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ORIGINAL RESEARCH PAPER

# Optimal planning of solar PV and battery storage with energy management systems for Time-of-Use and flat electricity tariffs

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**Abstract**

This paper determines the optimal capacity of solar photovoltaic (PV) and battery energy storage (BES) with novel rule-based energy management systems (EMSs) under flat and time-of-use (ToU) tariffs. Four schemes are investigated based on the combinations of flat and ToU tariffs for buying and selling the electricity: (1) Flat-Flat, (2) ToU-Flat, (3) Flat-ToU, and (4) ToU-ToU. For each scheme, two configurations are evaluated: (i) PV only, and (ii) PV-BES. The optimization of the grid-connected household is evaluated based on one-year realistic data. An uncertainty analysis is presented based on the variations of insolation, temperature, and load. Sensitivity analyses are implemented based on the average daily load, the grid constraint, and the costs of PV and BES. The operational analyses for 48 h in summer and winter are carried out to evaluate the dynamic performance of the systems for high and low solar insolation. The effectiveness of the proposed model is verified by comparing the results with that of common EMS based on the net metering scheme. It is found that the COE of the proposed EMS for a PV-BES house with ToU-Flat scheme (as the best option) is 2 ¢/kWh lower than that of the net metering scheme.

## 1 | INTRODUCTION

Increasing global electricity consumption and arising environmental problems have led to the popularity of renewable energy in the past decade. Electricity generated from renewable energy resources such as solar, wind and tidal is environmental-friendly and has zero carbon emissions [1]. In particular, solar photovoltaic (PV) represents a vital role for integration with the conventional energy systems. The price of solar PV modules has dropped significantly up to 92% since 2000 [2]. In addition to the reduced price, the conformity to the zero-carbon commitments also stimulates the development of solar PV worldwide.

Despite the generation of clean energy, there is always a mismatch between solar PV generation and household electricity consumption [2]. In other words, the intermittent feature of renewable energy sources indicates that it is essential to connect solar PV system to the grid or battery energy storage (BES) to ensure a reliable power supply. A study found that in 2020, more than 3 GW small-scale solar PV and 238 MWh batteries were installed in Australia [3]. With the integration of BES, the PV system can charge the battery with surplus solar energy, and then the battery can discharge to meet the load when solar energy is insufficient [4].

Currently, the added capacity of solar PV and BES in Australia is unbalanced. The newly added capacity of batteries is less than 10% of the installed capacity of solar PV [3]. Although the capability of batteries to flatten the household load profile or to avoid expensive electricity bills during peak hours is known, the achieved economic benefits and its high cost require great attention and investigation. In addition, the capacity of solar PV also affects the power flow between different energy sources, as well as the cost of the entire system [5]. Therefore, it is very important to select the optimal capacity of the solar PV and BES to achieve the minimum cost of the system.

The selection of appropriate rates for buying and selling the electricity also influences the performance of the PV and BES. Electricity tariffs such as flat and time-of-use (ToU) would influence the import and export energy prices of the grid, thereby affecting the economic performance of the entire system [6]. For example, consumers would benefit from the relatively low electricity prices in the off-peak period of the ToU scheme. Conventionally, optimal sizing of solar PV is studied based on a certain electricity rate, which needs to be extended to several electricity pricing tariffs. It is possible to reduce the electricity bill by appropriate management of power flow between solar PV, BES, and the grid under flat and ToU schemes.

Capacity optimization of solar PV and BES has been carried out in several studies. In [7], a grid-connected system with solar PV was proposed to minimize the total life cycle cost and maintain the stability of the system. The results showed that with the optimal capacity of PV, the electricity cost could be saved up to 64% compared to the system without PV. However, the storage system was not considered in this study. Refs. [8] and [9] developed optimization models for battery capacity to minimize the system cost. The optimal sizing of the battery was determined under flat electricity rates, and the results indicated that the price of the battery has a large influence on the economic aspect. However, the optimal sizing of the PV system was not included in those studies.

Several studies have investigated the system performance under different electricity tariffs such as flat rates [10–12], ToU rates [13–15], and real-time pricing (RTP) rates [16, 17]. However, the developed energy management systems (EMSs), in all those studies, are based on the net metering scheme. The net metering scheme is the simplest EMS which sells the extra power of PV to the grid, without considering the electricity rate, after supplying the load and charging the battery.

To obtain practical results by optimal sizing of PV and BES, all realistic and practical factors like PV and battery degradations, salvation value at the end of the project, realistic data, and electricity tariffs should be considered. Most studies on optimizing PV and BES capacity have not considered the impact of battery and PV degradation, which leads to unreliable long-term economic analysis. Furthermore, research on the renewable system under more than one electricity tariff was rarely reported, that is, most of the simulation results are obtained based on one specific electricity tariff (flat or ToU electricity rates). In [10], optimal sizing was conducted for a PV-BES system by applying grid constraints. However, the battery and PV degradations were ignored. In [11], an improved method was applied to the grid-connected PV-BES system to determine the number of PV panels and batteries. However, the maximum export power from PV to the grid was overlooked. Considering the exchange power limit between the consumer and the grid is to prevent the instability of the utility grid when many solar PV systems are used [12]. In [13], capacity optimization of PV was investigated without grid constraint. Optimal sizing of a hybrid renewable system was proposed in [16]. However, the data used for simulation was generated by a stochastic model, thus the actual data was not used, and the results were not practical.

In [15], the optimal sizing was conducted based on non-realistic data of load consumption and insolation. In addition, uncertainty analysis was not provided. In [17], a basic net metering scheme was used as the EMS to optimize the capacity of components under different electricity rates. However, variable electricity tariffs like ToU need more complicated EMSs. The current study is the continuation of earlier research work [18] where optimal sizing was conducted for PV and BES for different electricity tariffs. However, in [18], the EMS was based on the net metering scheme and their results are compared with this study.

To the best of the authors' knowledge, none of the existing studies has investigated the optimal capacity under different electricity tariff schemes for retail price (RP) and feed-in-tariff (FiT) by developing new EMSs. Hence, the main contributions of this paper compared to the existing studies can be summarized as follows:

- The existing studies have investigated the optimal sizing problem of PV and BES under a single electricity tariff for the consumers. However, this work develops a practical optimal sizing of PV and BES for a grid-connected house under four schemes of electricity tariffs.
- The existing EMSs for grid-connected houses are not compatible with different electricity tariffs. In this study, new EMSs are developed for each operating scheme based on the electricity tariffs of the grid-connected house.
- The existing studies for optimal sizing of PV and BES do not consider all practical aspects. This work applies all practical parameters like degradations and salvation values of PV and BES, as well as the grid constraint in the optimization model.
- Instead of using probability data, an uncertainty analysis is provided based on 10-year actual data of solar insolation, ambient temperature, and electricity consumption.

The EMSs are developed under two configurations (PV only and PV-BES) and four operating schemes, that is, (1) Flat-Flat, (2) ToU-Flat, (3) Flat-ToU, and (4) ToU-ToU. The control strategy of EMSs is adjusted according to different electricity price periods (peak, mid-peak, and off-peak) of ToU tariff. The main aim is to minimize the cost of electricity (COE) of the household by optimizing the capacity of PV and BES. The COE is obtained based on the net present cost (NPC) of the renewable components and the electricity exchange cost with the grid. The operation is evaluated based on one-year real data to ensure the reliability of optimized results. Sensitivity analyses are provided based on variations of daily load consumption, PV and BES costs, as well as the grid constraint. The effectiveness of the proposed model is proved by comparing the results with the common EMS based on the net metering scheme.

## 2 | OPERATIONAL STRATEGIES

The proposed system is designed for a grid-connected house with PV and BES. Figure 1 shows the configuration for such a typical household with EMS. Two system configurations are examined in this work. In the first configuration, the household load is only supplied by solar PV and the grid. In the second configuration, the load is supplied by PV, BES, and the grid. In this study, it is assumed that the behind-the-meter BES installed by consumers cannot trade electricity with the main grid. Hence, a system configuration that only considers BES is not possible. The EMS receives data from the renewable power delivered by the PV, the available charge and discharge power of BES, the load of the house, the grid constraint, and the electricity prices of the grid to determine the optimal power flow between these resources.

This study develops rule-based EMSs for the system configurations. The rule-based EMSs are selected because of simplicity, practicality, user-friendliness, ease of implementation in practice, and low calculation requirement [10]. In the rule-based EMSs, all the applied rules are explicit for the designers and customers. The other feature of the rule-based EMSs is the capability to update the rules by the designer since the rules are applied based on the expert's experiences on the system. This facilitates to achieve a feasible system operation and hence optimal planning.

Different electricity tariffs like flat and ToU directly affect the electricity buying and selling prices. Therefore, the EMS can be developed under four different schemes in terms of electricity buying and selling tariffs.

### 2.1 | Scheme 1: Flat-Flat

In this scheme, the flat rate is applied for electricity buying and selling. In other words, the cost of electricity during the whole day and year does not change. The EMS receives the signal which indicates the status of load consumption, renewable energy, and grid limitation. When the renewable energy is greater than the household load, the EMS will first store the excess energy in the battery unless the battery is fully charged.

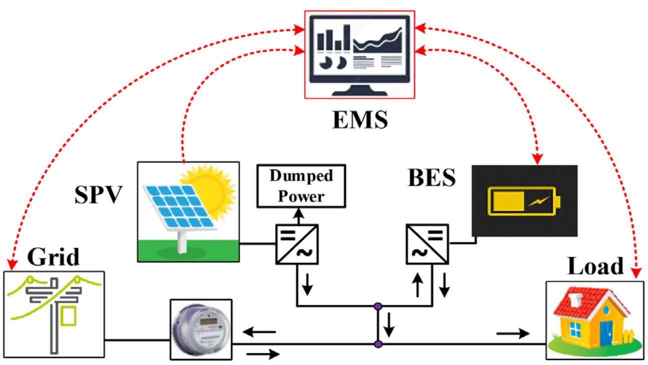


**FIGURE 1** EMS controlled model for a grid-connected house with PV and BES

When the battery is full, the remaining energy is sold to the grid. The charged power of the battery ($P_{BES}^{cha}$) and the export power to the grid ($P_{grid}^{ex}$) are formulated as follows:

$$P_{BES}^{cha}(t) = \min\left(P_{re}(t) - P_{load}(t),\ P_{BES}^{in}(t)\right) \tag{1}$$

$$P_{grid}^{ex}(t) = \min\left(P_{re}(t) - P_{load}(t) - P_{BES}^{cha}(t),\ P_{grid}^{max}\right) \tag{2}$$

where $P_{re}$ is the generated power by the solar PV, $P_{load}$ is the load consumption of the home, and $P_{grid}^{max}$ is the maximum allowable export power to the grid. $P_{BES}^{in}(t)$ is the available input power for charging of the battery that is calculated based on the state of charge (SOC) of the BES as follows:

$$P_{BES}^{in}(t) = \min\left(P_{BES}, \left(\frac{E_{BES}\cdot(SOC^{max} - SOC(t))}{\Delta t}\right)\right) \tag{3}$$

where $P_{BES}$ and $E_{BES}$ are the power and energy of the BES, respectively.

If the battery is fully charged and the excess power of the PV, after supplying the load, is greater than the grid's constraint, the extra power of the PV is dumped. It is assumed that the extra power is dumped using the control system of the PV's inverter. The dumped power ($P_{dump}$) is calculated by:

$$P_{dump}(t) = P_{re}(t) - P_{load}(t) - P_{BES}^{cha}(t) - P_{grid}^{max} \tag{4}$$

If the renewable energy is less than the household load, the EMS will first use the stored energy in the battery until it is fully discharged. Once the battery has no energy, insufficient energy will be provided by the grid. The discharged power of the battery and the import power from the grid are formulated as follows:

$$P_{BES}^{dis}(t) = \min\left(P_{load}(t) - P_{re}(t),\ P_{BES}^{out}(t)\right) \tag{5}$$

$$P_{grid}^{im}(t) = P_{load}(t) - P_{re}(t) - P_{BES}^{dis}(t) \tag{6}$$

The maximum power that can be discharged by BES in each time interval is considered as follows:

$$P_{BES}^{out}(t) = \min\left(P_{BES}, \left(\frac{E_{BES}\cdot\left(SOC(t) - SOC^{min}\right)}{\Delta t}\right)\right) \tag{7}$$

The SOC of the battery for charging and discharging is calculated by:

$$SOC(t+\Delta t) = SOC(t) + \frac{(P_{BES}^{cha}(t).\eta_{ch} - P_{BES}^{dis}(t).\eta_{dis})\cdot\Delta t}{E_{BES}} \tag{8}$$

Algorithm 1 presents the rule-based EMS for the Flat-Flat scheme.

**ALGORITHM 1** Ruled-based EMS for Flat-Flat scheme

```
for t = 1 : 8760
    if the PV output power is higher than load
        first supply the load, then charge the BES, then export the extra
        power to the grid, dump the extra power if any.
    else
        first supply the load by PV, then discharge the BES, then import
        the remaining power from the grid.
    end if
end for
```

**ALGORITHM 2** Ruled-based EMS for ToU-Flat scheme

```
for t = 1 : 8760
    if the PV output power is higher than load
            first supply the load, then charge the BES, then export the extra
            power to the grid, dump the extra power if any.
    else
        if the TOU_buy rate is at peak rate
            first supply the load by PV, then discharge the BES, then import
            the remaining power from the grid.
        else
            first supply the load by PV, then import the remaining power
            from the grid.
            end if
        end if
    end for
```

## 2.2 | Scheme 2: ToU-Flat

For this scheme, the electricity selling price is fixed; however, the buying price is determined by ToU rates. Therefore, the control strategy for selling electricity is the same as scheme 1 and remains unchanged. But the buying part of the control strategy is changed based on different periods of the ToU rates (peak, mid-peak, and off-peak). It may be mentioned that although the power flow is different from scheme 1, the action which is triggered by different conditions is the same. In other words, the power flow equations illustrated in the previous section remain unchanged. Therefore, to avoid unnecessary repetition, formulas of the power flow will not be stated in the following schemes.

During the peak period, the electricity buying price is relatively high; hence, the EMS tends to use energy in the BES rather than the grid for a better economic benefit. In other words, BES has a higher priority than the grid when the power generated from PV is not enough to supply the load. During mid-peak and off-peak hours, the electricity buying price is low. So, when the power delivered by solar PV is insufficient, the remaining power is supplied by the grid instead of BES. Algorithm 2 represents the rule-based EMS for the ToU-Flat scheme.

**ALGORITHM 3** Ruled-based EMS for Flat-ToU scheme

```
for t = 1 : 8760
    if the PV output power is higher than load
        if the TOU_sell rate is at peak rate
            first supply the load, then export power to the grid, then charge
            the BES, dump the extra power if any.
        else
            first supply the load, then charge the BES, then export the extra
            power to the grid, dump the extra power if any.
            end if
        else
            first supply the load by PV, then discharge the BES, then import
            the remaining power from the grid.
        end if
    end for
```

## 2.3 | Scheme 3: Flat-ToU

For scheme 3, the electricity buying price is fixed and the same as scheme 1, which means the control strategy remains the same when the renewable energy is less than the load. However, the electricity selling price is based on the ToU rates; hence, the corresponding control strategy should be modified for different ToU periods. During the peak period, the FiT is greater than the rest of the day. Hence, when there is surplus power of PV after supplying the load, it should be exported to the grid instead of being stored in the BES. During the off-peak period, the FiT is very low compared to the peak period, so the surplus power of PV should be stored in BES first. During the mid-peak period, the FiT is normal so the profit of selling electricity to the grid is not attractive. Besides, storing power in BES during mid-peak hours would make the system ready for the upcoming peak period. Hence, scheme 3 has the same power control during off-peak and mid-peak periods as described in scheme 1. Algorithm 3 presents the rule-based EMS for the Flat-ToU scheme.

## 2.4 | Scheme 4: ToU-ToU

In this scheme, during the peak period, the RP and FiT of the electricity are relatively high. Hence, the household should decrease the purchasing power from the grid and increase the sold power to the grid. In contrast, the RP and FiT are very low during the off-peak period. Hence, it is recommended to purchase power from the grid even when solar PV is high and store the surplus power into the BES. During the mid-peak period, the RP and FiT are normal prices. Hence, insufficient energy should firstly be supplied by the BES to decrease the electricity purchase cost. In addition, the extra PV power should be used to charge the BES for the next peak hours. Algorithm 4 presents the rule-based EMS for the ToU-ToU scheme.

In summary, for the flat-flat scheme, because the RP and FiT are fixed, there is no change in control strategy throughout the day. For ToU-flat and flat-ToU schemes, the ToU rates are

**ALGORITHM 4** Ruled-based EMS for ToU-ToU scheme

```
for t = 1 : 8760
  if the PV output power is higher than load
    if the TOU_sell rate is at peak rate
      first supply the load, then export power to the grid, then charge
      the BES, dump the extra power if any.
    Else
      first supply the load, then charge the BES, then export the extra
      power to the grid, dump the extra power if any.
      end if
  else
    if the TOU_buy rate is at peak rate
      first supply the load by PV, then discharge the BES, then import
      the remaining power from the grid.
    else
      first supply the load by PV, then import the remaining power
      from the grid, then discharge the BES.
      end if
    end if
  end for
```

applied to one side (buying or selling). The EMS would determine the power flow of one side during different ToU hours (peak, mid-peak, and off-peak). For ToU-ToU rates, the EMS would determine the optimal power flow on two sides.

## 3 | OPTIMIZATION MODEL

The system model used to optimize the capacity of the components is explained in this section. The objective function of this study is to minimize the system COE by optimal sizing of the components. The COE is calculated from the system NPC, capital recovery factor (CRF), and load consumption as follows [19]:

$$COE = \frac{NPC_c \cdot CRF_c + NPC_e \cdot CRF_e}{E_{load}} \tag{9}$$

The CRF of components ($CRF_c$) is based on the interest rate and project horizon is as follows:

$$CRF_c = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \tag{10}$$

The CRF of electricity ($CRF_e$) is formulated based on an escalation rate above the interest rate as follows:

$$CRF_e = \frac{(1+g)^n - 1}{g \cdot (1+g)^n} \tag{11}$$

$$g = \frac{i-q}{1+q} \tag{12}$$

where $g$ is the real interest rate that is calculated based on the escalation rate $q$, and interest rate $i$.

$NPC_c$ includes the capital cost, replacement cost, and operation and maintenance (O&M) cost of PV and BES, and it is calculated as follows:

$$\begin{aligned} NPC_c = N_{PV} \cdot \left(C_{PV}^{cap} + C_{PV}^{o\&m} + C_{PV}^{r} - C_{PV}^{sal}\right) \\ + N_{BES} \cdot \left(C_{BES}^{cap} + C_{BES}^{o\&m} + C_{BES}^{r} - C_{BES}^{sal}\right) \end{aligned} \tag{13}$$

It is to be noted that $C_{PV}^{sal}$ and $C_{BES}^{sal}$ are the salvation values of the PV and the BES, respectively. The salvation value is the cost of the component at the end of project lifespan. To calculate the salvation value, the lifetime of the component should be available. The lifetime of PV is considered as 25 years [10]. In this study, the battery's life is calculated based on its capacity degradation. It is notable that the effect of BES's degradation on the system operation has not been considered. In this study, the BES's capacity degradation has been calculated when the annual operation of the system is terminated. Hence, it is not possible to consider that degradation in the operation. This approach is considered acceptable by several studies for optimal sizing of battery [1, 20, 21]. To calculate the degradation, the Rainflow Cycling algorithm is used to extract the number of charge/discharge cycles and the value of SOC in each cycle. Then, an experimental model is used to calculate the degradation in each full cycle ($D_{BES}$) as follows [21]:

$$D_{BES}(c) = \frac{20}{33000.e^{-0.06576.DOD(c)} + 3277} \tag{14}$$

Using the cycling algorithm, the DOD number is extracted for full and half cycles. The degradation of half cycles is assumed as the half of (14). When the degradation of BES exceeds 20%, it should be replaced in the planning problem.

$NPC_e$ consists of the import cost of power from the grid and the export cost of power to the grid, which is calculated by:

$$NPC_e = \sum_{t=1}^{U} \left(P_{grid}^{im} \cdot C_p(t) - P_{grid}^{ex} \cdot C_s(t)\right) \cdot \Delta t \tag{15}$$

The restrictions that need to be considered during the optimization process are as follows:

$$0 \le P_{pv} \le P_{pv}^{max} \tag{16}$$

$$0 \le P_{BES} \le P_{BES}^{max} \tag{17}$$

$$SOC_{min} \le SOC \le SOC_{max} \tag{18}$$

$$0 \le P_{grid}^{ex} \le P_{grid}^{max} \tag{19}$$

$$0 \le P_{BES}^{cha}, P_{BES}^{dis} \le P_{BES} \tag{20}$$

Equations (16) and (17) define the maximum output power of solar PV and battery. SOC constraint is stated in Equation (18). Equation (19) shows the maximum power that can be exported to the grid. And Equation (20) is the battery constraint to limit the discharging power.

In this study, the current tools like HOMER software are not used for optimization since it is not easy to model the proposed rule-based EMSs in those tools. In addition, it is not possible to apply the battery degradation model eqn. (14) in HOMER. Although the optimization model can be optimized using suitable optimization tools in MATLAB, particle swarm optimization (PSO) has been proven as a reliable tool for such a study and provide reliable solutions. This method has been efficiently applied for power system planning studies [10, 18, 19], and its results have been approved for optimal sizing compared to other methodologies [22, 23]. It is notable that the optimization algorithm is not a contribution of this study. The superiorities of PSO over other optimization methodologies are easy handling of system nonlinearities, simplicity of the concept, easy implementation, high convergence rate, less dependency on initial points, and computational efficiency [23, 24]. Figure 2 shows the optimization process of the particle swarm optimization algorithm. Generally, a high number of populations and generations are selected to achieve a wide search space for the PSO and hence convergence to the global solution. In this study, the numbers of population and generation of the PSO algorithm are both selected as 300. It means that the PSO runs the simulation for 300*300 times to achieve the results. Moreover, this study repeats the whole process of simulation for 10 runs to assure that global optimal results are achieved by the PSO algorithm. After the initiation of the particle swarm optimization algorithm, each particle will have a specific solution, and the minimum one is the particles' best position of the entire particle swarm. Particles' best position will vary for the next generation, and the best solution among the particles' best position is the global best solution. The number of runs determines the repetition of the optimization process, and the final optimal results are obtained from the best global best solution of all runs. It is notable that the other hyper-parameters of the PSO algorithm are inertia weight, cognition weight, and social weight that are selected as 0.5, 2, and 2 [23].

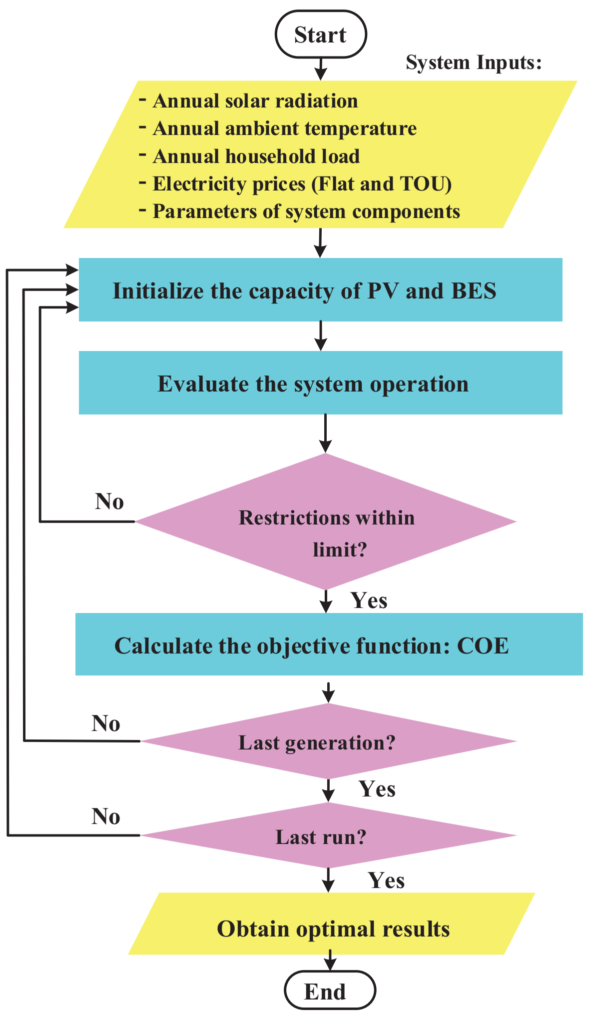


**FIGURE 2** The flowchart of the proposed optimization process in this study

## 4 | SYSTEM MODEL

The proposed EMS is general and suitable for all typical grid-connected houses with solar PV and BES to optimize their capacity and control the power flow. In this study, the case study presents a typical grid-connected house in South Australia. The data received by the EMS, such as meteorological data for PV, load profile, and prices of RP and FiT, will be explained in this section.

### 4.1 | Annual meteorological data of the solar PV

Annual weather data for a typical house in South Australia is available from the Australian Government Bureau of Meteorology [25]. Figure 3 indicates the insolation and ambient temperature of the solar cell during the whole year (8760 h). Since South Australia is in the southern hemisphere, meteorology data of solar is generally higher on both sides and lower in the middle of the year. In terms of solar insolation, more solar energy can be harnessed in summer due to the longer sunshine duration. The maximum insolation reaches 0.79 $kWh/m^2$, and the average insolation for one year is 0.18$kWh/m^2$. The maximum and minimum temperatures of the solar cells are 41.9 and 2.2 °C, respectively. It is to be noted that the average temperature for the summer and winter seasons are 22.4 and 13.9 °C, respectively.

### 4.2 | Load profile and electricity prices data

The load consumption of the house is taken from [26] and shown in Figure 4. The average load consumption for one year

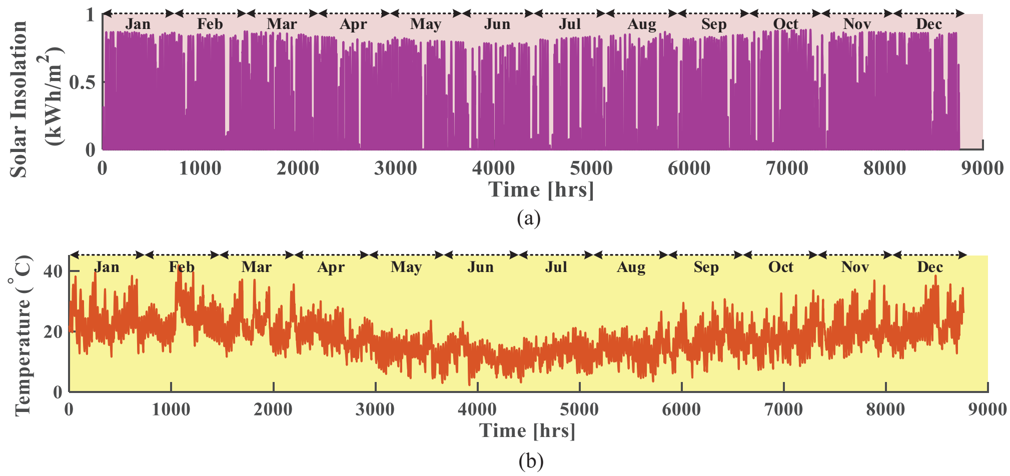


**FIGURE 3** Annual meteorological data of a general house in South Australia. (a) Solar insolation. (b) Ambient temperature

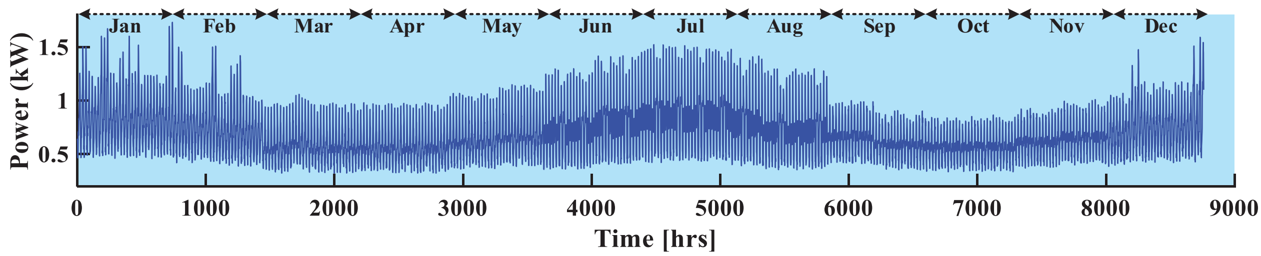


**FIGURE 4** Annual household load consumption in the case study

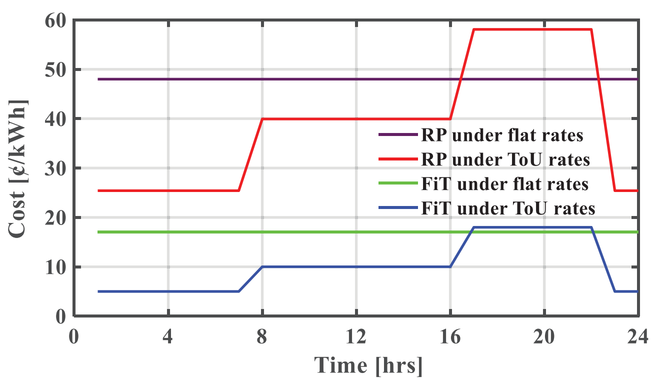


**FIGURE 5** Cost of energy for RP and FiT under flat and ToU rates [4, 16]

**TABLE 1** Parameters of the solar PV and BES in this study

| Parameters | Value | Parameters | Value |
|---|---|---|---|
| PV capital cost | $1,500/kW | BES capital cost | $350/kWh |
| PV overhaul cost | $300/kW | BES overhaul cost | $200/kWh |
| PV O&M cost | $50/year | Time between overhauls | 10 years |
| Battery SOC minimum | 20% | BES efficiency | 93% |
| Battery SOC maximum | 95% | Maximum grid export power | 5 kW |

is 0.65 kWh, and the peak demand is 1.65 kWh. The total annual energy consumption of a typical household is 5.7 MWh.

Electricity buying and selling prices for flat and ToU tariffs are presented in Figure 5. The electricity buying price for flat rates is 48.0 ¢/kWh, which is almost three times the selling price (17.0 ¢/kWh). The electricity price for ToU rates is not fixed and varies with different periods [27]. The peak period means that the household demand is usually high, and it starts from 6 to 10 PM. The RP and FiT during the peak period are 58.0 and 18.0 ¢/kWh, respectively. The off-peak period indicates lower usage of electricity, and it is between 11 PM and 8 AM. The RP and FiT during the off-peak period are 25.4 and 5.0 ¢/kWh, respectively. The mid-peak period starts at 8 AM and ends at 6 PM. The RP and FiT during the mid-peak period are 39.9 and 10.0 ¢/kWh, respectively.

### 4.3 | Components configuration and costs

Table 1 demonstrates the parameters and expenditures of the solar PV and BES. It may be noted that all the prices in this paper are in Australian dollars. The cost data of PV and BES is based on [18]. The lifetime of the solar PV system is considered as 25 years. It is considered that a maximum of 5 kW power can be exported to the grid according to SA Power Networks [28].

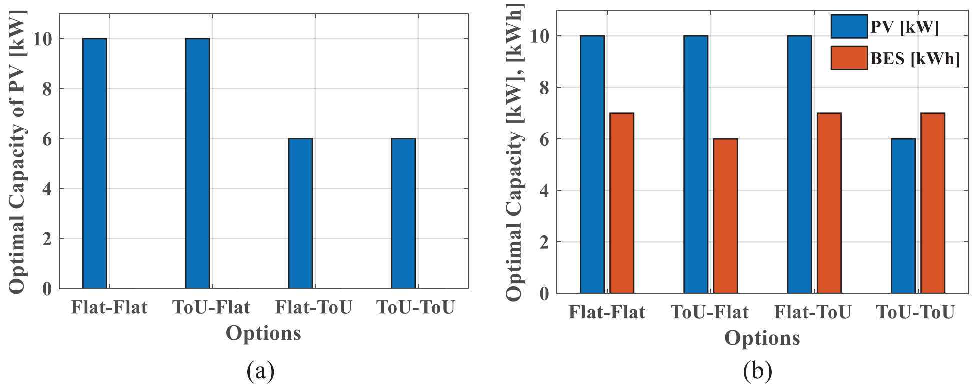


**FIGURE 6** Optimal capacity for each component. (a) PV only configuration. (b) PV-BES configuration

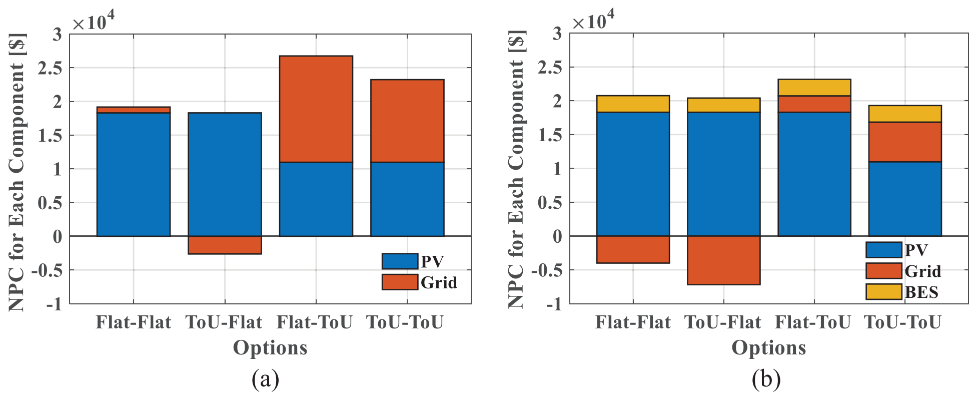


**FIGURE 7** Total NPC division between PV, BES and grid. (a) PV only configuration. (b) PV-BES configuration

The minimum and maximum limitations of the battery's SOCs are selected as 20% and 95%, respectively [18].

## 5 | RESULTS AND DISCUSSIONS

The economic and technical results of the optimized system for a typical house are demonstrated in this section. The optimal sizing of the PV and BES, analysis of the power flow, sensitivity analyses, and uncertainty analysis are presented.

### 5.1 | Optimal capacity of solar PV and BES

The optimal capacity of PV and BES for two configurations (PV only, PV and BES) in four schemes (Flat-Flat, ToU-Flat, Flat-ToU, and ToU-ToU) are shown in Figure 6. The optimal capacity of PV varies from 6 to 10 kW, and it remains the same in both configurations for Flat-Flat, ToU-Flat, and ToU-ToU schemes. The optimal capacity of BES is 6 kWh for the ToU-Flat scheme and 7 kWh for the other three schemes.

Figure 7 shows the NPC division. For PV only configuration, the ToU-Flat scheme has the lowest total NPC at $15,672, followed by Flat-Flat scheme ($19,164), ToU-ToU scheme ($23,228), and Flat-ToU ($26,740). For PV-BES configuration, the lowest NPC is also under ToU-Flat scheme at $13,209, followed by Flat-Flat scheme ($16,753), ToU-ToU scheme ($19,293), and Flat-ToU ($23,168). Negative NPC of the grid only occurs under the ToU-Flat scheme in PV only configuration, which means that this scheme is profitable by selling power to the grid. For PV-BES configuration, Flat-Flat and ToU-Flat are the only two schemes with a negative NPC of the grid.

Figure 8 shows the total NPC and COE of the system configurations for different options. For the considered systems, the PV-BES configuration has the lowest NPC and COE, followed by PV only configuration and normal condition. It can be noted that the normal condition means that the load of the house is totally supplied by the grid without the installation of rooftop solar PV. Between the proposed schemes, the ToU-Flat scheme is the best compared to other schemes.

Table 2 lists the economic data and comparison of two configurations for four schemes. The minimum COE is obtained for the PV-BES configuration under the ToU-Flat scheme (25.54 ¢/kWh), which is almost half of the COE in the PV only configuration under the Flat-ToU scheme. Flat-ToU seems to be the worst scheme with the highest COE around 43.46 ¢/kWh. Besides, installing the BES in the PV-BES configuration would

 

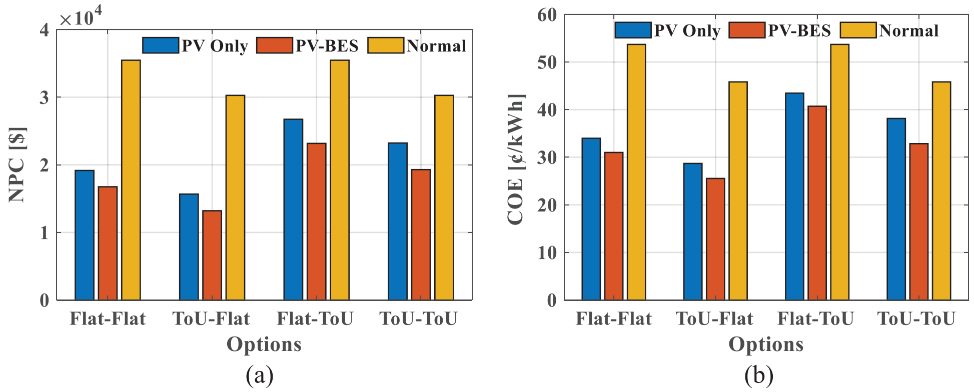


**FIGURE 8** Comparison of optimal results for four schemes and three configurations. (a) NPC. (b) COE

**TABLE 2** Comparison of economic benefits of the proposed EMSs for one year under four schemes and two configurations

| Scheme | Flat-Flat | | ToU-Flat | | Flat-ToU | | ToU-ToU | |
|---|---|---|---|---|---|---|---|---|
| Configuration | PV only | PV-BES | PV only | PV-BES | PV only | PV-BES | PV only | PV-BES |
| Cost of Energy (¢/kWh) | 33.98 | 31.00 | 28.69 | 25.54 | 43.46 | 40.71 | 38.14 | 32.85 |
| Economic benefits compared to PV only | – | 8.77% | – | 10.98% | – | 6.33% | – | 13.87% |
| COE when load met by the grid (c/kWh) | 53.69 | | 45.82 | | 53.69 | | 45.82 | |
| Economic benefits of proposed system | 36.71% | 42.26% | 37.39% | 44.26% | 19.05% | 24.18% | 16.76% | 28.31% |

achieve 6.33% to 13.87% economic benefits compared to the PV only configuration. It is more economical to install a PV-BES system for a grid-connected household with the ToU-Flat electricity scheme. The outstanding performance for the proposed EMS under ToU-Flat may promote the installation of the rooftop solar system and the expansion of the PV and BES market.

This work only attempts to optimize the capacity of solar PV and BES for grid-connected houses under different electricity tariffs. It is notable that the rates of the tariffs are constant, and they are not optimized in this paper as they are determined by grid authority. Based on the combinations of the electricity tariffs for RP and FiT, four options have been investigated for optimal sizing. The results of tariff schemes are different, and hence a practical guideline can be provided for the consumers. For example, if the consumers would like to first select the tariff scheme and then purchase PV and BES, then the ToU-Flat tariff scheme is the most economical one if the consumers purchase 10 kW of PV and 6 kWh of BES. On the other hand, if the consumers already have their own electricity tariff scheme, they can simply follow the results in Figure 6 to purchase the correct capacity of PV and BES.

## 5.2 | Calculation time for optimal planning

The calculation time for optimal planning varies with the scheme and configuration. An Intel® Core i7-7700 CPU @ 3.60 GHz, RAM 16.0 GB computer is used to run the simulations on MATLAB. It should be noted that, to execute the user-written codes, MATLAB uses only one core of CPU. Table 3 shows the needed calculation time to solve the optimal planning problem of the systems for 1 and 10 runs. As shown in the table, the calculation time of the PV-BES system configuration is greater than that of the PV only configuration for all schemes. This is due to the fact that the number of decision variables is higher in the PV-BES system. On the other hand, the calculation time increases for the schemes with ToU tariff since the rule-based EMS is more complicated. Optimal planning of the PV-BES configuration under ToU-ToU scheme needs the highest calculation time.

## 5.3 | Sensitivity analysis of the system

Since the previous section determined ToU-Flat as the best scheme in terms of COE, this section investigates the sensitivity analyses of the system under ToU-Flat tariffs by varying the household load, export power limitation, as well as PV and BES costs. The purpose is to determine how different parameters affect the performance and optimization results of the proposed system.

Figure 9 shows the COE and optimal capacity of components for two configurations. In Figure 9a, for PV only configuration, with the increase of household load, the PV capacity will gradually increase from the initial capacity of 9–12 kW. When the

**TABLE 3** Comparison of calculation time for optimal planning of four schemes and two configurations

| Scheme | Flat-Flat | | ToU-Flat | | Flat-ToU | | ToU-ToU | |
|---|---|---|---|---|---|---|---|---|
| **Configuration** | **PV only** | **PV-BES** | **PV only** | **PV-BES** | **PV only** | **PV-BES** | **PV only** | **PV-BES** |
| Calculation time (one run) | 34.56 s | 81.23 s | 43.87 s | 93.11 s | 45.01 s | 97.38 s | 59.41 s | 112.02 s |
| Calculation time (10 runs) | 402.15 s | 948.01 s | 498.65 s | 998.79 s | 523.87 s | 1076.25 s | 597.21 s | 1145.69 s |

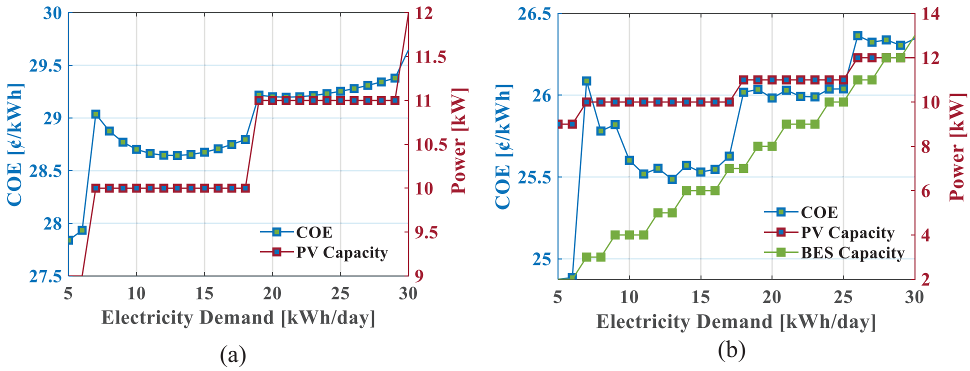


**FIGURE 9** Sensitivity analysis for the household average daily load consumption. (a) PV only. (b) PV-BES

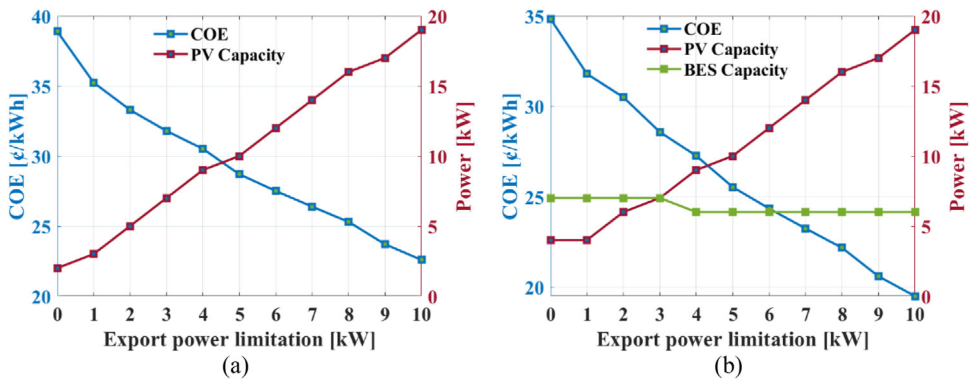


**FIGURE 10** Sensitivity analysis for power that can be exported to the grid. (a) PV only. (b) PV-BES

PV capacity changes, the COE will increase significantly due to the additional NPC of components. In Figure 9b for configuration 2, the maximum COE is 26.36 ¢/kWh, which is less than 29.65 ¢/kWh in configuration 1. The variation of PV capacity is almost the same, but it reaches its maximum (i.e. 12 kW) at a lower demand. The capacity of BES is gradually increased from 2 to 13 kWh. In terms of the COE, there is a decline in the first half of the graph. The COE in the second half fluctuates slightly under the same PV capacity.

Figure 10 indicates the sensitivity analysis of COE and capacities of PV and BES for different export power limits. For the PV only configuration, a 2-kW solar PV is the best capacity when selling power to the grid is prohibited. With the increase of export power limit, the optimal capacity of solar PV also increases, reaching 19 kW when the export power limit is 10 kW. At the same time, the COE decreases as the allowable export power increases, which is 38.89 ¢/kWh when the allowable export power is zero, and 22.58 ¢/kWh when the allowable export power is limited to 10 kW. Dumped energy in this configuration fluctuates between 0.13 and 0.79 MWh. For the PV-BES configuration, the BES capacity is not sensitive to the variation of export power limitation. Higher export power limitation reduces the BES capacity from 7 to 6 kWh. When exporting power to the grid is not allowed, the PV capacity is 4 kW, which is larger than that of the PV-only configuration. The maximum PV capacity is the same as configuration 1 (19 kW). The COE is reduced with the installation of BES, ranging from 34.84 to 19.5 ¢/kWh under the minimum and maximum export power restrictions, respectively. Dumped energy fluctuates between 0.22 and 1.34 MWh with the use of BES.

Figure 11 shows the sensitivity analysis of COE and optimal capacities of PV and BES versus the cost of PV. Figure 11a shows that, in the PV only configuration, the relationship between the COE and the PV cost is almost linear. The COE

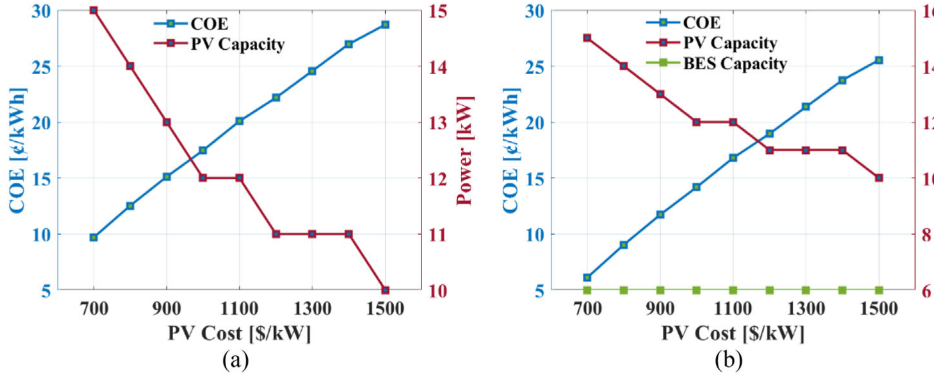


**FIGURE 11** Sensitivity analysis for the unit price of PV of the typical home in Australia. (a) PV only. (b) PV-BES

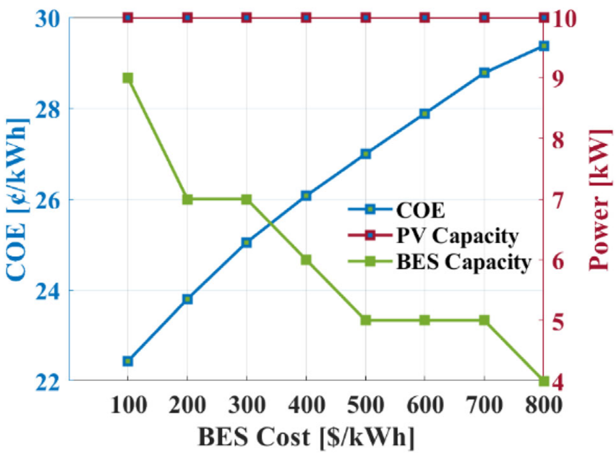


**FIGURE 12** Sensitivity analysis for the unit price of the typical home in Australia for PV-BES configuration

increases from 9.70 ¢/kWh at a unit PV cost of $700 to 28.69 ¢/kWh at a unit cost of $1500. The optimal capacity of PV is decreased from 15 to 10 kW with the increase in PV cost. Figure 11b shows that the variation of the PV capacity in the second configuration is the same as the first configuration. The optimal BES capacity is not sensitive to the cost of PV, and it remains constant at 6 kWh. The COE starts at 6.11 c/kWh and accounts for 63% of the PV only configuration. Moreover, the COE ends up at 25.54 ¢/kWh, which is 89% of the PV only configuration. This means that the PV-BES configuration has better economic benefits at a lower PV cost compared to the PV only configuration.

Figure 12 illustrates the value of COE and optimal capacity of components when the cost of BES varies. It is found that the optimal PV capacity is insensitive to the cost of BES as it remains unchanged at 10 kW. The increase in the price of BES leads to a downward trend in the BES capacity. When the BES cost is cheap ($100/kWh), the optimal capacity of BES is 9 kWh. When the BES cost is expensive ($800/kWh), the optimal capacity of BES is 4 kWh. In terms of the value of COE, it increases from 22.43 to 29.37 ¢/kWh when the BES cost increases from $100/kWh to $800/kWh. The slope of the COE graph is decreased, which means that when the cost of BES increases, the effectiveness of BES installation for economic benefits decreases.

## 5.4 | Operational analysis of the system

Although this study considers the operation for the entire year, the operational analysis has been illustrated for sample 48 h in summer and winter. It is notable that these two sample days for different seasons were selected due to high and low solar insolation and temperature in summer and winter, respectively. It aims at the dynamic performance illustration of the system under two extreme conditions of high and low generated power by the PV. Figure 13 shows the 48-h power flow results. Due to the higher solar insolation, the output power of solar PV is much higher in summer. The peak power delivered by the 10-kW solar PV in summer and winter is 6.4 and 2.3 kW, respectively. In terms of the grid power, the total import and export energies are 18.41 and 71.49 kWh, respectively. The corresponding values for winter are 23.87 and 13.03 kWh. It may be noted that the negative value of the grid means selling power to the grid. Regarding the dumped energy, it only occurs in one day in summer (2.7 kWh). At that time, the electricity that can be sold to the grid reaches its limit of 5 kW.

Figure 14 illustrates the power flow results of the PV-BES configuration. The total import and export energies in summer are 11.64 and 62.83 kWh, respectively. The corresponding values for winter are 16.40 and 2.5 kWh. Regarding the BES power, it may be mentioned that the positive value of BES means the battery is charged, and the negative value of BES is for discharging. The overall charged and discharged energies of BES in summer are 9.83 and 6.77 kWh, respectively. The corresponding values for winter are 10.54 and 7.46 kWh. It can be found that the exchanged power of the BES is increased, and exchanged power of the grid is decreased in winter. Dumped energy of two days in summer is 1.94 kWh.

Comparing Figures 13 and 14, it can be found that with installing the BES, the import power from the grid during the peak period (6–10 PM) is reduced and replaced by the power released by BES. Besides, less energy is dumped because it is

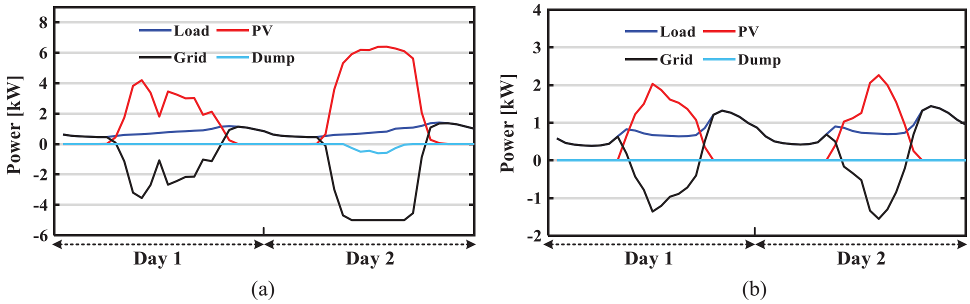


**FIGURE 13** Power flow analysis of PV only configuration. (a) Two days in summer. (b) Two days in winter

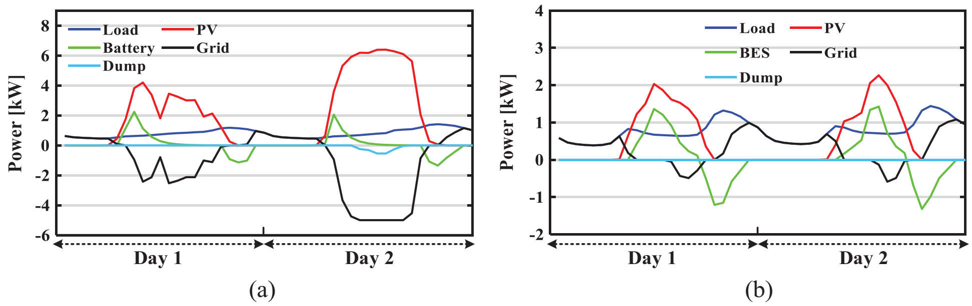


**FIGURE 14** Power flow analysis of PV-BES configuration. (a) Two days in summer. (b) Two days in winter

**TABLE 4** Daily average energy demand, daily average insolation, and annual average temperature for each scenario

| Scenario | Average temperature (°C) | Daily average insolation (kWh/day) | Daily averageenergy demand (kWh) |
|---|---|---|---|
| 1 | 16.7 | 5.3 | 15.6 |
| 2 | 17.4 | 5.1 | 15.0 |
| 3 | 16.5 | 5.6 | 16.3 |
| 4 | 16.6 | 5.2 | 15.1 |
| 5 | 16.8 | 5.0 | 15.2 |
| 6 | 16.4 | 5.1 | 15.9 |
| 7 | 17.2 | 5.7 | 14.4 |
| 8 | 17.1 | 5.0 | 14.7 |
| 9 | 17.5 | 5.3 | 16.9 |
| 10 | 17.8 | 5.4 | 16.1 |

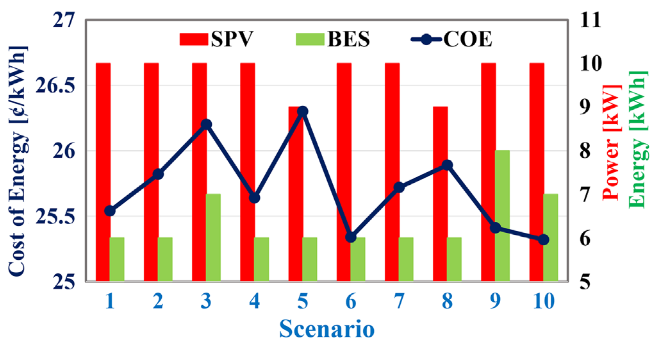


**FIGURE 15** Optimal capacity and COE in various uncertainty scenarios for the ToU-Flat scheme in PV-BES system

used to charge the BES. The PV-BES configuration reduces the dependency on the grid, and it increases the benefits from the electricity price variation of ToU.

## 5.5 | Uncertainty analysis

It is important to approve the results of the optimal sizing method under uncertainties of load and solar. Hence, various scenarios of load consumption and solar data variations are investigated based on 10-year actual data. Table 4 presents the daily average energy demand, daily average insolation, and annual average temperature for data in ten different scenarios [10].

The uncertainty analysis is investigated for the ToU-Flat scheme in PV-BES configuration. Figure 15 indicates the COE and optimal capacity of PV and BES in various uncertainty scenarios. It is demonstrated that the capacity of PV is obtained as 10 kW for eight of ten scenarios, and the capacity of BES is obtained as 6 kWh for seven of ten scenarios. This can confirm the obtained capacities of the PV and BES, which almost remain constant against the uncertainties of load, insolation, and temperature. The COE varies between 25.4 and 26.1 ¢/kWh for the conducted scenarios.

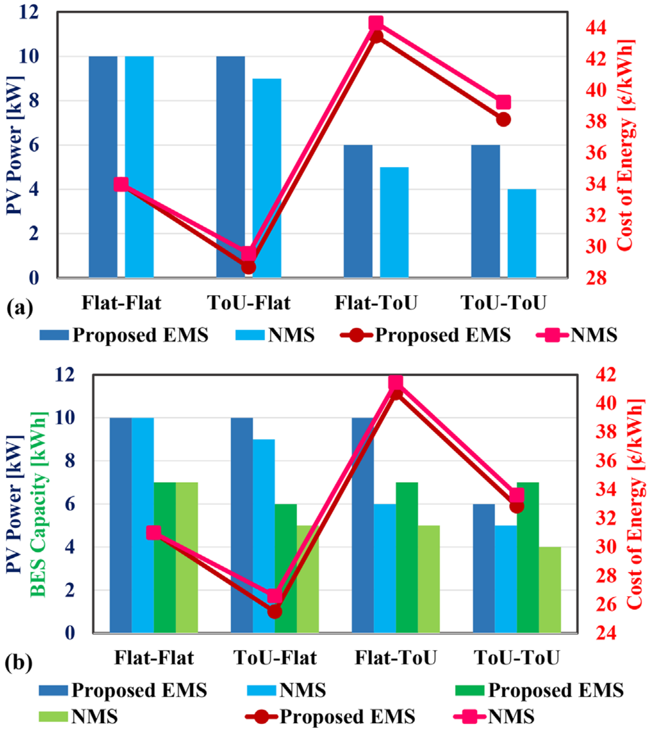


**FIGURE 16** Comparison of the new EMSs with the net metering scheme, (a) PV only system, and (b) PV-BES system

### 5.6 | Comparison with net metering scheme

The optimal sizing method based on the developed EMSs in this study is compared with that of traditional net metering scheme (NMS). The NMS was investigated for the same system configurations in [18]. Figure 16 illustrates the comparison of the results in this study and those of [18]. As indicated, the COE and optimal capacity of PV and BES are obtained the same in both studies. This is because of the constant rates for RP and FiT, which makes the EMS simple. In all other schemes, the COE of both system configurations is obtained lower within the proposed EMSs of this study. Furthermore, the capacities of PV and BES are obtained higher when the proposed strategy is applied. It can be inferred that while the proposed strategy obtained a higher capacity of components, it resulted in lower COE.

## 6 | CONCLUSION AND FUTURE WORK

The main contribution of this study was to optimize the capacity of PV and BES with new rule-based EMSs according to the ToU and Flat electricity tariffs for grid-connected households in four schemes of the RP and FiT: (1) Flat-Flat, (2) ToU-Flat, 3) Flat-ToU, and (4) ToU-ToU. It was found that the ToU-Flat scheme (i.e. ToU rate for electricity purchase and Flat rate for electricity sale) acquired the lowest COE of 25.54 ¢/kWh for PV-BES configuration. The ToU-Flat scheme saved about 11% of COE compared with the PV only configuration, and it saves 46% of COE compared with the case of completely purchasing electricity from the grid. The Flat-ToU scheme was not recommended because it is the most expensive between the options. The uncertainty analysis showed that 10 kW of PV and 6 kWh of BES are reliable capacities for the components against the uncertainties of load consumption and solar insolation. Comparison between the proposed EMSs and the well-known net metering scheme showed that the proposed EMSs result in lower COE for all options. It is notable that a case study of South Australia was considered to examine the methodology; however, the proposed method is generic and can be applied to any other case study.

This work can be further extended by applying the RTP electricity scheme. The RTP has a high resolution in terms of price changes, which can expand the schemes of consumers to deploy the best scheme for buying and selling electricity. Additionally, another future work includes developing a long-term (multi-year) system operation to include the battery's capacity degradation during the system operation. This is due to the fact that the battery degradation over years may affect the system operation.

## CONFLICT OF INTEREST

None

## DATA AVAILABILITY STATEMENT

None

## ACKNOWLEDGEMENT

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## NOMENCLATURE

### Parameters

| | |
|---|---|
| $C_s, C_p$ | Selling/purchase price of electricity ($). |
| $C_{PV}^{cap}, C_{BES}^{cap}$ | Capital cost of PV/BES ($). |
| $C_{PV}^{o\&m}, C_{BES}^{o\&m}$ | Operation and maintenance cost of PV/BES ($). |
| $C_{PV}^{r}, C_{BES}^{r}$ | Replacement cost of PV/BES ($). |
| $CRF_c$, $CRF_e$ | Capital recovery factor of components/electricity. |
| $g$ | Real interest rates (%). |
| $i$ | Interest rates (%). |
| $n$ | Year. |
| $P_{BES}^{max}$ | Maximum output power of BES (kW). |
| $P_{grid}^{max}$ | Maximum export power limit to the grid (kW). |
| $P_{pv}^{max}$ | Maximum output power of PV (kW). |
| $q$ | Escalation rates (%). |
| $r$ | Component's lifetime (year). |
| $SOC^{max}, SOC^{min}$ | Maximum/minimum SOC of BES (%). |
| $U$ | Total time intervals of operation (hr). |
| $\Delta t$ | Time interval (hr). |
| $\eta_{ch}, \eta_{dis}$ | Charging/discharging efficiency of the BES (%). |

## Variables

$COE$ Cost of energy of the system (¢/kWh).
$E_{BES}$ BES capacity (kWh).
$E_{load}$ Annual household load (MWh).
$N_{BES}$ Number of BESs.
$N_{PV}$ Number of PVs.
$NPC_c$ Net present cost of components ($).
$NPC_e$ Net present cost of electricity trade with grid ($).
$P_{BES}$ Rated power of BES (kW).
$P^{cha}_{BES}$, $P^{dis}_{BES}$ Charged/discharged power of BES (kW).
$P^{in}_{BES}$, $P^{out}_{BES}$ Available input/output power for charging/discharging of BES (kW).
$P_{dump}$ Dumped power (kW).
$P^{im}_{grid}$, $P^{ex}_{grid}$ Import/export power from/to the grid (kW).
$P_{pv}$ PV capacity (kW).
$P_{load}$ Household load power (kW).
$P_{re}$ Solar PV generations (kW).

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