am to 6 pm	
ToU rates during Off-Peak	25.41	5.00	11 pm to 8 am	

2.1. Option 1: Flat-Flat

The flow chart of the developed rule-based EMS for this option is demonstrated in Figure 2. The inputs of the EMS are the PV generation, load consumption, and grid constraint. In this option, the buying and selling electricity are both flat rates which means the electricity price remains constant all the time.

When renewable energy exceeds the household load, the extra power charges the battery storage by considering the input power limit. This can be expressed as:

$$P_b^{cha}(t) = \min(P_b^{in}(t), P_r(t) - P_d(t)) \quad (1)$$

where P_b^{cha} represents the charged power of battery, P_r is renewable power delivered by PV, and P_d is the household load. The input power limit of battery (P_b^{in}) is formulated as follows:

$$P_b^{in}(t) = \min(P_b, (E_b / \Delta t) \cdot (SOC_{max} - SOC(t))) \quad (2)$$

where P_b and E_b are the available power and energy rating of the battery storage. State of charge (SOC) of battery is limited during the charging interval by the maximum limit (SOC_{max}).

The SOC of battery at charging time interval (Δt) is calculated as follows:

$$SOC(t + \Delta t) = SOC(t) + \frac{P_b^{cha}(t) \cdot \eta_{ch}}{E_b / \Delta t} \quad (3)$$

where η_{ch} is the charging efficiency of battery.

Any extra power of PV after charging the battery will be exported to the grid by considering the grid constraint for the maximum export power. Hence, the exported power is formulated as follows:

$$P_g^{ex}(t) = \min(P_r(t) - P_d(t) - P_b^{in}(t), P_{grid}^{max}) \quad (4)$$

where P_g^{ex} is the exported power from the household to grid and P_{grid}^{max} stands for the maximum power that the grid can accept from the household.

If the generated power of solar PV exceeds the load, charging of battery, and export power limit of the grid, then the extra power is dumped by the control system of the inverter:

$$P_{dump}(t) = P_r(t) - P_d(t) - P_b^{in}(t) - P_{grid}^{max} \quad (5)$$

When PV generation cannot supply the household load, the energy deficiency is supplied by the battery and grid. If there is enough energy in the battery to fully supply the load, then the battery is discharged by considering its output power limit:

$$P_b^{dis}(t) = \min(P_b^{out}(t), P_d(t) - P_r(t)) \quad (6)$$

where P_b^{dis} is the discharged power of battery.

The output power limit of battery (P_b^{out}) is formulated as follows:

$$P_b^{out}(t) = \min(P_b, (E_b / \Delta t) \cdot (SOC(t) - SOC_{min})) \quad (7)$$

where SOC_{min} is the minimum SOC of the battery in the operation.

The SOC of battery at discharging time interval (Δt) is calculated as follows:

$$SOC(t + \Delta t) = SOC(t) - \frac{P_b^{dis}(t) \cdot \eta_{dis}}{E_b / \Delta t} \quad (8)$$

where η_{dis} is the discharging efficiency of battery.

If battery and PV could not supply the household load completely, then the power deficiency is purchased (i.e., imported from the grid):

$$P_g^{im}(t) = P_d(t) - P_r(t) - P_b^{out}(t) \quad (9)$$

where P_g^{im} is the imported power from the grid.

2.2. Option 2: ToU-Flat

For option 2, the electricity selling price is fixed; however, the electricity purchasing price is based on ToU rates. Therefore, the EMS retains the selling method used in option 1 and it only changes the purchase method. During the peak period of ToU, the purchased electricity price of the grid is very high, so that the energy in the battery should be consumed when PV energy is insufficient. Therefore, the electricity supply priority of battery and grid during the peak period is for the battery storage. The flow chart is the same as Figure 2.

The flow chart of the developed rule-based EMS during shoulder and off-peak periods of option 2 is demonstrated in Figure 3. It may be mentioned that the power flow equations

are only stated for option 1 to avoid repetition in this paper. During the shoulder (8 am to 6 pm) and off-peak (11 pm to 8 am) periods, the purchase electricity price of the grid is relatively low, so the insufficient energy of the household should be firstly supplied by the grid. Therefore, the electricity supply priority of battery and grid during shoulder and off-peak periods is for purchasing from the grid. Two benefits can be noted for the developed EMS for this option: (i) the electricity is purchased from the grid with lower price during shoulder and off-peak, and (ii) the energy is saved in the battery for the upcoming peak period.

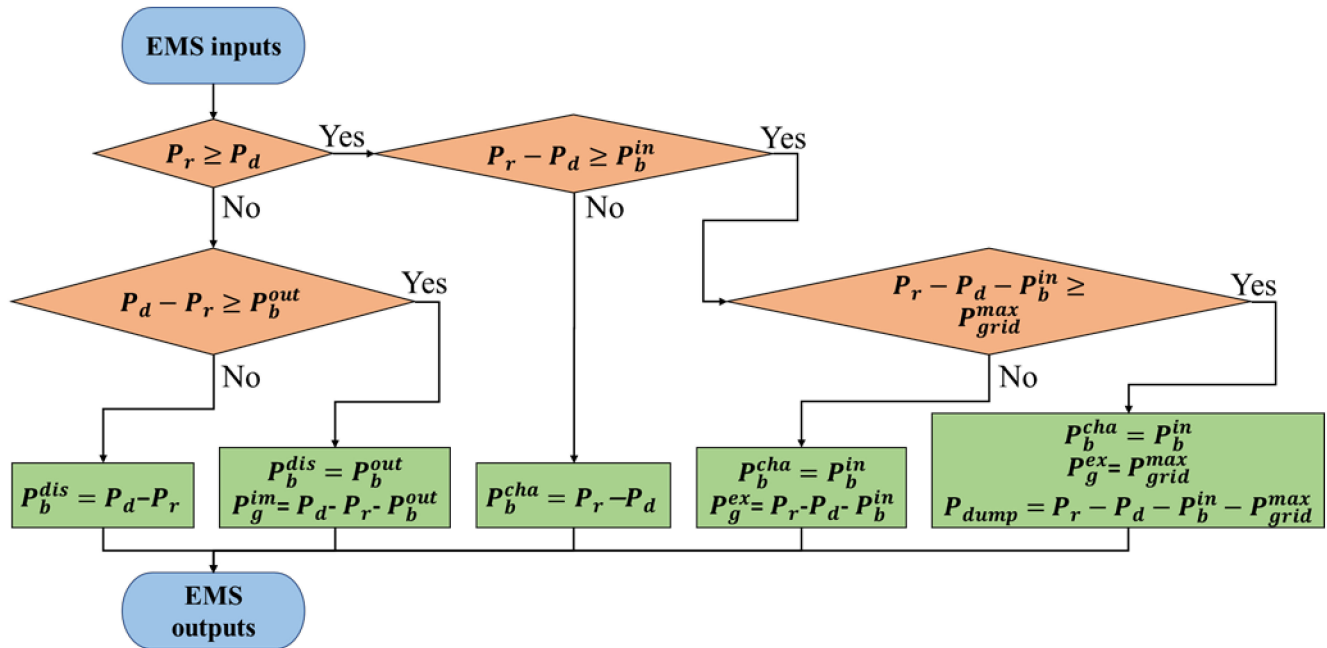


Figure 2. Rule-based flow chart of EMS under Flat-Flat rates.

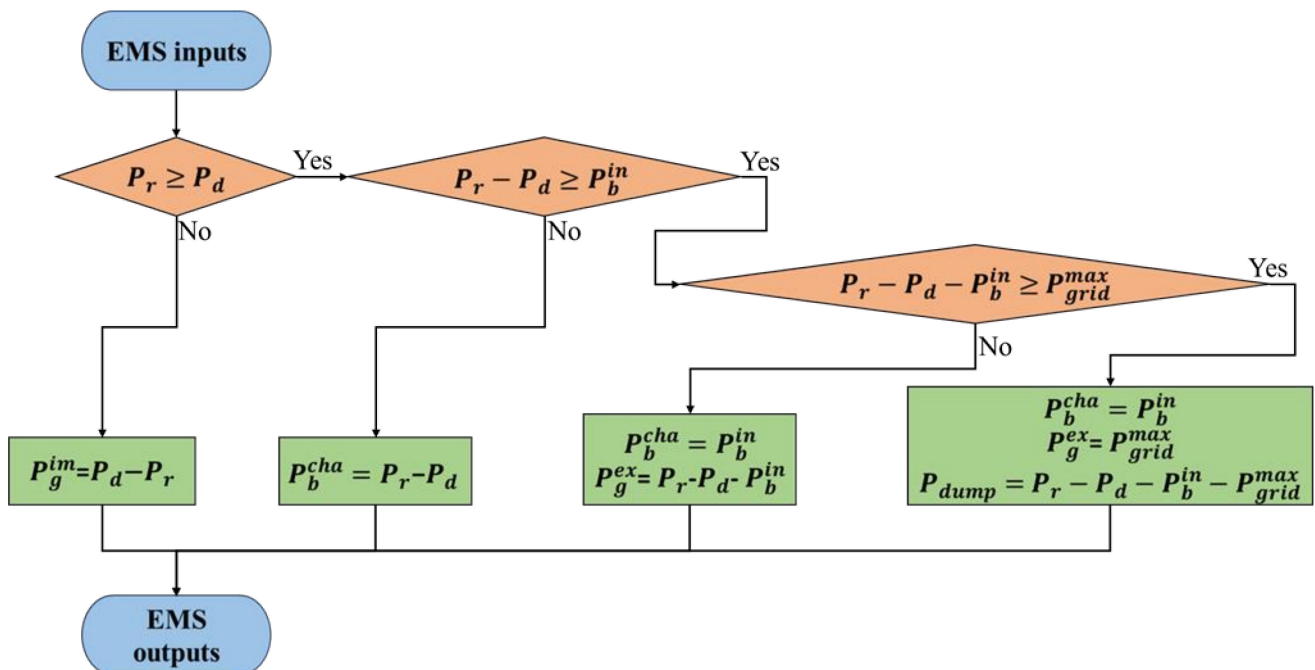


Figure 3. Rule-based flow chart of EMS under ToU-Flat rates during shoulder and off-peak periods.

2.3. Option 3: Flat-ToU

For option 3, the purchase price is fixed; however, the electricity selling price is based on ToU rates. Therefore, the rule-based EMS retains the purchase method used in option 1 and only changes the selling method. During the peak period, the FiT is higher than other periods, so the surplus power of solar PV should firstly be exported to the grid. The flow chart of the developed rule-based EMS during the peak period for this option is demonstrated in Figure 4.

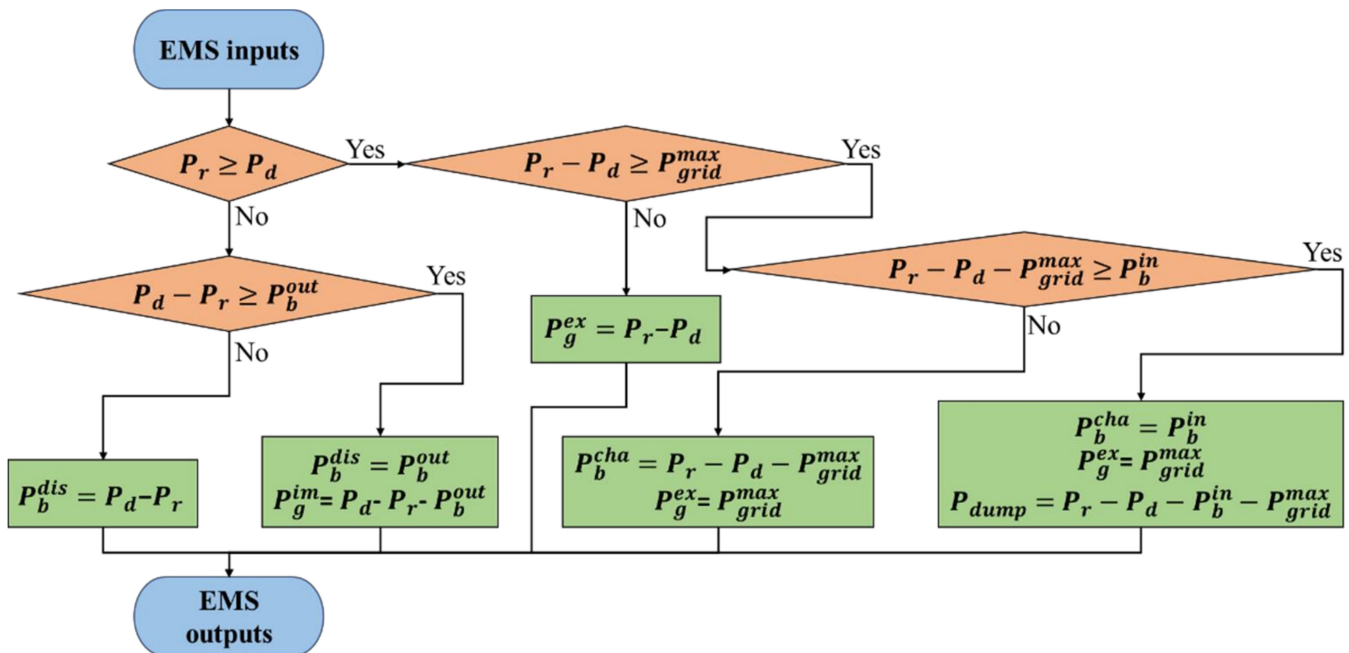


Figure 4. Rule-based flow chart of EMS under Flat-ToU rates during the peak period.

During the off-peak period, the selling price is low, so that the household would prefer to store energy in the battery. During the shoulder, storing energy in the battery can reduce the energy purchased from the grid in the upcoming peak hours. Hence, the flow chart for shoulder and off-Peak is the same as Figure 3.

2.4. Option 4: ToU-ToU

For option 4, both purchase and selling prices are based on ToU rates. During the peak period, the purchase and selling prices are relatively high. Hence, the household should increase electricity selling to the grid and reduce electricity purchase from the grid. This method is similar to that used in the peak period of option 3, and the flow chart for the EMS in option 4 during the peak period is the same as Figure 4. During the off-peak period, the purchase and selling prices are relatively low. Therefore, the household should reduce electricity selling to the grid and increase electricity purchase from the grid. This method is similar to that of the off-peak period of the option 2, and the flow chart for the EMS in option 4 during the off-peak period is the same as Figure 3. During the shoulder period, the extra energy in the PV can be stored in the battery for the upcoming peak period. The other parts remain normal as the flat-flat method. Therefore, the flow chart of the shoulder period for option 4 is the same as Figure 2.

In summary, there is only one flow chart used in option 1 (Flat-Flat). Option 2 (ToU-Flat) and option 3 (Flat-ToU) include two flow charts for the rule-based EMS. In option 4 (ToU-ToU), there are three flow charts used for peak, off-peak, and shoulder periods of the developed rule-based EMS.

3. System Cost Model

In this section, the system cost model is explained for the developed EMSs. It is notable that the nine-step cost-benefit analysis is generally used for the long-term projects where the net present cost of the project should be calculated based on the discount rate. The authors have done this analysis for optimal sizing of solar PV and BES in a 20-year project lifespan for the same case study [4,23]. However, in this work, the main focus is on energy management of the household in which the operation cost is calculated only for one week (168 h).

The total operation cost of the EMS can be calculated based on the costs of PV generation, battery degradation, as well as the electricity trading cost with the grid.

$$Cost_t = C_{pv} \cdot E_{pv} + C_b \cdot E_b^{ch/dis} + \sum_{t=1}^T (C_g^{im} \cdot E_g^{im} - C_g^{ex} \cdot E_g^{ex}) \quad (10)$$

Here, $Cost_t$ is the total operation cost. C_{pv} , C_b , and C_g are the equivalent costs of PV, battery, and grid, respectively. The superscripts *im* and *ex* indicate the import and export of the variables. E_{pv} , $E_b^{ch/dis}$, and E_g are the corresponding energy of PV generation, battery charging/discharging, and grid, respectively. T is the total hours of the simulation.

The imported or exported energies are calculated based on the trading power. In the simulation, the data is processed in each hour, therefore one power results in one energy. The energy transferred by each component is calculated as:

$$E_{pv} = \sum_{t=1}^T P_r(t) \quad (11)$$

$$E_b^{ch/dis} = \sum_{t=1}^T (P_b^{cha}(t) + P_b^{dis}(t)) \quad (12)$$

where $P_r(t)$ is the generated power by the solar PV at time t . In addition, $P_b^{cha}(t)$ and $P_b^{dis}(t)$ are the charging and discharging power of battery at time t .

The equivalent cost of PV production can be expressed by:

$$C_{pv} = \frac{C_{pv}^{cap} / PVF}{P_{pv} \cdot E_{pv}^{annual}} \quad (13)$$

where E_{pv}^{annual} is the annual generated energy by 1-kW PV. P_{pv} and C_{pv}^{cap} are the rating power and capital cost of the installed solar PV system, respectively.

The equivalent cost of the PV is obtained by its capital cost in the first year. Hence, PVF which is the present value function is used. PVF is calculated based on the discount rate (i) and component lifetime (n) as follows:

$$PVF = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \quad (14)$$

The degradation cost of battery can be calculated by [29]:

$$C_b = \frac{C_b^{cap} + C_b^m}{Q_b \cdot E_b^{lifetime}} \quad (15)$$

where C_b^m is the maintenance cost of battery, C_b^{cap} is the capital cost of battery, and $E_b^{lifetime}$ is the deliverable energy of 1-kWh battery during its lifetime, and Q_b is the capacity of the installed battery.

4. Case Study

The developed rule-based EMSs are generic and can be applied for any case study. In this paper, a grid-connected house in SA is selected as the case study. It is assumed that the household is already equipped with rooftop solar PV and battery storage. The meteorological data required for solar PV, load data of the household, electricity prices, and components parameters and economic data of the system are explained in this section.

4.1. Meteorological Data

The weekly meteorological data of the location of the case study is obtained from the Australian Government Bureau of Meteorology [30]. Figure 5 demonstrates the temperature and insolation for a week in summer and a week in winter. The ambient temperature in SA varies significantly between summer and winter. The averages of temperature in summer and winter are 34.3 °C and 13.5 °C, respectively. In terms of solar insolation, more insolation can be obtained in summer compared to winter. The peaks of solar insolation for summer and winter are 1.03 kWh/m² and 0.58 kWh/m², respectively.

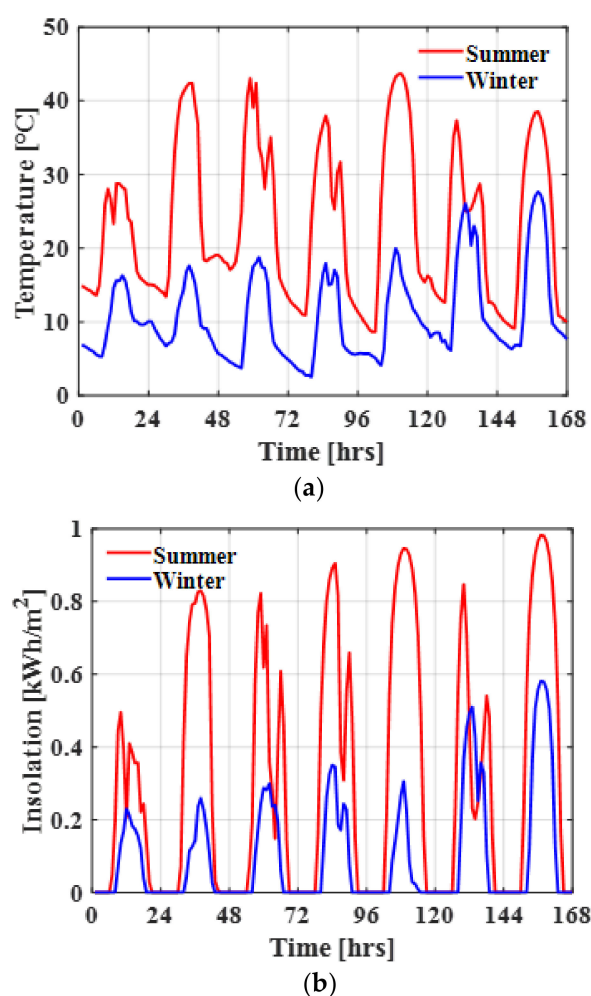


Figure 5. Meteorological data for two sample weeks in summer and winter in urban area South Australia (34.56 S, 138.32 E). (a) Ambient temperature. (b) Solar insolation [23].

4.2. Household Load Data

The weekly load consumption of the grid-connected household in SA is shown in Figure 6 [23]. The average load consumption during summer and winter is 0.788 kW and 0.796 kW, respectively. And the peak load of winter in this case study is 1.44 kW, which is about 0.4 kW higher than that of summer [31].

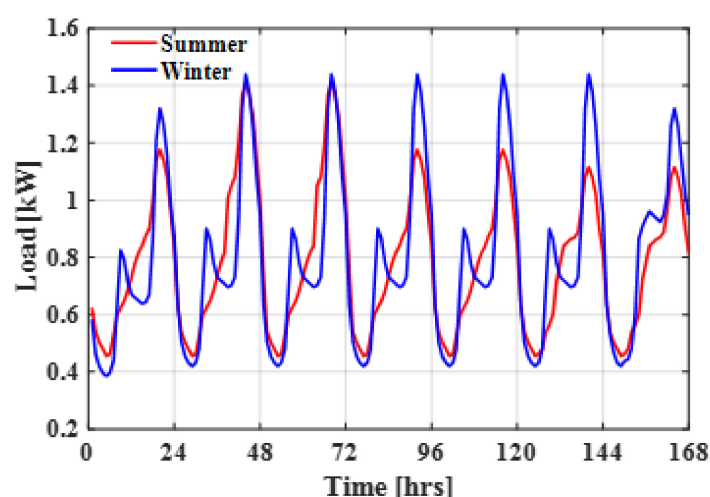


Figure 6. Load profile of a typical house in SA for a week in summer and a week in winter.

4.3. Parameters and Economic Data of Components

Table 4 lists the parameters and economic data of solar PV and battery storage. All the economic values are in the Australian dollar. The economic data of solar PV is taken from [32]. The capacity of solar PV and battery is selected based on the optimal configuration of a PV-Battery system following the actual data of SA. In [23], optimal sizing of solar PV and battery storage was developed for a typical grid-connected household in South Australia. It was found that a grid-connected household can achieve the lowest electricity cost with a 9 kW solar PV and 11 kWh battery system. Hence, in this study, the capacities of PV and battery are selected as 9 kW and 11 kWh for the economic analysis of the rule-based EMSs. The total deliverable energy of 1-kWh battery during its lifetime is considered as 6200 kWh.

Table 4. Parameters of the proposed EMS.

Parameters	Value	Parameters	Value
PV power	9 kW [23]	Battery power	5 kW [23]
PV lifetime	25 years [23]	Battery energy	11 kWh [23]
PV capital cost	\$9000 [32]	Battery lifetime	10 years [29]
PV system efficiency	86%	Battery maintenance cost	\$60/year [23]
Battery SOC minimum	10%	Battery efficiency	91% [29]
Battery SOC maximum	90%	Battery capital cost	\$350/kWh [23]

It may be noted that according to South Australian Power Network policies, the single-phase customers cannot export more than 5 kW to the grid at any time [33].

5. Results and Discussions

This section presents the economic and operational results of the proposed rule-based EMSs for each option of the case study.

5.1. Weekly Power Flow

The simulation results of power flow during a week in summer and winter are investigated to examine the proper operation of the system based on the proposed EMSs.

5.1.1. Power Flow in Option 1 (Flat-Flat)

Figure 7 shows the weekly power flow of the house with the rule-based EMS under Flat-Flat rates for a week in summer and winter. According to Table 3, the electricity buying and selling prices are fixed at 0.48 AUD/kWh and 0.17 AUD/kWh, respectively. The solar PV output generation in summer is much higher than that of winter. The peak output power of the 9-kW solar PV panel in summer and winter is 7 kW and 4.34 kW, respectively.

In terms of the household load, electricity consumption in winter has increased slightly compared to summer. The total electricity consumption in the considered weeks of summer and winter is 132.31 kWh and 133.76 kWh, respectively. It may be mentioned that the last two days of the week demonstrate the weekend in the profile. The green line indicates the battery power where a positive value means the battery is charged, and a negative value means the battery is discharged. Regarding the grid power, the total purchased and sold electricity from/to the grid in summer are 7.82 kWh and 229.97 kWh, respectively. The corresponding values in winter are 44.20 kWh and 23.15 kWh, respectively, which show that higher electricity should be purchased from the grid. In contrary, the household sells more electricity to the grid in summer week. The sold electricity to the grid does not exceed 5 kW at any time which shows that the grid constraint is properly satisfied by the rule-based EMS.

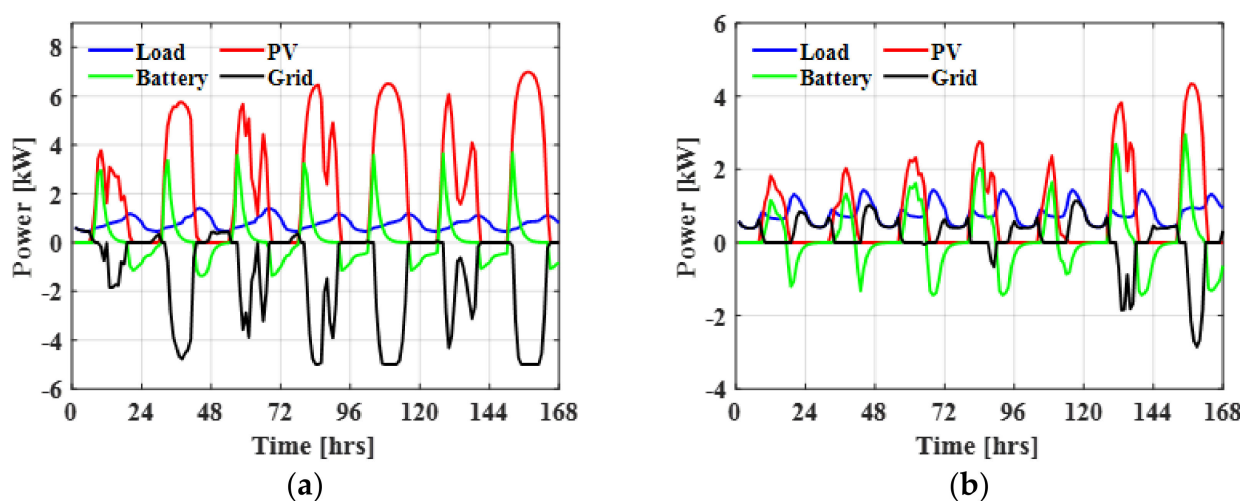


Figure 7. Weekly power flow of the household under Flat-Flat rates: (a) Summer week, and (b) Winter week.

5.1.2. Power Flow in Option 2 (ToU-Flat)

Figure 8 illustrates the weekly power flow of the household with the rule-based EMS under ToU-Flat rates for a week in summer and winter. The profiles of load consumption and PV generation remain the same, and the battery charging/discharging as well as grid exchange are changed according to the different power flow. Compared to the Flat-Flat, this operation option enables the EMS to stop buying electricity from the grid when the electricity price is relatively high at peak time. The battery is discharged during the peak period (from 6 pm to 9 pm) compared to Flat-Flat option. In summer, the purchased electricity from the grid is 34.97 kWh, and the sold electricity to the grid is 260.76 kWh. In winter, the purchased and sold electricity of the grid are 49.51 kWh and 28.10 kWh, respectively. It can be noted that the exchanged electricity between the grid is increased for both seasons compared to Flat-Flat option. The reason can be explained by the fact that no electricity is purchased from the grid during the peak period, so the energy of the battery is consumed in advance. Therefore, in the following off-peak periods, the energy purchased from the grid is increased due to the drop in electricity purchase price and the insufficient energy storage of the battery.

Figure 9 shows another analysis for one day (24 h) power flow and electricity rates variations for the grid-connected house under Flat-ToU rates in summer and winter.

As shown, when the electricity buying is at peak time, the battery storage discharges to supply the load. In winter, the amount of battery discharging is not enough during the peak time to supply the load and hence the remaining electricity is purchased from the grid.

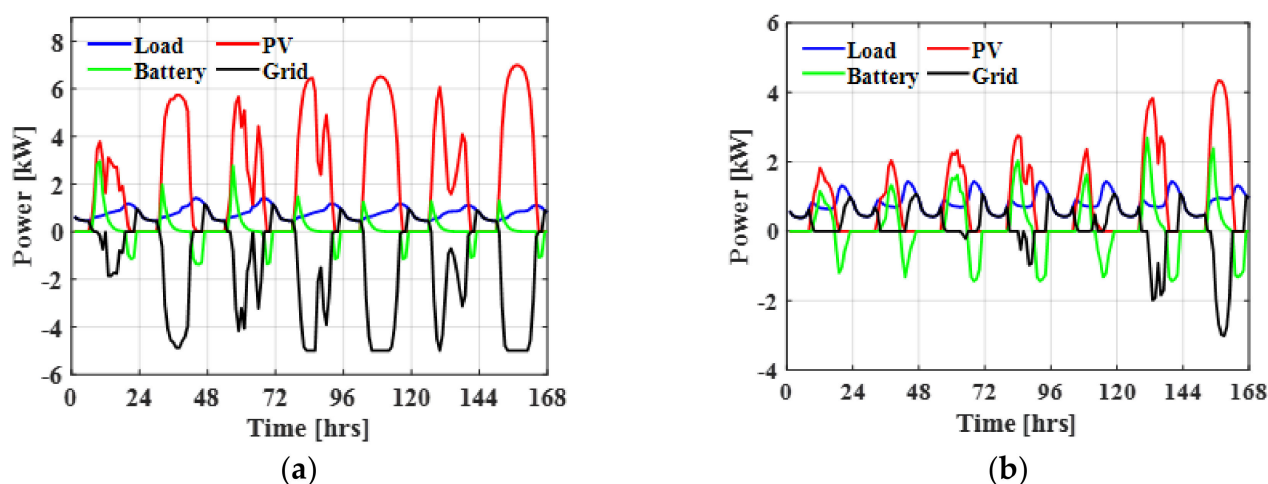


Figure 8. Weekly power flow of the household under ToU-Flat rates: (a) Summer week, and (b) Winter week.

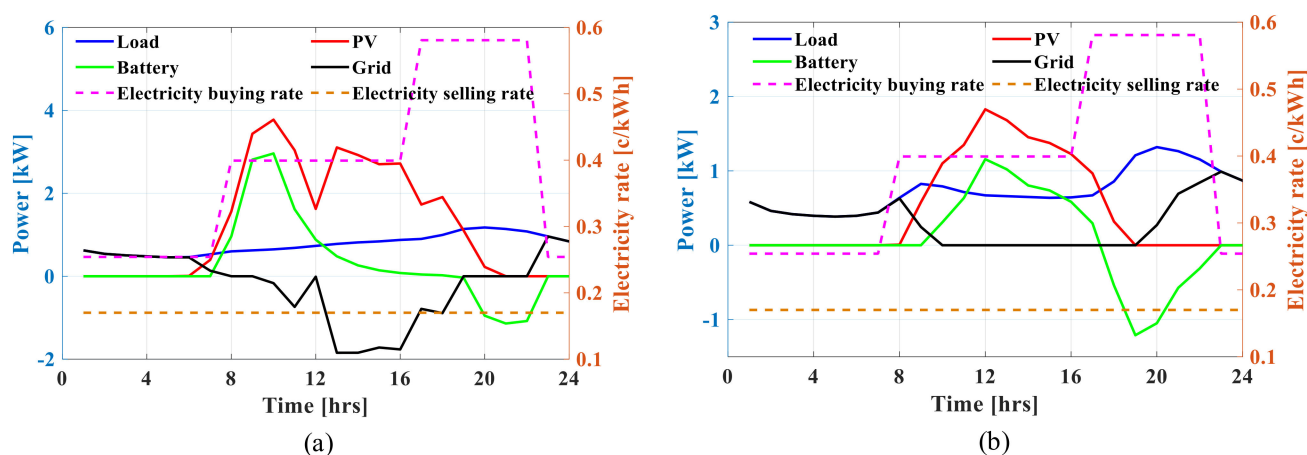


Figure 9. One day power flow and electricity rates under Flat-ToU rates: (a) Summer week, and (b) Winter week.

5.1.3. Power Flow in Option 3 (Flat-ToU)

Figure 10 shows the weekly power flow of the household with the rule-based EMS under Flat-ToU rates for a week in summer and winter. Unlike Figure 8, the purchase price is fixed at 0.48 AUD/kWh and the selling price varies in different periods. In this option, the rule-based EMS sells excess renewable energy generation to the grid during peak periods, while it stores the excess renewable energy in the battery for off-peak and shoulder periods. A clear difference can be noticed during the peak period in winter between Figures 8 and 10. However, there is no significant difference between those in summer.

5.1.4. Power Flow in Option 4 (ToU-ToU)

Figure 11 indicates the weekly power flow of the household with the rule-based EMS under ToU-ToU rates for a week in summer and winter. In this option, both the purchase and sale prices vary according to Table 3 over time. During peak periods, the developed rule-based EMS would prefer to discharge the battery and sell the remaining PV power to the grid. Similarly, the EMS would prefer to use the utility grid to supply the load and store the available power in the battery during off-peak period. According to Figure 11, the battery is discharged during peak hours, so the green line coincides with the x-axis in the early morning. The electricity sold to the grid has a significant rise during the peak period.

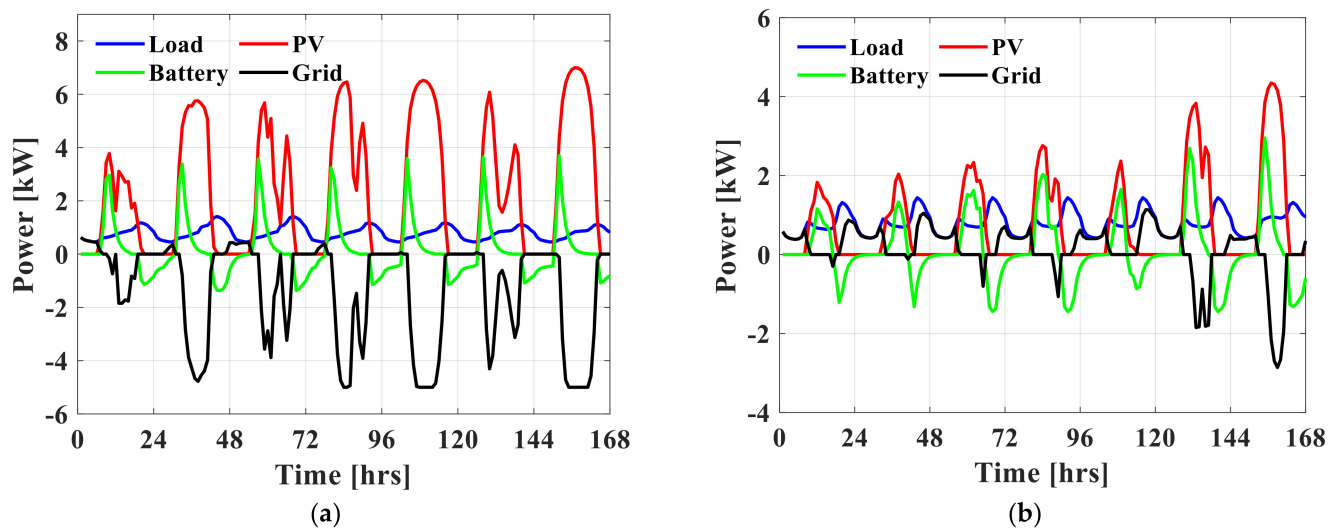


Figure 10. Weekly power flow of the household under Flat-ToU rates: (a) Summer week, and (b) Winter week.

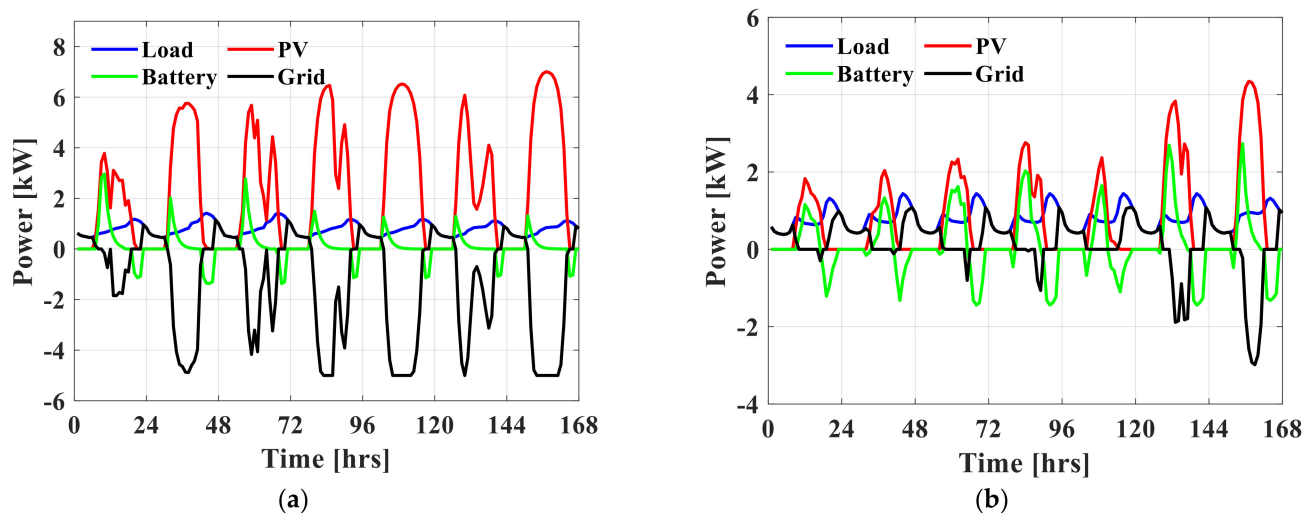


Figure 11. Weekly power flow of the household under ToU-ToU rates: (a) Summer week, and (b) Winter week.

5.2. Electricity Cost Variations

The electricity cost variation of the proposed rule-based EMSs is investigated in this section. According to the previous section, the power flow between different components was obtained, and hence the household electricity cost can be calculated according to the cost model section for each component.

5.2.1. Electricity Cost in Option 1 (Flat-Flat)

Figure 12 demonstrates the electricity cost variations under Flat-Flat rates for both seasons. The positive value means the expenditure (household payment) and the negative value mean the income (household's income by selling electricity) of the household. For both summer and winter, the cost reduces when the solar PV system generates power, which is shown in the figure as a sharp curve at noon. The majority of the cost is negative in summer, which suggests that the householder can earn money from the system. The hourly cost of the household ranges from -0.62 AUD to 0.39 AUD in summer and the average cost of the system is -0.8 AUD per hour. In winter, the cost has increased substantially due to the insufficiency of solar insolation. There are still three days in a week to earn profits when solar radiation is adequate. The electricity cost in winter varies between -0.31 AUD and 0.56 AUD, with an average cost of 0.17 AUD per hour.

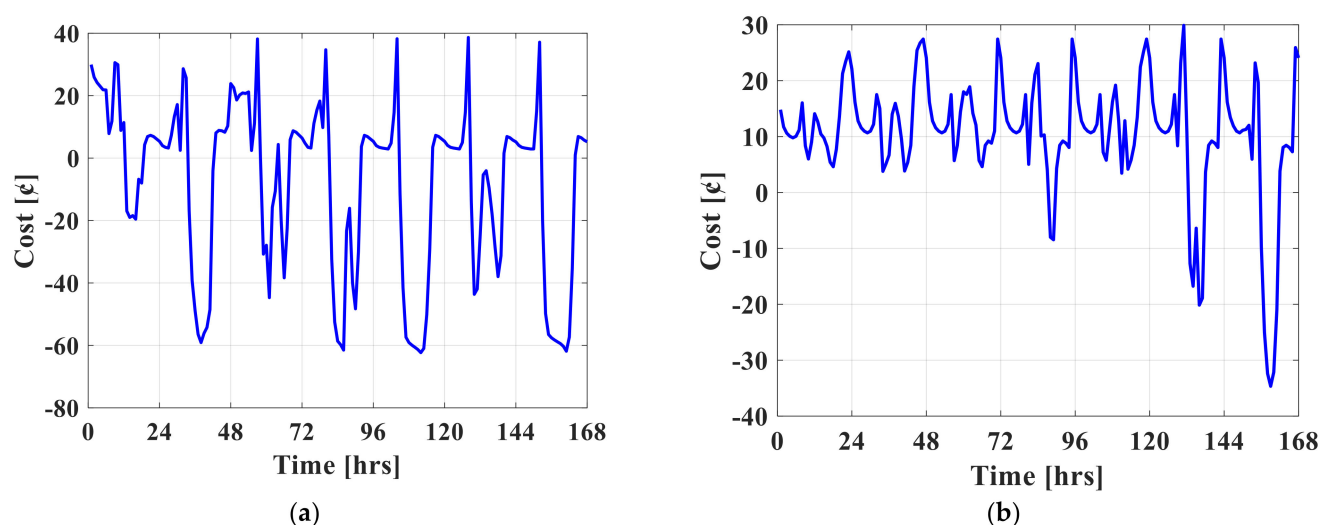


Figure 12. Electricity cost variations under Flat-Flat rates for one week in: (a) Summer, and (b) Winter.

5.2.2. Electricity Cost in Option 2 (ToU-Flat)

Figure 13 indicates the electricity cost variations under ToU-Flat rates for both seasons. Similar to the previous results, the economic income in summer is significantly higher than that of winter. In summer, the electricity cost varies between -0.63 AUD and 0.31 AUD with an average cost of -0.11 AUD per hour. The maximum and minimum costs in winter are 0.0 AUD and -0.35 AUD, respectively. The average cost is obtained as positive 0.11 AUD per hour in winter. In addition, the maximum expenditure in this option is reduced compared to that of option 1, especially in summer where the peak cost is 0.30 AUD.

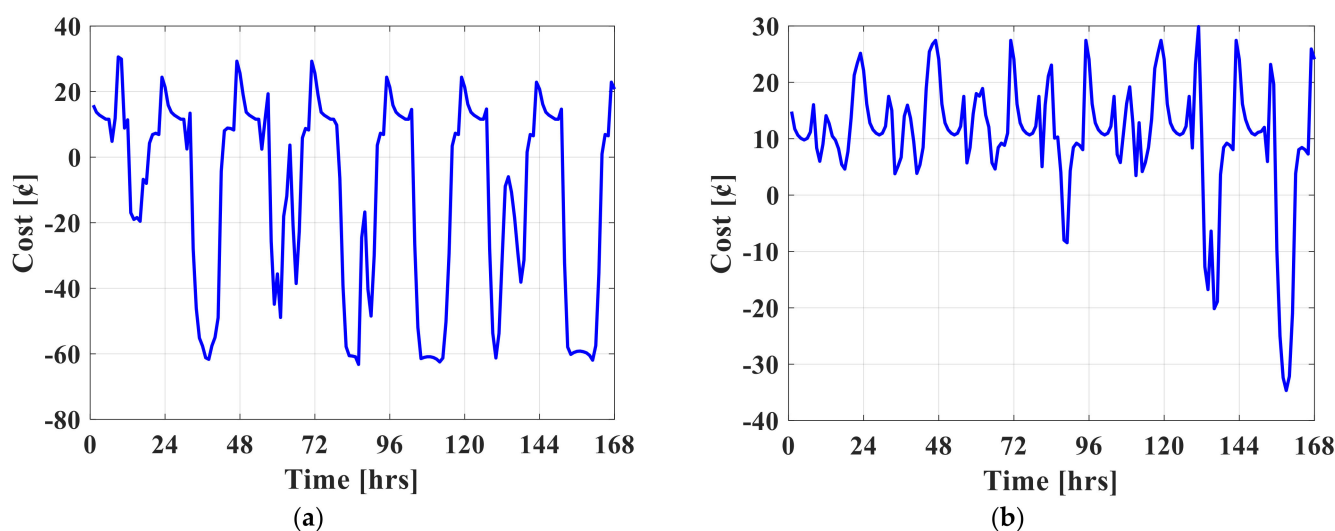


Figure 13. Electricity cost variations under ToU-Flat rates for one week in: (a) Summer, and (b) Winter.

5.2.3. Electricity Cost in Option 3 (Flat-ToU)

Figure 14 illustrates the electricity cost variations under Flat-ToU rates for both seasons. The ToU rates of selling electricity are low in off-peak and shoulder periods. On the other hand, the output power of solar PV is mostly available during those periods. Therefore, it can be seen that the electricity cost variations are almost positive for both seasons. It means that the household profit by selling electricity to the grid is significantly decreased compared to previous options. The electricity cost in summer varies from -0.3 AUD to

0.39 AUD with an average of 0.8 AUD per hour. This scenario becomes serious in winter, with the cost variation from 0.0 AUD to 0.56 AUD with an average of 0.19 AUD per hour.

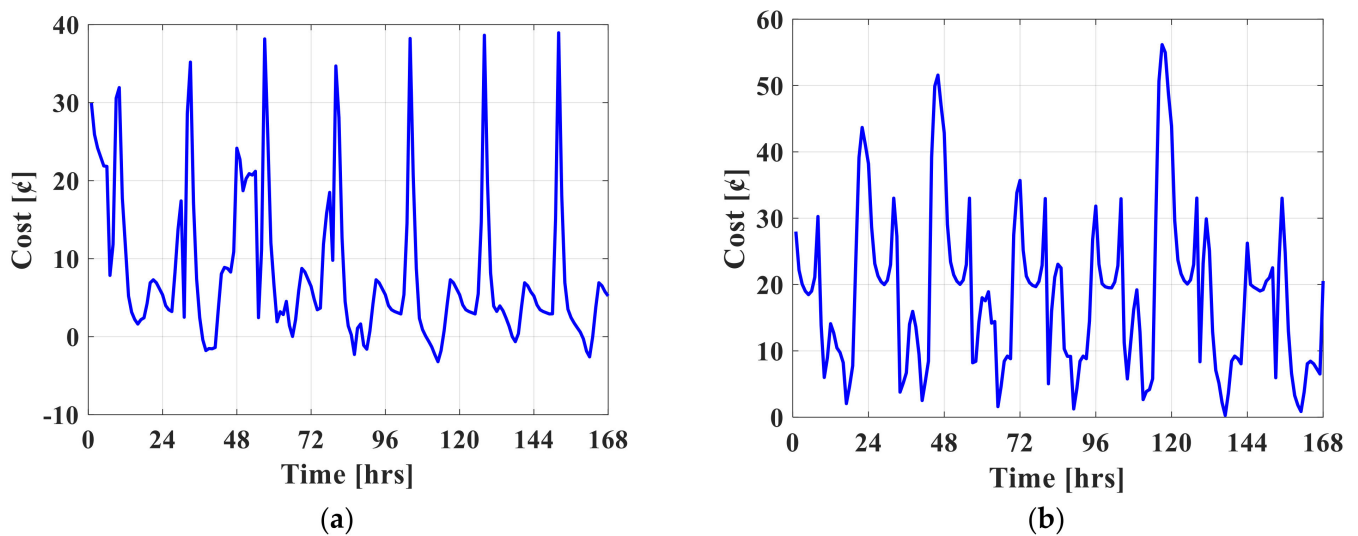


Figure 14. Electricity cost variations under Flat-ToU rates for one week in: (a) Summer, and (b) Winter.

5.2.4. Electricity Cost in Option 4 (ToU-ToU)

Figure 15 demonstrates the electricity cost variations under ToU-ToU rates for both seasons. It can be noted that both expenditure and income of the household are reduced compared to other options, which is reasonable because the ToU-ToU mode has the characteristics of both the ToU-flat option and the flat-ToU option. The cost of the household in summer fluctuates from -0.3 AUD to 0.32 AUD, with an average cost of 0.8 AUD per hour. However, in winter, the costs are between 0.0 AUD and 0.30 AUD, and the average cost is 0.13 AUD per hour.

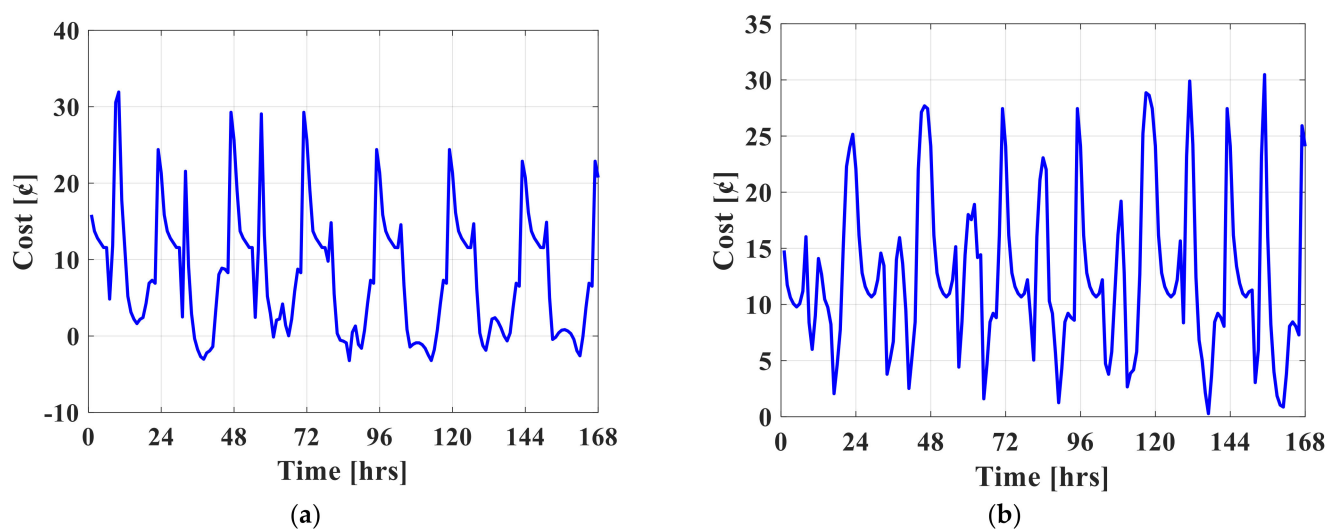


Figure 15. Electricity cost variations under ToU-ToU rates for one week in: (a) Summer, and (b) Winter.

5.3. Economic Analysis and Comparison of the Rule-Based EMSs

This section investigates the total electricity cost of the proposed rule-based EMSs for the households with each option. Hence, the best option can be found with the highest economic benefits. The comparison is provided for both summer and winter seasons separately.

Table 5 shows the key performance indicators (KPIs) for comparison of the economic analysis of the proposed EMS under four different options in summer. The last row in the table indicates the anticipated cost when the load (132.3 kWh) is completely supplied by the utility grid. The cost of PV generation is the same for all options because the same environmental data is used to calculate the PV output power. Due to the sufficient solar resources in summer, the proposed EMS can significantly reduce the electricity cost of the customer for all options. The Flat-Flat option and ToU-Flat option have larger energy sales revenue than that of the other two options. In terms of the total cost, the ToU-Flat option has the minimum cost and hence the best economic benefit compared to other options. In ToU-Flat option, the customer can earn 17.86 AUD during the week in summer. The system also has the lowest battery degradation cost.

Table 5. Key performance indicators (KPIs) for comparison of economic analysis of the proposed EMSs for one week in summer under four options.

Option	Flat-Flat	ToU-Flat	Flat-ToU	ToU-ToU
Total operation cost of the system (\$)	−13.80	−17.86	13.83	13.43
Battery degradation cost (\$)	7.45	3.49	7.42	3.49
PV generation cost (\$)	14.09	14.09	14.09	14.09
Cost of exchanged electricity with grid (\$)	−35.34	−35.44	−7.69	−4.15
Cost when load met by grid (\$)	63.51	33.62	63.51	33.62

Table 6 shows the key performance indicators (KPIs) for comparison of the economic analysis of the proposed EMS under four different options in winter. The total electricity consumption for this sample week in winter is 133.8 kWh. Similarly to the week in summer, the minimum cost (17.90 AUD) is obtained under the ToU-Flat option. Although no profit could be obtained by the EMSs in winter, the actual cost under the ToU-Flat mode is 47% lower than the case of completely importing power from the grid to meet the load.

Table 6. Key performance indicators (KPIs) for comparison of economic analysis of the proposed EMSs for one week in winter under four options.

Option	Flat-Flat	ToU-Flat	Flat-ToU	ToU-ToU
Total operation cost of the system (\$)	28.03	17.90	31.13	21.24
Battery degradation cost (\$)	6.06	5.41	5.87	5.50
PV generation cost (\$)	4.69	4.69	4.69	4.69
Cost of exchanged electricity with grid (\$)	17.28	7.80	20.57	11.05
Cost when load met by grid (\$)	64.20	33.99	64.20	33.99

By comparing Table 5 with Table 6, it can be concluded that the best economic profit can be obtained for option 2 where the ToU rates are used for electricity buying and the Flat rate is used for electricity selling. The main reason can be discussed first by Flat rate for electricity selling and ToU rate for electricity buying. The current Flat rate is 0.17 AUD/kWh; however, within the ToU rate, the selling electricity rate is 0.18 AUD/kWh only for the peak time and it is too low for shoulder and off-peak. Hence, since the peak time is the evening and PV cannot sell electricity at that time, the ToU rate for electricity selling is not affordable. On the other hand, the Flat rate for electricity buying is not affordable since it imposes a 0.48 AUD/kWh for purchased electricity at any time. However, within the ToU for the electricity buying, the customer only pays a high rate of 0.58 AUD/kWh for the peak time, and at shoulder and off-peak the electricity price is low.

6. Conclusions and Future Works

The main contribution of this paper was to develop four novel practical rule-based home EMSs for grid-connected households with solar PV and battery by considering different tariffs for purchasing and selling electricity. An important feature of the developed

rule-based EMSs was their practicality which means that they could be easily employed for the customers. Flat and ToU rates were evaluated for four different options for electricity purchase and sale prices: (1) Flat-Flat, (2) ToU-Flat, (3) Flat-ToU, and (4) ToU-ToU. The developed rule-based EMSs considered the electricity price, generation of PV, load consumption of home, energy in the battery, and the grid constraint. As a new contribution, the proposed EMSs updated the power flow not only based on the PV generation, but also based on the electricity price. The operation cost was calculated based on the electricity exchange with main grid, equivalent cost of PV generation, as well as the degradation cost of battery storage. It was found that the ToU-Flat option reached the lowest electricity cost in both seasons for the customers based on the developed rule-based EMS. The Flat-ToU option is not recommended for the customers since it has the highest electricity cost for both weeks of operation. The total operation cost for the ToU-Flat option (17.90 AUD) was almost half of that of Flat-ToU option (31.30 AUD) for winter. In addition, it was almost one third for the summer season.

Future studies can focus on new rule-based energy management based on real-time pricing. In such a study, an accurate electricity price forecasting plays an important role to develop the rules of the EMS.

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Nomenclature

Abbreviations

EMS	Energy management system
FiT	Feed-in-tariff
PV	Photovoltaic
RES	Renewable energy system
RP	Retail price
SA	South Australia
ToU	Time-of-use

Parameters

C_b	Equivalent operation cost of battery (\$)
C_b^m	Maintenance cost of battery (\$)
C_b^{cap}	Capital cost of battery (\$)
C_g^{ex}	Equivalent cost of exported energy to the grid (\$)
C_g^{im}	Equivalent cost of imported energy from the grid (\$)
C_{pv}	Equivalent operation cost of PV (\$)
C_{pv}^{cap}	Capital cost of the installed solar PV system (\$)
$Cost_t$	Total operation cost of the system (\$)
E_b	Energy rating of battery (kWh)
$E_b^{ch/dis}$	Total charging/discharging energy of battery in the operation period (kWh)
$E_b^{lifetime}$	Deliverable energy of 1-kWh battery during its lifetime (kWh)
E_g^{ex}	Exported energy to grid (kW)

E_g^{im}	Imported energy from grid (kW)
E_{pv}	Generated energy of the installed solar PV system (kWh)
E_{pv}^{annual}	annual generated energy by 1-kW PV
i	Discount rate (%)
n	Component's lifetime (year)
p_b^{cha}	Charging power of battery (kW)
p_b^{dis}	Discharging power of battery (kW)
p_b^{in}	Available input power of battery (kW)
p_b^{out}	Available output power of battery (kW)
P_d	Load consumption (kW)
P_{dump}	Dumped power (kW)
p_g^{ex}	Export power to grid (kW)
p_g^{im}	Import power from grid (kW)
p_{grid}^{max}	Maximum export power limit to grid (kW)
P_{pv}	Rating power of the installed solar PV system (kW)
P_r	Generated power of solar PV (kW)
PVF	Present value function
Q_b	capacity of the installed battery (kWh)
SOC	State of charge of battery (%)
SOC_{min}/SOC_{max}	Minimum/maximum limit of SOC (%)
T	Total time intervals (hr)
η_{ch}/η_{dis}	Charging/discharging efficiency of battery (%)
Δt	Interval of time (hr)

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