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ORIGINAL RESEARCH

# Optimal capacity of solar photovoltaic and battery storage for grid-tied houses based on energy sharing

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**Abstract**

This paper determines the optimal capacity of solar photovoltaic (PV) and battery energy storage (BES) for a grid-connected house based on an energy-sharing mechanism. The grid-connected house, also mentioned as house 1 where it is relevant, shares electricity with house 2 under a mutually agreed fixed energy price. The objective is to minimize the cost of electricity (COE) for house 1 while decreasing the electricity cost of house 2. Practical factors such as real data for solar insolation, electricity consumption, grid constraint, ambient temperature, electricity rate, and battery degradation are considered based on actual data. The developed methodology is examined by taking the actual load data of two houses in South Australia. Different scenarios of contract years between the houses are investigated to make it more practical in real life. Sensitivity analyses are conducted for the sharing of energy between the houses and by changing parameters like export power limitation, load of houses, and costs of PV and BES. Likewise, operational analysis is done for two days of summer and winter. It is found that when energy sharing is applied, the optimal design of the PV-BES system will achieve lower COE for both houses.

## 1 | INTRODUCTION

Global energy demand is increasing with an annual incremental rate of 4% due to population growth, human comfort, and increased industrialisation [1]. A total of 36% of carbon emission is from residential and commercial buildings, as it is estimated that 40% of global energy demand is consumed by these buildings [1]. To decrease the carbon footprints and satisfy the increment of electricity demand, renewable energy (RE) is seen as the only option as of today and the rooftop photovoltaic (PV) system is considered the most effective RE source for the residential sector. The PV systems installed in residential buildings are expected to increase from 104 GW in 2014 to 1.8 TW by 2040 [2]. Solar PV households fulfil the electricity demand by the RE source and sell the extra electricity to the grid; however, the current restriction on the amount of energy that can be sold to the grid, low feed-in tariff (FiT) rate, and the current price of battery energy storage (BES) make selling energy to the grid less attractive option for the householders [3].

At the end of December 2020, 2.66 million Australian households had installed PV panels on their rooftop which accounts for 21% of houses in Australia which is the highest installation of residential rooftop PV panels worldwide. Additionally, the installation has increased steadily over the past 5 years [3]. Exponential growth started in the year 2018 in which five rooftop PV systems were installed every hour, and more than one-third of the Australian residents had solar PV integrated systems by the end of June 2019 [4]. Not only the PV system, over the last 5 years, growth is also seen in the home BES systems in Australia. Since 2015, it has been outlined that 73,000 home has installed the BES system in Australia which is only 8% of households that installed rooftop PV system [1]. To achieve the maximum economic and technical benefits for households, it is important for grid-connected houses to select the optimal capacity of PV and BES which is considered a major problem. There are important parameters such as incorporating actual data, degradation and salvation value of BES system and PV, as well as grid constraints, to find the optimal solution [5].

The growing penetration of distributed energy resources will become an issue which affects the energy market. Thus, it is important to implement new approaches in the market to make the energy market flexible and decentralized. The best method is to create a local market by cutting off the intermediaries such as electricity providers. This is known as energy sharing that enables electricity trading between consumers and prosumers directly [6]. Research in energy sharing between houses has been done during the last few years.

The major elements and technologies involved in peer-to-peer (P2P) energy trading were identified and classified using a hierarchical architecture model [7]. A framework for P2P energy trading was created and game theory was used to simulate P2P energy trade-in [7]. This paper mainly focused to make a platform for trading but does not include the conditions that lead to benefits for households like mutually agreed prices. The authors in [8] have proposed a P2P trading platform with the idea of multiclass energy management between prosumers with heterogeneous preferences. It does not give a clear idea about the flexibility of the contract, and it is also not scalable, as mentioned in the paper. As it also has a trading platform, it does not discuss what happens in the context of mutually agreed energy prices. The authors in [9] have created a marketplace where households who cannot afford PV can buy electricity from the house with PV. A part of this paper resembles our research paper, but the optimal solution is missing and constraints such as grid restriction are not applied.

The game theoretic approach is one of the popular and widely used trading mechanisms for fairness of cost between the household. Ref. [10] has proposed energy management in P2P networks using a game theoretic approach. Additionally, this paper also discusses electric vehicles, distributed RE, and storage while the proposed P2P network is just for the prosumers and the households who do not have PV and BES systems. Refs. [11–14] propose similar approaches as [10] where game theoretic approach is used for P2P energy trading. However, design constraints and whether consumers can take part in the network, or it is just for the prosumers are not clear in these papers. The mixed integer linear programming model is presented in [15] to reduce the energy cost for commercial and residential households and guarantees fairness in trading in addition to the scheduled demand response without clarifying the flexibility of consumer joining the network and coming out of the network. However, the existing studies on P2P have not applied optimal sizing of solar PV and BES.

Table 1 shows the summary of current approaches in P2P energy sharing and optimal sizing for grid-connected households. The existing studies are investigated in terms of energy sharing, mutually agreed price, contract flexibility, and optimal sizing. As indicated in Table 1, the optimal sizing of PV and BES for a grid-connected house by considering energy sharing is not studied before.

The main contributions of this paper compared to the previously studied works on energy sharing have been summarized below:

**TABLE 1** Summary of current studies on energy sharing and optimal sizing.

| Papers | Energy sharing | Mutually agreed price | Contract flexibility | Optimal sizing |
|---|---|---|---|---|
| 6 | √ | × | × | × |
| 7 | √ | × | × | × |
| 8 | √ | × | × | × |
| 9 | √ | × | × | × |
| 10 | √ | × | × | × |
| 11 | √ | × | × | × |
| 12 | √ | × | × | × |
| 13 | √ | × | × | × |
| 14 | √ | × | × | × |
| 15 | √ | × | × | × |
| This Paper | √ | √ | √ | √ |

- Optimal sizing of PV and BES is conducted for the first time by considering energy-sharing mechanisms between two households. The system is modelled such that the household who intends to purchase PV and BES can consider energy sharing with house 2 from the beginning of the project. All practical parameters like actual data, grid constraint, battery degradation, and salvation value are applied in the developed model.
- A mutually agreed price is applied for the shared energy between the houses. In the main scenario, it is assumed that this price is in between the FiT and retail price so that the household with PV and BES benefits by selling energy to house 2 despite simply selling back to the grid at a low price. On the other hand, the other households who purchase energy from the house with PV and BES can buy electricity at a lower price compared to the retail tariff. Then, a sensitivity analysis is conducted to investigate the impact of various mutually agreed prices on the optimal sizing.
- A flexible contract is considered between the houses for energy sharing. Unlike the existing studies that consider a fixed contract between the houses, this study applies flexible contracts where the houses can extend or intercept their contracts for any reason after an annual operation during the planning horizon. This means that the applied contract is yearly. Different cases of flexible contracts are investigated and discussed.

The remainder of this paper is structured as follows: Section 2 presents the methodology which is divided into the developed home energy management system (EMS) and the optimization model. Section 3 describes the case study used to examine the methodology. Section 4 includes the results of the optimization problem and Section 5 includes the conclusion and future works.

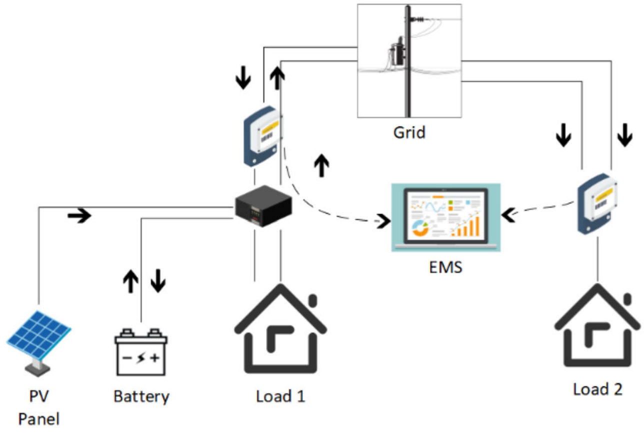



**FIGURE 1** System configuration with energy sharing between house 1 and house 2.

## 2 | METHODOLOGY

A system configuration with two houses (i.e., loads) connected to the main grid is considered in this study. It is assumed that house 1 intends to purchase the optimal capacity of PV and BES, considering energy sharing with house 2. Figure 1 shows the connections between house 1, house 2, PV, battery, and grid. It is notable that the electricity provider can monitor the agreement between the two houses. But the agreement for the electricity rate of energy sharing should be approved by house 1 and house 2 subject to the electricity provider. The home EMS is scalable, and an algorithm can be developed for $n$ number of houses. House 1 can be taken as a load of n number of houses with PV and battery and house 2 can be taken as a load of n number of houses without renewable energy systems. This case study is a baseline study for future similar work and developing the algorithm for multiple houses at this stage is out of the scope of this study. Below is the discussion on the home EMS for this configuration.

### 2.1 | Home energy management system

Figure 2 shows the flowchart for the rule-based home EMS used in this study. When RE generation is greater than load demand and the available input power of the battery is greater than the net power of generation and load demand of house 1, the remaining power will be used to charge the battery. No electricity will be sold to house 2 and the grid, and no power will be dumped in this case. Grid satisfies all the load demands of house 2.

If RE generation is greater than the load demand of house 1 and the available input power of the battery is less than the net power generation and load demand of house 1, then the remaining power of RE will be shared with house 2 (Equation (1)) and the extra power will be sold to the grid by house 1 (Equation (2)). Any power remaining of RE will be dumped by the control system of PV's inverter (Equation (3)).

$$P^{H1}_{ex,H2}(t) = P_{PV}(t) - P_{L1}(t) - P_{bat,in}(t) \tag{1}$$

$$P^{H1}_{ex,grid}(t) = \max(P_{ex,grid_{max}}, P_{PV}(t) - P_{L2}(t) - P_{bat,in}(t) - P_{L2}(t)) \tag{2}$$

$$P_{dump}(t) = P_{PV}(t) - P_{L1}(t) - P_{bat,in}(t) - P_{L2}(t) - P^{H1}_{ex,H2}(t) \tag{3}$$

The extra electricity needed by house 2 that is purchased from the grid is formulated as:

$$P^{H2}_{im,grid}(t) = P_{L2}(t) - P^{H1}_{ex,H2}(t) \tag{4}$$

When RE generation is less than the load demand of house 1, the available output power of the battery and grid satisfies the load demand of house 1. It is obvious that in this case all the load demand for House 2 is satisfied by the grid. No electricity is sold to the grid and no electricity is dumped.

$$P^{H1}_{im,grid}(t) = P_{L1}(t) - P_{PV}(t) - P_{bat,out}(t) \tag{5}$$

The state of charge (SOC) of the battery in each time interval is measured by:

$$SOC(t + \Delta t) = SOC(t) + \frac{\left(P_{bat,ch}(t)\,\eta_{bat,ch} - P_{bat,dis}(t)/\eta_{bat,dis}\right)}{E_{bc}} \tag{6}$$

Available output power ($P_{bat,out}$) and input power ($P_{bat,in}$) of the battery are calculated by:

$$P_{bat,out}(t) = \frac{E_{bc}}{\Delta t}(SOC_{max} - SOC(t)) \tag{7}$$

$$P_{bat,in}(t) = \frac{E_{bc}}{\Delta t}(SOC(t) - SOC_{min}) \tag{8}$$

### 2.2 | Optimization model

#### 2.2.1 | Objective function

The main objective of this paper is to find the lowest possible COE for house 1 by the optimal capacity of PV and BES. The ratio of total annual electricity cost and total consumption of electricity in a year by a given household is COE for that house. COE of both houses should be calculated by different formulas as house 2 does not have the system components (i.e., PV and

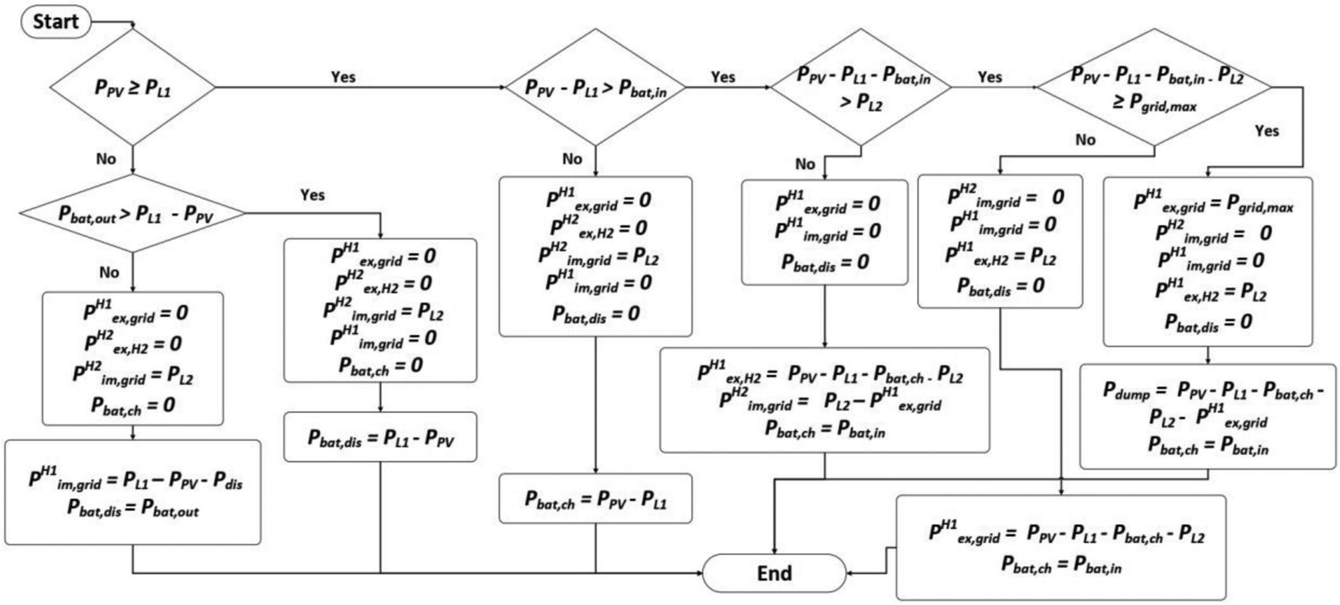



**FIGURE 2** Configuration flow chart for rule-based home energy management system.

BES) and thus net present cost (NPC) and capital recovery factor of system components are not included. The COE can be calculated by the below formula [16]:

$$f = min\left(COE^{H1}\right) \tag{9}$$

$$COE^{H1} = \frac{NPC^{H1}_{comp} CRF_{comp} + NPC^{H1}_{elec} CRF_{elec}}{L^{H1}_{annual}} \tag{10}$$

$$CO\,E^{H2} = \frac{NPC^{H2}_{elec}\,CRF_{elec}}{L^{H2}_{annual}} \tag{11}$$

$NPC^{H1}_{comp}$ which is the NPC of system components is obtained as a function of capital cost, maintenance cost, replacement cost, and salvation cost.

$$NPC^{H1}_{comp} = N_{PV}\left(PC_{c(PV)} + PC_{m(PV)} + PC_{r(PV)} - PC_{sv(PV)}\right) + N_{bat}\left(PC_{c(bat)} + PC_{m(bat)} + PC_{r(bat)} - PC_{sv(bat)}\right) \tag{12}$$

The capital cost of PV panels and battery storage systems is the initial cost invested in the first year when the project starts. We can calculate the present replacement cost for every $Y$ years is calculated as:

$$P\,C_r = C_r \sum_{t=1}^{tY<M} \frac{1}{(1+i)^{tY}} \tag{13}$$

where $M$ is the components' lifetime.

The maintenance cost can be calculated by the following formula:

$$PC_m = C_m\,\frac{(1+i)^M - 1}{i(1+i)^M} \tag{14}$$

where fixed annual maintenance present cost is calculated with the expected interest rate $i$ over the component's life span.

The salvation value of system components can be calculated by the following formula:

$$PC_{sv} = N.PC_c.\frac{A}{T} \tag{15}$$

where $T$ is the total lifetime of system components and $A$ is the remaining lifetime of system components at the end of project life.

The company determines the lifetime of the PV component whereas, for the BES system, the lifetime depends on the degradation of the battery during its operation. When degradation reaches 20%, it is the end of battery life [6]. The BES capacity degradation is a function of depth of discharge (DOD) which is calculated in terms of SOC as follows:

$$DOD\ (t) = 1 - SOC\ (t) \tag{16}$$

The total number of cycles and their linked DOD should be extracted to calculate the degradation of the battery. Battery cycles data were pulled out from yearly DOD data, and Rainflow cycle counting algorithm [6] was used for this purpose. From the algorithm, battery degradation is determined with the help of the experimental data. The laboratory cycle was examined under different stress levels and factors of battery. To find out the battery degradation for each cycle ($c$), this experimental model was calculated as a function of DOD [6].

$$DB\ (c) = \frac{20}{33000.e^{-0.06576.DOD(t)} + 3277} \tag{17}$$

The annual degradation of battery (ADB) for its operating time can be shown below:

$$ADB = \sum DB\ (c) \tag{18}$$

To calculate $NPC_{elec}$, the electricity rate is considered to escalate $e$ on top of interest rate $i$. The real interest rate to calculate the NPC of electricity is the following [4]:

$$r = \frac{i - e}{1 + e} \tag{19}$$

The formula to calculate the annual electricity cost for House 1 integrating with the new formula $r$ will be:

$$NPC_{elec}^{H1} = C_{elec}^{H1} \frac{(1 + r)^n - 1}{r(1 + r)^n} \tag{20}$$

where $n$ is project lifetime.

$C_{elec}^{H1}$ is the sum of buying electricity from the grid with the retail grid rate, selling electricity to the grid with a tariff rate and selling electricity to house 2 with the mutually agreed rate. It can be calculated as follows:

$$\begin{aligned} C_{elec}^{H1} = & \sum_{t=1}^{8760} \left( P_{im,grid}^{H1} (t)\, \Delta t \right) R_{elec} \\ & - \sum_{t\,=\,1}^{8760} \left( P_{ex,grid}^{H1} (t)\, \Delta t \right) R_{tariff} \\ & - \sum_{t\,=\,1}^{8760} \left( P_{ex,H2}^{H1} (t)\, \Delta t \right) R_{H1\_H2} \end{aligned} \tag{21}$$

To calculate the NPC of electricity for house 2 integrating with a real interest rate, the following equation can be used:

$$NPC_{elec}^{H2} = C_{elec}^{H2} \frac{(1 + r)^n - 1}{r(1 + r)^n} \tag{22}$$

$C_{elec}^{H2}$ is the sum of buying electricity from the grid with the retail rate and buying electricity with the mutually agreed rate. It can be calculated by the following formula:

$$C_{elec}^{H2} = \sum_{t\,=\,1}^{8760} \left( P_{im,grid}^{H2} (t)\, \Delta t \right) R_{elec} + \sum_{t\,=\,1}^{8760} \left( P_{ex,H2}^{H1} (t)\, \Delta t \right) R_{H1\_H2} \tag{23}$$

Capital recovery factor is the ratio to calculate the present value of the annuity. Capital recovery factor has a separate formula for components and electricity which is represented below:

$$CRF_{comp} = \frac{i(1 + i)^n}{(1 + i)^n - 1} \tag{24}$$

$$CRF_{elec} = \frac{r(1 + r)^n}{(1 + r)^n - 1} \tag{25}$$

Annual electricity demand for each house can be calculated by the following formulas:

$$L_{annual}^{H1} = \sum_{t=1}^{8760} P_{L1}\ (t)\ \Delta t \tag{26}$$

$$L_{annual}^{H2} = \sum_{t=1}^{8760} P_{L2}\ (t)\ \Delta t \tag{27}$$

Total NPC is calculated by adding NPC of system components ($NPC_{comp}$) and net present cost of electricity ($NPC_{elec}$). The total NPC of each house can be calculated by the following formulas:

$$NPC_{tot}^{H1} = NPC_{comp}^{H1} + NPC_{elec}^{H1} \tag{28}$$

$$NPC_{tot}^{H2} = NPC_{elec}^{H2} \tag{29}$$

### 2.2.2 | Design constraints

Equation (30) represents the constraint for the capacity of the PV panel. Equation (31) represents the constraint for the battery's charge and discharge with respect to available input and output power, respectively, of the battery storage. Equation (32) restricts the state of charge of the battery between its minimum and maximum values. Equation (33) is the constraint for energy balance in each time interval. Equation (34) is the mandatory constraint set up by the Australian government to not sell more than 5 kW of electricity by the single-phase houses.

$$0 \le P_{PV}\ (t)\ \le\ P_{PV,max} \tag{30}$$

$$0 \le P_{bat,im}\ (t)\,,\ P_{bat,ex}\ (t)\ \le\ P_{bat,max} \tag{31}$$

$$SOC_{min} \le SOC\ (t)\ \le\ SOC_{max} \tag{32}$$

$$\begin{aligned} & P_{PV}\ (t) + P_{bat,in}\ (t) + P_{im,grid}^{H1} + P_{im,grid}^{H2}\ (t) \\ & - P_{ex,grid}^{H1}\ (t) \ge\ L_{H1}\ (t) + L_{H2}\ (t) \end{aligned} \tag{33}$$

$$0 \le P_{ex,grid} \le P_{ex,grid_{max}} \tag{34}$$

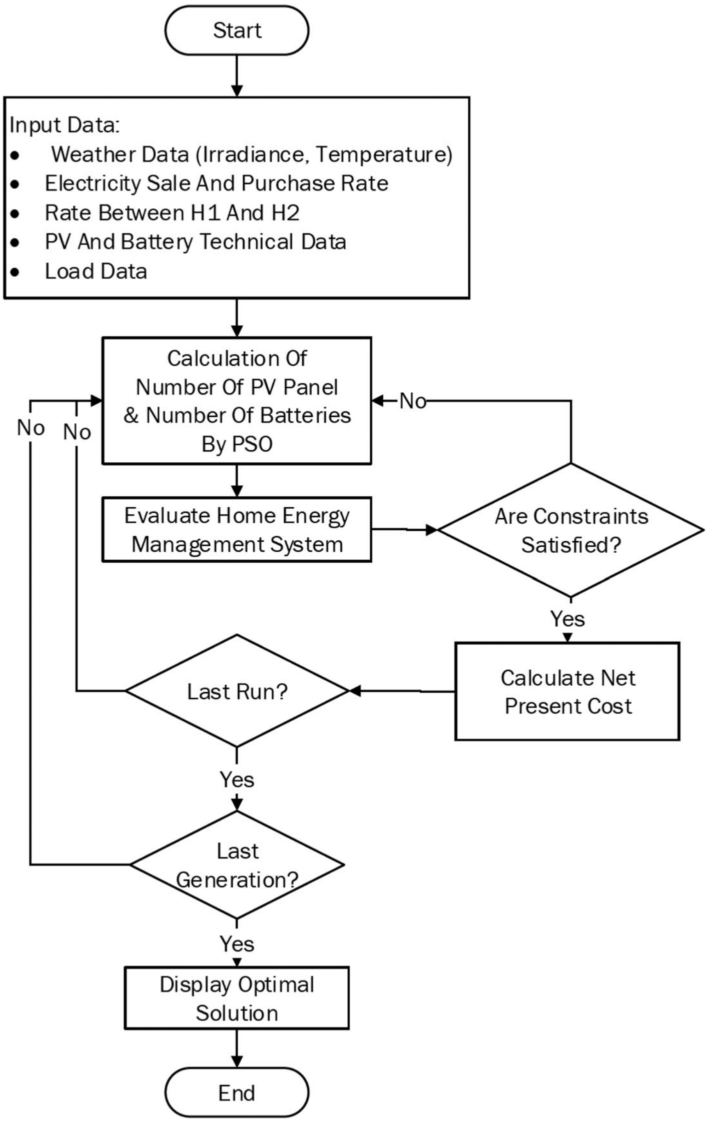



**FIGURE 3** Optimization flow chart for photovoltaic (PV) system and battery energy storage (BES). (PSO: particle swarm optimization, H1: House 1, H2: House 2).

### 2.2.3 | Optimization procedure

The application of a suitable optimization algorithm for the proposed optimal sizing problem is within the scope of this study. Performance of the optimization algorithm as compared to those of available heuristic optimization methods is out of the scope of the paper. Particle swarm optimization (PSO) is used in this study which is widely utilized in power system optimization problems due to its simplicity, suitable convergence rate, not much dependency on initial points, the potential to find global optima, and minimum space requirement [1, 5]. The PSO has been successfully used in the residential system for the optimization of components and optimal results were found [3–5] which verifies the suitability of the PSO for our case study. Figure 3 demonstrates the flowchart of the optimization of the PV panel and BES capacity by the PSO algorithm.

Firstly, all the input data is collected that includes load data, electricity (purchase/sell) rates, the fixed rate between the houses, solar insolation, ambient temperature, and technical data for system components. All the details of the system data are discussed in the next section. The system operation is investigated for a year after number of PV and BES is initially sized by the PSO algorithm. After each operation, the algorithm checks whether design constraints are satisfied. If the design constraints are not satisfied, then it repeats the process of sizing the components. If the design constraints are satisfied, the algorithm calculates the NPC of electricity. After calculating the NPC of electricity, the algorithm checks whether it is the last generation; if not, the sizing of components repeats for other feasible sizes of PV and BES. In this way, many values of NPC are found until the last generation. Then, all the process is repeated for a certain number of runs and optimal solutions are obtained with the lowest NPC. Finally, the results for the run with the lowest NPC are displayed as the best results. To achieve optimum results in this research, 20 runs are carried out for optimization with 200 populations and 200 generations in each run.

For more details, the search space of PSO consists of different particles where each particle contains its velocity and position components. PSO runs by initializing the entire particle population. The velocity and position of particles are iteratively updated using (35). Every particle can save its experienced best position $\chi^{P-best}$ and global best position $\chi^{G-best}$ from earlier states.

$$\begin{cases} v_i\ (g+1) = w.v_i\ (g+1) \\ +c_1\zeta_1 \left[\chi_i^{P-best}(g) - \chi_i(g)\right] + c_2\zeta_2\left[\chi_i^{G-best}(g) - \chi_i(g)\right] \\ \chi_i\ (g+1) = \chi_i(g) + v_i\ (g+1) \end{cases} \tag{35}$$

where $\chi_i$ and $v_i$ are the velocity and position of the particle at $i$ iteration; $c_1$ and $c_2$ are coefficients of acceleration, respectively. Local and global search is balanced in the algorithm by inertia weight represented ($w$). $\zeta_1, \zeta_2 \in [0, 1]$ are two random and independent numbers. $\chi^{P-best}$ and $\chi^{G-best}$ are compared with the current state value for each iteration. According to the swarm's and particle's individual search, each particle moves forward to its local best after each iteration [17]. The parameters such as social weight, cognition weight and inertia weight are selected as 2, 2 and 0.5 respectively.

## 3 | CASE STUDY AND SCENARIOS

The case study is selected as 2 typical houses in South Australia (SA). House 1 has a PV panel and BES and is connected to the grid. House 2 does not have any RE generation and storage system. If house 1 cannot fulfil the demand of house 2, house 2 buys electricity from the grid. The electricity is shared between the houses with mutually agreed energy prices between the houses to benefit both houses.

### 3.1 | Meteorological data

Weather data for a year in South Australia was pulled out from the Australian Government Bureau of Meteorology [18]. Figure 4 shows the ambient temperature and solar insolation for the entire year. The temperature varies from 2.2°C lowest to 41.9°C highest with an average of 17.9°C for a year. The average temperature in winter and summer is 13.9°C and 22.4°C. The average solar insolation is 0.18 kWh/m$^2$, and the peak insolation in a particular year is 0.79 kWh/m$^2$.

### 3.2 | Load profile data

The optimisation model which is developed for this case study is of general nature and can be used for any two houses that agree to share the energy with a mutually agreed price. We took two houses in South Australia for our research. Load consumptions of house 1 and house 2 are shown in Figure 5a,b taken from [6] and [19], respectively. The minimum load demand for house 1 is 0.32 kW, the average load demand is 0.65 kW, and the maximum load demand is 1.65 kW. Whereas for house 2 the minimum load demand is 0.19 kW, the average load demand is 0.63 kW, and the maximum load demand is 2.97 kW.

**TABLE 2** Electricity prices and economic rates. (PV: photovoltaic, BES: battery energy storage, SOC: state of charge).

| Parameters | Value | Parameters | Value |
|---|---|---|---|
| Project lifetime | 20 years | Retail price | 0.34$/kWh |
| Interest rate | 8% | Feed in tariff | 0.12$/kWh |
| Grid escalation rate | 2% | Daily supply of charge | 0.99$/day |
| Mutually agreed rate | 0.20 | PV capital cost | 1500$/kW |
| PV overhaul cost | 300$/kW | BES capital cost | 350$/kWh |
| PV O&M cost | 50$/year | BES overhaul cost | 200$/kWh |
| Maximum grid export power | 5 kW | Time between overhauls | 10 years |
| Battery SOC minimum | 20% | BES efficiency | 95% |
| Battery SOC maximum | 95% | | |

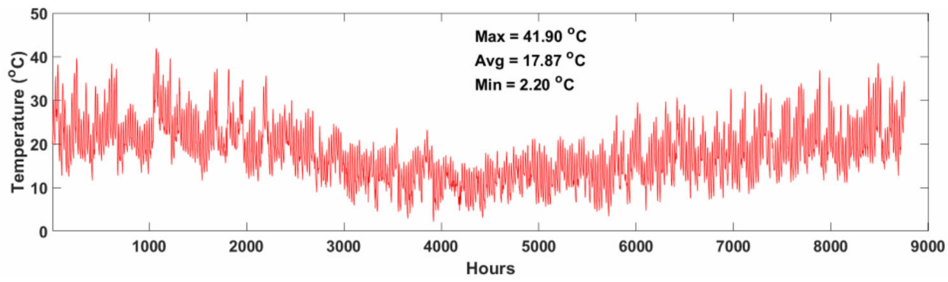
### 3.3 | System components cost, electricity prices and economic rates

Table 2 shows the retail price, daily supply of charge and FiT rate taken from the AGL website, one of the energy providers of Australia [20]. The inflation rate and interest rate are 2% and 8% respectively [21]. Table 2 also shows the components' capital cost, replacement cost, maintenance cost and BES state of charge and efficiency taken from [5]. The project's lifetime is for 20 years. The battery's unit size is considered as 0.5 kW/1 kWh.To any single-phase household, it is restricted to export not more than 5 kW to the grid at any point of time [4]. Mutually agreed rate between the houses is assumed as 0.20$/kWh, and different analysis is done by changing the parameters.

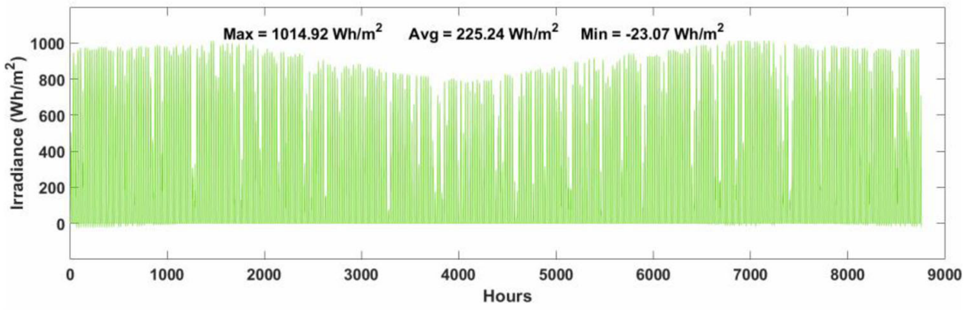
### 3.4 | Different scenarios on mutually agreed rate

The first part of the case study was done for 20 years. Electricity price which was mutually agreed between the houses for 20 years was 20 ¢/kWh. The second part of the case study is done to make it more realistic. There is a good chance that house 2 might not take the whole 20 years of the contract. For this case study house 2 will make a certain year of 1$^{st}$ contract and extends 2$^{nd}$ contract for 70% of the project life if it is happy with the initial contract. The optimal sizing and COE of both houses are calculated for different scenarios.

Figure 6 shows the mutually agreed rate for different scenarios considered in this study. It can be seen in Figure 6 what would be the rate between the two houses if it takes the 1$^{st}$ contract and 2$^{nd}$ contract. To simply understand, in the first row we can see that house 1 and house 2 initial contract is for 2 years, and the rate house 2 is paying to house 1 is 25¢/kWh, House 2 is happy with the contract and amount he saved on electricity, he made a second contract for 13 years with the electricity rate of 21.94¢/kWh. And the remaining 5 years house 2 bought electricity from the grid as the project life is 20 years. All




(a)




(b)

**FIGURE 4** General house in South Australia (SA) annual meteorological data, (a) ambient temperature, (b) solar insolation.

these numbers are reasonably assumed by dividing the cost from 25¢/kWh to 20¢/kWh in equal 20 parts, here when the rate is divided into equal 20 parts, each scenario mutually agreed rate is decreased by 0.27¢/kWh for the initial contract. Four scenarios from the below figure are taken to see the effects on COE for both the houses and discussed in the result section of the paper.

In this study, it is assumed that the optimal sizing is done for one house (house 1 or prosumer) that shares energy with another house (house 2 or consumer). If the economic analysis for each individual house is not required, the EMS and optimization model are extendible and can be easily applied for $n$ houses of prosumers and consumers. In this case, the designed EMS is extendible by collecting all the loads of prosumers and consumers. However, if the economic analysis is required to be clear for each prosumer and consumer, multiple EMSs should be considered in the optimization problem. This means multiple contracts are required between the prosumers and consumers. This type of analysis is out of the scope of the study and can be further studied in future.

# 4 | RESULTS AND DISCUSSION

## 4.1 | Optimization results and discussion

PSO is run 20 times with 100 generations for each run. We selected the best run with the minimum objective function. In this case, the optimal solution was achieved similarly for all runs. Table 3 lists the optimal capacity of the PV and battery storage system, along with the total net present cost and COE of house 1. It also shows dumped annual energy and import and export energy to the grid by house 1. Additionally, it shows the electricity sold to house 2 by house 1. For the below configuration, the optimized PV capacity is found as 10 kW and the battery capacity as 7 kWh. Due to the limitation of 5 kW power export to the grid in South Australia, extra energy produced and not sold would be dumped.

For the first configuration, no PV system is installed in house 1. Hence, the total NPC for house 1 is $26,560.23 and COE is 40.20 ¢/kWh. COE includes a daily supply of charge. Import energy is maximum in this case because there is no Energy source to produce electricity. All the needed electricity to satisfy the load is imported from the grid. Due to the absence of PV and BES, house 1 cannot produce and sell anything to the grid or house 2.

For the second configuration, COE decreased to 33.81 ¢/kWh which is 15.9% reduction in COE compared to the first configuration. Extra energy produced during the daytime is exported back to the grid and insufficient energy needed during the household peak consumption period is imported from the grid. 18 kWh is dumped because of the grid constraint.

For the third configuration, COE was reduced to 31.23 ¢/kWh. This is a 22.3% reduction in COE compared to the first configuration and a 7.6% reduction in COE compared to the second configuration. The net present component cost is the same as the optimal solution of the component is same. Total net present cost decreased 9% compared to the second configuration as the reduction of COE and the net present cost is completely due to energy sold to house 2 as it is found that total annual energy sold is 1552.50 kWh. Export energy to the grid is

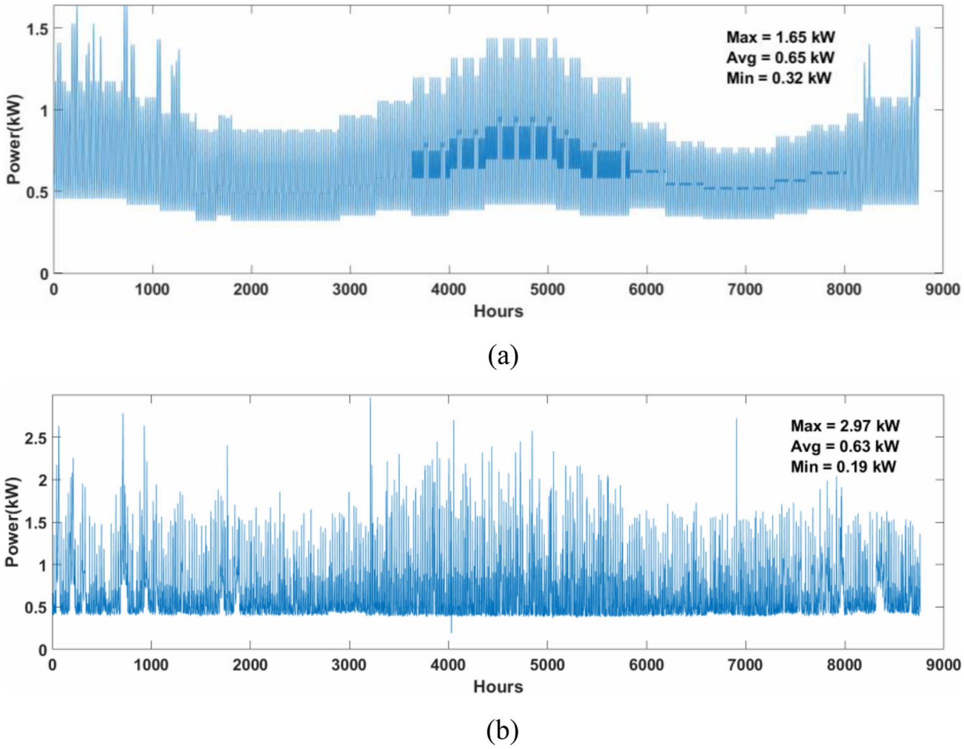



**FIGURE 5** Annual load consumption, (a) house 1, (b) house 2.

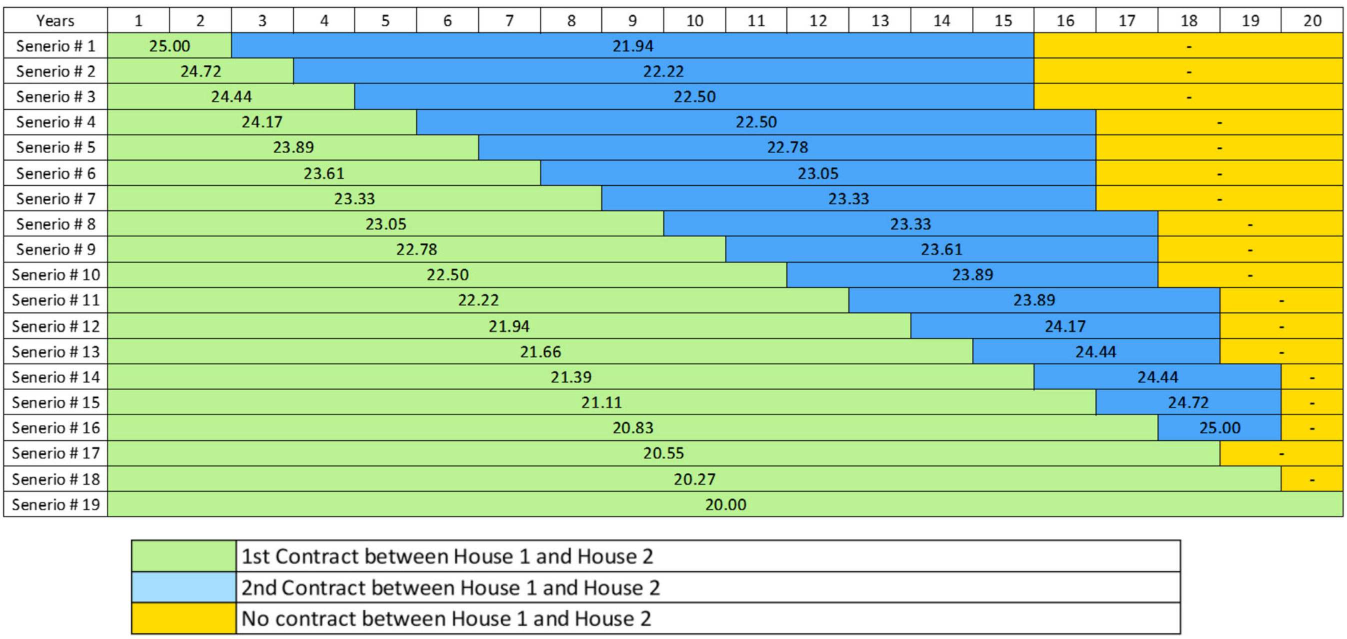

<table>
<tr><th>Years</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th></tr>
<tr><td>Senerio # 1</td><td colspan="2">25.00</td><td colspan="13">21.94</td><td colspan="5">-</td></tr>
<tr><td>Senerio # 2</td><td colspan="3">24.72</td><td colspan="12">22.22</td><td colspan="5">-</td></tr>
<tr><td>Senerio # 3</td><td colspan="4">24.44</td><td colspan="11">22.50</td><td colspan="5">-</td></tr>
<tr><td>Senerio # 4</td><td colspan="5">24.17</td><td colspan="11">22.50</td><td colspan="4">-</td></tr>
<tr><td>Senerio # 5</td><td colspan="6">23.89</td><td colspan="10">22.78</td><td colspan="4">-</td></tr>
<tr><td>Senerio # 6</td><td colspan="7">23.61</td><td colspan="9">23.05</td><td colspan="4">-</td></tr>
<tr><td>Senerio # 7</td><td colspan="8">23.33</td><td colspan="8">23.33</td><td colspan="4">-</td></tr>
<tr><td>Senerio # 8</td><td colspan="9">23.05</td><td colspan="8">23.33</td><td colspan="3">-</td></tr>
<tr><td>Senerio # 9</td><td colspan="10">22.78</td><td colspan="7">23.61</td><td colspan="3">-</td></tr>
<tr><td>Senerio # 10</td><td colspan="11">22.50</td><td colspan="6">23.89</td><td colspan="3">-</td></tr>
<tr><td>Senerio # 11</td><td colspan="12">22.22</td><td colspan="6">23.89</td><td colspan="2">-</td></tr>
<tr><td>Senerio # 12</td><td colspan="13">21.94</td><td colspan="5">24.17</td><td colspan="2">-</td></tr>
<tr><td>Senerio # 13</td><td colspan="14">21.66</td><td colspan="4">24.44</td><td colspan="2">-</td></tr>
<tr><td>Senerio # 14</td><td colspan="15">21.39</td><td colspan="4">24.44</td><td>-</td></tr>
<tr><td>Senerio # 15</td><td colspan="16">21.11</td><td colspan="3">24.72</td><td>-</td></tr>
<tr><td>Senerio # 16</td><td colspan="17">20.83</td><td colspan="2">25.00</td><td>-</td></tr>
<tr><td>Senerio # 17</td><td colspan="18">20.55</td><td colspan="2">-</td></tr>
<tr><td>Senerio # 18</td><td colspan="19">20.27</td><td>-</td></tr>
<tr><td>Senerio # 19</td><td colspan="20">20.00</td></tr>
</table>



**FIGURE 6** Different scenarios case study and mutually agreed rate.

less compared to the second configuration because energy sold was divided between the grid and house 2 for this configuration. Import energy came similar as it depends on the time of use.

Table 4 shows the total NPC and COE of house 2 for two different configurations. One without the contract and another one with 20 years of the contract. As seen in Table 4, the installation of the PV system on house 1 has affected the electricity rate for house 2, this rate is decreased by 9.7% from 40.42¢/kWh to 36.51¢/kWh due to cheap electricity bought from house 1. Likewise, the total net present cost also decreased by 9.6%.

**TABLE 3** Optimized 20 years net present cost (NPC) and cost of electricity (COE) for house 1 with import, export and dumped energy. (PV: photovoltaic, BES: battery energy storage).

| Summary for H1 | PV (kW) BES (kWh) | $NPC^{H1}_{comp}$ (\$) | $NPC^{H1}_{tot}$ (\$) | $COE^{H1}$ (¢/kWh) | Export energy (kWh) | Import energy (kWh) | Sold to H2 (kWh) | Dumped energy (kWh) |
|---|---|---|---|---|---|---|---|---|
| No PV/BES system | 0<br>0 | – | 26,560.2 | 40.2 | – | 5704.9 | – | – |
| PV/BES system, no contract | 10<br>7 | 20,748.7 | 18,610.4 | 33.81 | 7513.0 | 1468.0 | – | 18.0 |
| PV/BES system, 20-year contract | 10<br>7 | 20,748.7 | 16,908.2 | 31.23 | 7236.40 | 1435.90 | 1552.50 | 37.60 |

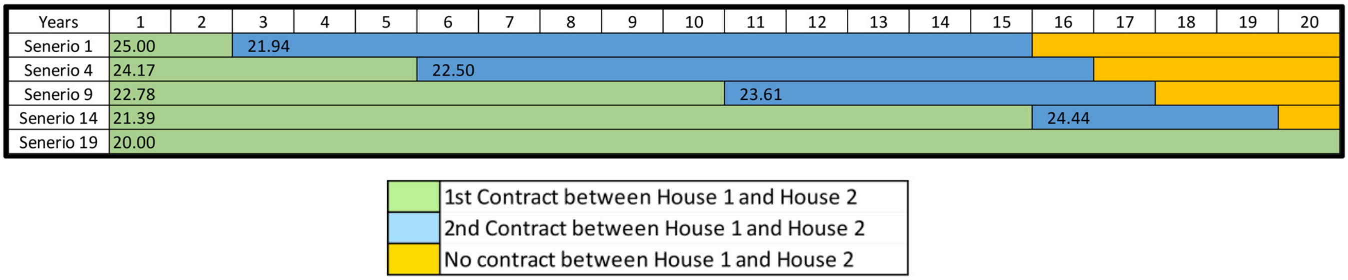



**FIGURE 7** Five real-life scenarios.

**TABLE 4** Total net present cost (NPC) and cost of electricity (COE) for house 2.

| Summary | Years | H1 & H2 electricity rate (¢/kWh) | $NPC^{H2}_{tot}$ (\$) | $COE^{H2}$ (¢/kWh) |
|---|---|---|---|---|
| H2 without any Contract | 20 | – | 25,813.1 | 40.42 |
| H2 with 20 years contract with H1 | 20 | 20.00 | 23,317.7 | 36.51 |

## 4.2 | Calculation time for optimal planning

The optimal planning calculation time varies for different runs. MacBook Pro (M1, 2020), M1 chip, RAM 8 GB computer is used to run the simulations on MATLAB. It is important to know that only one core of the CPU is used by MATLAB to execute the user-written codes. The calculation time of the systems needed to solve the optimal planning problem for 1 run and 20 runs are 19,7s and 332,9s, respectively.

## 4.3 | Case study on a real life scenario

In this section, some real scenarios are studied which is shown in Figure 7.

Five scenarios are discussed in Figure 7 where there are two different contracts between house 1 and house 2, each for a different duration. NPC and COE comparisons for houses 1 and 2 are shown in Tables 5 and 6.

Total NPC is high when house 1 does not have a PV system or when house 1 has a PV system but does not have any contract with house 2 and it gets lower when house 1 sells electricity to house 2. Among them, the lowest NPC for house 1 will be when it makes the initial contract for 10 years, 2nd contract for 7 years, and sell electricity to the grid for the remaining 3 years.

The total COE for house 1 without any PV system is 40.20¢/kWh and with a PV system but no contract with house 2 is 33.81¢/kWh. COE decreases after the contract between house 1 and house 2. The lowest COE is when the initial contract is 15 years, 2nd contract is 4 years and 1 year selling electricity to the grid.

The highest NPC for house 2 is when it buys electricity just from the grid and its NPC decreases gradually as the length of the contract with house 1 increases and it is lowest when it takes a contract of 20 years. COE for house 2 including daily supply of charge follow the same trend as its NPC and it is the lowest when the total contract period is 20 years.

# 5 | ANALYSIS

## 5.1 | Sensitivity analysis

### 5.1.1 | When H1 and H2 electricity contract rate differs

Figure 8 shows the total COE for house 1 is 33.41 ¢/kWh and for house 2 is 34.26¢/kWh when the mutually agreed energy price is 12¢/kWh. When the contract price between the houses increases from 12¢/kWh to 33.88¢/kWh, the electricity cost for house 1 decreases from 33.41¢/kWh to 27.45¢/kWh.

**TABLE 5** Net present cost (NPC) and cost of electricity (COE) Summary for five scenarios of house 1.

| Summary | 1st contract curation (year)<br>2nd contract duration (year)<br>No contract duration (year) | H1 & H2 electricity rate (¢/kWh) | $NPC^{H1}_{elec}$ ($) | $NPC^{H1}_{comp}$ ($) | $NPC^{H1}_{tot}$ ($) | COE (¢/kWh) |
|---|---|---|---|---|---|---|
| H1 (No PV) | 20 | – | 26,560.2 | – | 26,560.2 | 40.20 |
| H1 with PV system without any contract | 20 | – | −2138.25 | 20,749 | 18,610.4 | 33.81 |
| Scenario 1 | 2 | 25 | −751.57 | 20,749 | 16,789.7 | 31.39 |
| | 13 | 21.94 | −2876.28 | | | |
| | 5 | – | −331.06 | | | |
| Scenario 4 | 5 | 24.17 | −1675.03 | 20,749 | 16,607.9 | 31.09 |
| | 11 | 22.5 | −2208.67 | | | |
| | 4 | – | −257.07 | | | |
| Scenario 9 | 10 | 22.78 | −2773.96 | 20,749 | 16,560.4 | 30.89 |
| | 7 | 23.61 | −1227.09 | | | |
| | 3 | – | −187.19 | | | |
| Scenario 14 | 15 | 21.39 | −3457.04 | 20,749 | 16,642.3 | 30.83 |
| | 4 | 24.44 | −590.48 | | | |
| | 1 | – | −58.87 | | | |
| Scenario 19 | 20 | 20 | −3840.43 | 20,749 | 16,908.2 | 31.23 |

**TABLE 6** House 2′s net present cost (NPC) and cost of electricity (COE) summary for five considered scenarios.

| Summary | 1st contract duration (year)<br>2nd contract Duration (year)<br>No contract duration (year) | H1 & H2 electricity rate (¢/kWh) | $NPC^{H2}_{elec}$ ($) | $NPC^{H2}_{tot}$ ($) | COE (¢/kWh) |
|---|---|---|---|---|---|
| H2 without any contract | 20 | – | 25,813.12 | 25,813.1 | 40.42 |
| Scenario 1 | 2 | 25 | 3,840.32 | 24,086.1 | 37.99 |
| | 13 | 21.94 | | 16,249.23 | |
| | 5 | – | | 3,996.55 | |
| Scenario 4 | 5 | 24.17 | 8,782.69 | 24,122.7 | 37.98 |
| | 11 | 22.5 | | 12,236.66 | |
| | 4 | – | | 3,103.36 | |
| Scenario 9 | 10 | 22.78 | 15,222.46 | 24,033.0 | 37.85 |
| | 7 | 23.61 | | 6,550.76 | |
| | 3 | – | | 2,259.79 | |
| Scenario 14 | 15 | 21.39 | 19,918.73 | 23,699.2 | 37.26 |
| | 4 | 24.44 | | 3,069.87 | |
| | 1 | – | | 710.64 | |
| Scenario 19 | 20 | 20 | 23,317.72 | 23,317.7 | 36.51 |

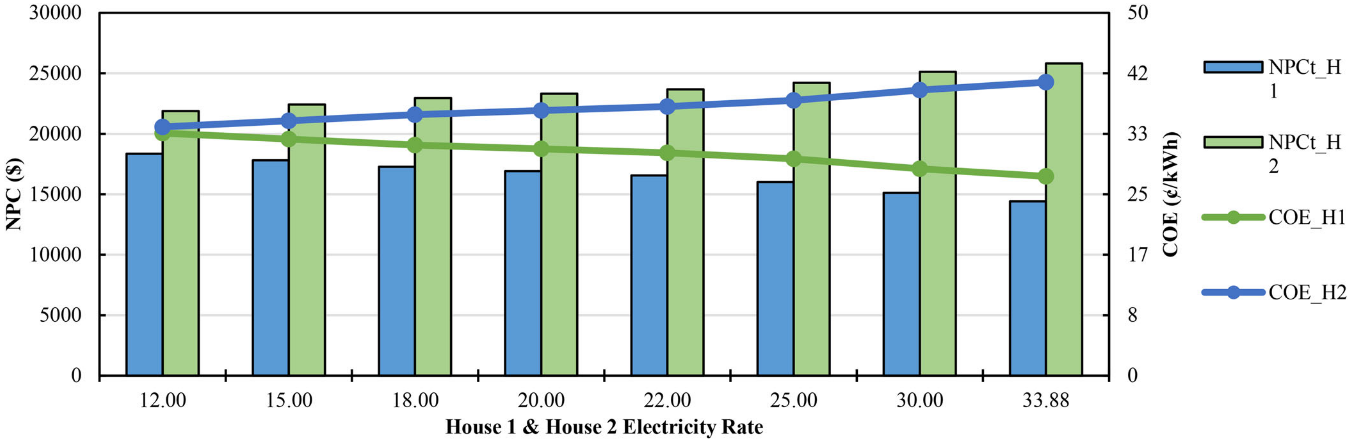



**FIGURE 8** Sensitivity analysis. Comparison of (a) net present cost (NPC) and (b) cost of electricity (COE) of house 1 for 20 years of contract with different electricity rates between houses.

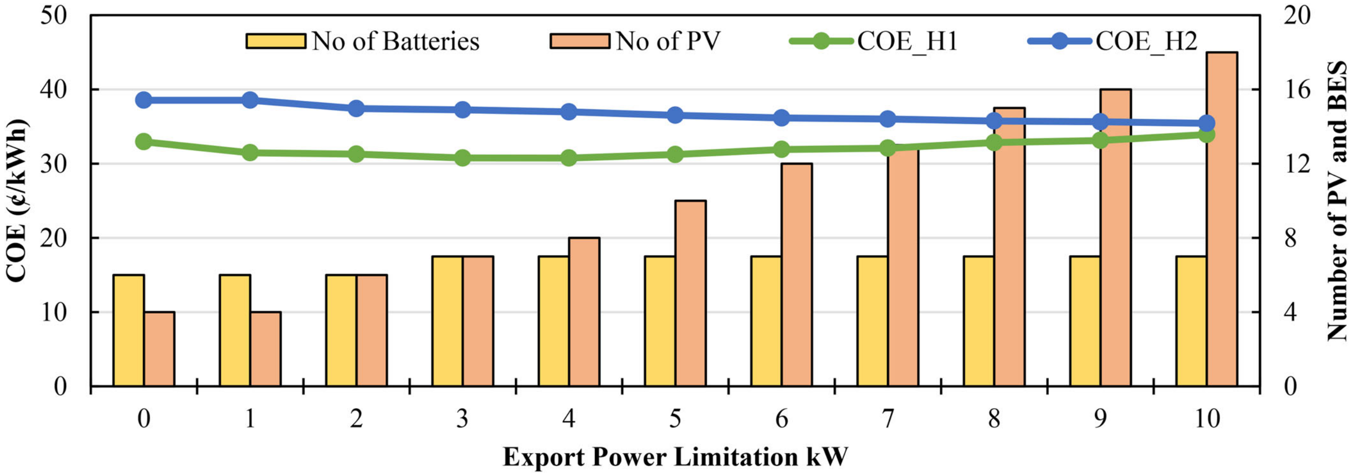



**FIGURE 9** Sensitivity analysis on cost of electricity (COE) when export power limitation is changed from 0–10 kW for (a) house 1 and (b) house 2. (PV: photovoltaic, BES: battery energy storage).

In addition, with the same contract rate between the houses, the electricity cost for house 2 increases from 34.26¢/kWh to 40.42¢/kWh. We can conclude that it is better for house 1 if the mutual sharing energy prices are more and better for house 2 if the mutual sharing of energy prices is less.

### 5.1.2 | When export power limitation is changed

There is a grid restriction in SA for single-phase houses to not export more than 5 kW to the grid. It is important to analyse the effects in COE and optimal sizing for any houses on its impacts which is shown in Figure 9. It presents the graph when grid export limitation varies from 0 to 10 kW for house 1 and house 2 respectively. It is observed that the lowest COE for house 1 is at 3 and 4 kW. This is because as the limitation increases the number of PV starts to increase exponentially which increases COE as COE depends on the components' cost as well. For house 2 COE keeps on decreasing from 0 to 10 kW. This is because the number of PV panels increases, more energy is produced, and house 2 can buy more electricity from house 1. House 2′s COE is not affected by system component cost.

### 5.1.3 | Changing export power limitation (with fixed PV and batteries)

Next analysis is done for an optimal solution when PV and batteries number are fixed which is shown in Figure 10. House 1 sells extra electricity to house 2 and anything extra electricity which house 1 is unable to sell to the grid due to export power limitation at 5 kW will be dumped. As house 1 is unable to take advantage of selling to the grid, its COE is highest when export power limitation is less. When export power limitation is an increased house 1 COE decreases as it can sell extra electricity to the grid. After 6 kW, there will be no power left to sell to the grid as 10 PV and 7 battery is fully functional at that stage and COE remains constant after that value whereas, for house 2, export power limitation does not have any impacts.

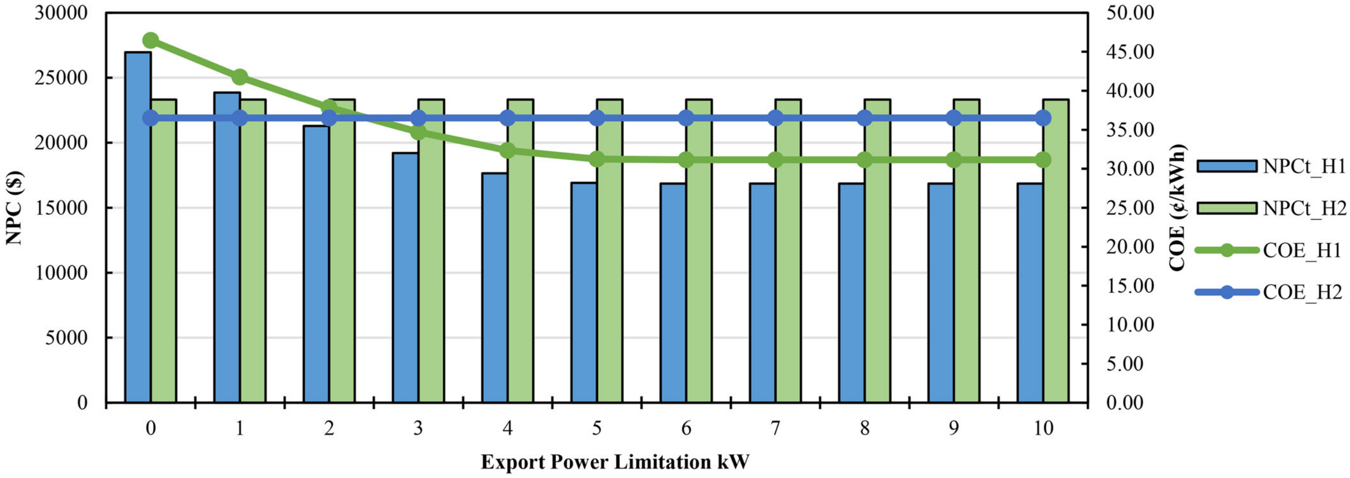



**FIGURE 10** Sensitivity analysis when export power limitation is between 0 –10 kW, and system components are fixed of an optimal solution.

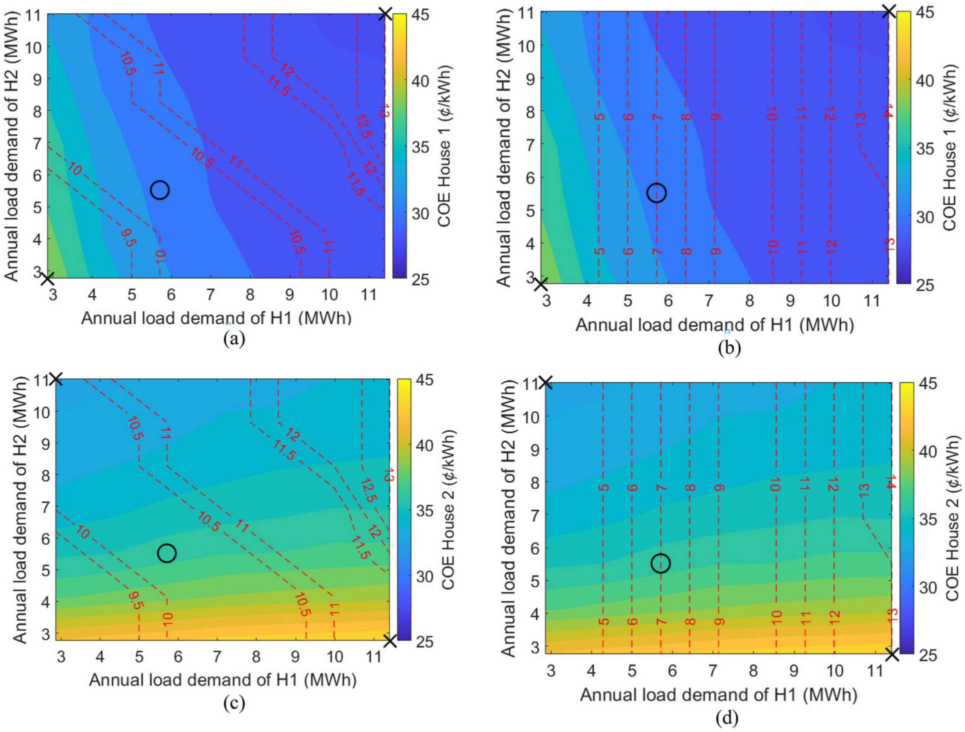



**FIGURE 11** Sensitivity analysis: cost of electricity (COE) for house 1 (a) annual load demand of house 1 versus house 2 (dotted line presents optimal photovoltaic (PV) components), (b) annual load demand of house 1 versus house 2 (dotted line presents optimal battery components), COE for house 2 (c) annual load demand of house 1 versus house 2 (dotted line presents optimal PV components), and (d) annual load demand of house 1 versus house 2 (dotted line presents optimal battery components).

### 5.1.4 | Variation of loads for house 1 and house 2

The sensitivity analysis is done to see the effects on COE when the load of house 1 and house 2 is changed. Figure 11 shows the contour plot diagram of the sensitivity analysis. It can be seen the higher the load of house 1 lesser the COE for house 1. When the load of house 1 is smaller, the cost of PV and battery components are included for COE and the daily supply charge is added on top of these; hence, the COE will be very high for house 1. As the component cost and daily supply charge are fixed, COE decreases with the increase in load demand of house 1 and house 2 because COE is inversely proportional to the annual load demand of houses. The increment of a load of house 2 affects the COE of house 1, this is because of the mutual sharing rate between the houses. If the energy demand of house 2 increases, house 1 can sell more electricity to house 2 utilizing the full capacity of PV and battery. This can be seen in Figure 11a,b

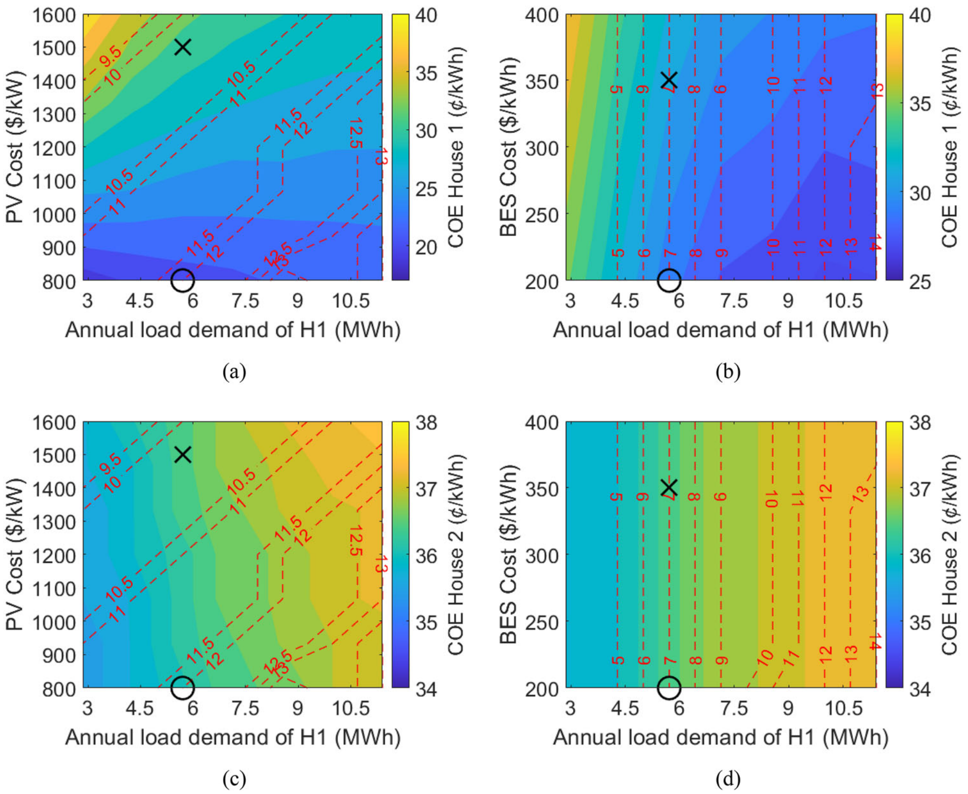



**FIGURE 12** Sensitivity analysis: cost of electricity (COE) for house 1 (a) photovoltaic (PV) cost versus annual load demand of house 1 (dotted line presents optimal PV components), (b) battery energy storage (BES) cost versus annual load demand of house 1 (dotted line presents optimal battery components), COE for house 2 (c) PV cost versus annual load demand of house 1 (dotted line presents optimal PV components), and (d) BES cost versus annual load demand of house 1 (dotted line presents optimal battery components).

Figure 11c,d shows another colour region where the COE of House 2 is shown with the change in a load of both house. The lowest COE for house 2 is when the load of house 2 is highest and the load of house 1 is lowest. House 2 can take full advantage of a PV panel with a lower rate compared to the grid rate. Cross mark (x) in the figure shows the point with the highest and lowest COE and the dot mark (o) in the figure shows the COE of the load of houses that we used in this paper.

### 5.1.5 | PV and battery energy storage cost variations

As PV and BES costs are decreasing due to increasing investment on RE generation, it is important to see their price effects on COE. The sensitivity analysis is done to see the effects on COE for both the house when PV and BES cost varies. Figure 12a shows the colour region for COE of house 1 when PV cost decreases from 1600$/kW to 800$/kW. It can be seen in the cross sign (x) in the figure that presents COE for this paper which decreases substantially when PV cost is reduced to $800 shown in dot sign(o). Figure 12b shows the colour region for COE of house 1 when BES cost decreases from 400$/kWh to 200$/kWh. There is a slight decrease in COE when BES cost decreases to $200 shown in a dot sign.

Figure 12c,d presents the COE for house 2 when PV and BES change respectively. There is almost no change in COE because house 2 does not own PV and BES and change is insignificant.

## 5.2 | Operational analysis

The power flow for two consecutive days in summer and winter is shown in Figure 13a,b, respectively. Please note that the seasons in the southern hemisphere are opposed to those of seasons in the northern hemisphere. Solar PV generation is high in summer due to more sunlight and more solar isolation whereas it is the opposite in winter. During the daytime, almost all the energy for house 1 and house 2 is satisfied by the PV generation whereas at night-time or peak hours, battery satisfies the load of house 1 and buys very less amount of power from the grid. House 2 buys most of the power from the grid during peak hours. As shown in the figure, the export power to the grid does not exceed 5 kW at any time.

# 6 | CONCLUSION AND FUTURE WORKS

This study presented the optimal capacity of PV panel and battery storage for grid-connected houses with sharing of energy.

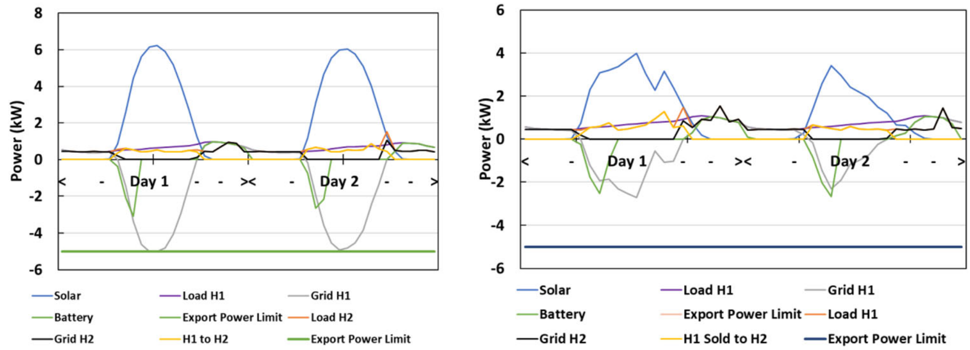



**FIGURE 13** Operational analysis for 2 days of: (a) summer and (b) winter.

All the practical factors such as load data, ambient temperature, and solar insolation which affect the planning model are also taken into consideration. Mutually agreed rate between the houses has helped to reduce the COE for both houses. The objective function to minimize the COE of house 1 is achieved. Sensitivity analysis was done and observed to see the change in COE when the agreed electricity rate between houses was changed. Additionally, analysis was also done when load of house 1 and house 2 changed and how it affects the COE of both houses, when export power limitation changed, and finally when the PV and BES cost varies. Furthermore, operational analysis is done for 2 summer days and 2 winter days.

The COE of house 1 was reduced by 7.6% due to energy sharing instead of just selling electricity to the grid. The COE of house 2 was also reduced by 9.7% due to energy buying from house 1 instead of buying from the grid. No matter the scenarios, if electricity was shared between the houses with a mutually agreed rate, both the houses got benefit as the COE of House 1 was found less than 33.81¢/kWh in all scenarios and the COE of House 2 was found less than 40.42¢/kWh in all the scenarios.

Future studies can be done based on real-time electricity rates for house with PV and BES. The study can also be conducted when the houses have electric vehicles. Another aspect that should be considered as a future study is to develop the optimization problem and energy management system for multiple prosumers and consumers in order to achieve economic analysis for each house.

## NOMENCLATURE

| | |
|---|---|
| $C_{elec}^{H1}$ | Annual cost of electricity for house 1($) |
| $C_{elec}^{H2}$ | Annual cost of electricity of house 2 ($) |
| $C_m$ | Annual maintenance cost of components ($) |
| $C_r$ | Annual replacement cost of components ($) |
| $E_{bc}$ | Total capacity of the battery (kWh) |
| $L_{annual}^{H1}$ | Annual electricity demand of house 1 (MWh) |
| $L_{annual}^{H2}$ | Annual electricity demand of house 2 (MWh) |
| $NPC_{comp}^{H1}$ | Net present cost of components for House 1 ($) |
| $NPC_{elec}^{H1}$ | Net present cost of electricity of house 1(kWh) |
| $NPC_{elec}^{H2}$ | Net present cost of electricity of house 2 (kWh) |
| $NPC_t$ | Total NPC |
| $NPC_{tot}^{H1}$ | Total net present cost of house 1 ($) |
| $NPC_{tot}^{H2}$ | Total net present cost of house 2 ($) |
| $N_{PV}$ | Total number of PVs |
| $N_{bat}$ | Total number of batteries |
| $P_{L1}$ | Load power of house 1 (kW) |
| $P_{L2}$ | Load power of house 2 (kW) |
| $P_{PV}$ | PV system power production (kW) |
| $P_{bat,ch}$ | Power delivered to battery during charging (kW) |
| $P_{bat,dis}$ | Power delivered by battery during discharging (kW) |
| $P_{bat,ex}$ | Export power of the battery (kW) |
| $P_{bat,im}$ | Import power of the battery (kW) |
| $P_{bat,in}$ | Available input power of battery (kW) |
| $P_{bat,max}$ | Maximum allowable battery power (kW) |
| $P_{bat,out}$ | Available output power of battery (kW) |
| $P_{dump}$ | Dump power (kW) |
| $P_{ex,H2}^{H1}$ | Export power from house 1 to house 2 by house 1 (kW) |
| $P_{ex,grid_{max}}$ | Maximum allowable power to export on grid (kW) |
| $P_{ex,grid}^{H1}$ | Export power to grid by house 1 (kW) |
| $P_{im,grid}^{H1}$ | Import power from grid by house 1 (kW) |
| $P_{im,grid}^{H2}$ | Import power from grid by house 2 (kW) |
| $R_{H1\_H2}$ | Electricity rate for energy sharing between house 1 and house 2 (¢/kWh) |
| $R_{elec}$ | Grid electricity rate (¢/kWh) |
| $R_{tariff}$ | Feed-in-tariff price (¢/kWh) |
| $SOC_{max}$ | Maximum state of charge of battery (%) |
| $SOC_{min}$ | Minimum state of charge of battery (%) |
| $\eta_{bat,ch}$ | Charging efficiency of battery (%) |
| $\eta_{bat,dis}$ | Discharging efficiency of battery (%) |
| $ADB$ | Annual degradation of battery (%) |
| $COE^{H1}$ | Cost of electricity for house 1 (¢/kWh) |
| $COE^{H2}$ | Cost of electricity of house 2 (¢/kWh) |
| $CRF_{comp}$ | Capital recovery factor of components |
| $CRF_{elec}$ | Capital recovery factor of electricity |
| $DB$ | Degradation of battery (%) |
| $DOD(t)$ | Depth of discharge of battery (%) |
| $N$ | Total number of components |
| $PC_{c(PV)}$ | Capital present cost of PV system ($) |
| $PC_{c(bat)}$ | Capital present cost of battery system ($) |

| | |
|---|---|
| $PC_{m(PV)}$ | Maintenance present cost of PV ($) |
| $PC_{m(bat)}$ | Maintenance present cost of battery ($) |
| $PC_{r(PV)}$ | Replacement present cost of PV system ($) |
| $PC_{r(bat)}$ | Replacement present cost of battery system ($) |
| $PC_{sv}$ | Present salvation value of components ($) |
| $SOC$ | State of charging (%) |
| $e$ | Escalation rate (%) |
| $i$ | Interest rate (%) |
| $n$ | Project lifetime (years) |

## AUTHOR CONTRIBUTIONS

Siraj Khanal: Conceptualization; formal analysis; investigation; methodology; software; writing—original draft. Rahmat Khezri: Conceptualization; formal analysis; Software; writing—original draft; writing—review andediting. Amin Mahmoudi: Resources; supervision; writing—review andediting. Solmaz Kahourzade: Resources; supervision; writing—review andediting.

## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Data is not available for this study.

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## REFERENCES

1. Khezri, R., Mahmoudi, A., Aki, H.: Optimal planning of solar photovoltaic and battery storage systems for grid-connected residential sector: Review, challenges and new perspectives. Renewable Sustainable Energy Rev. 153, 111763 (2022)
2. Huang, P., Sun, Y., Lovati, M., Zhang, X.: Solar-photovoltaic-power-sharing-based design optimization of distributed energy storage systems for performance improvements. Energies 222, 119931 (2021)
3. Merrington, S., Khezri, R., Mahmoudi, A.: Optimal planning of solar photovoltaic and battery storage for electric vehicle owner households with time-of-use tariff. IET Gener. Transm. Distrib. 16(3), 535–547 (2022)
4. Khezri, R., Mahmoudi, A., Haque, M.H.: optimal capacity of solar PV and battery storage for Australian grid-connected households. IEEE Trans. Ind. Appl. 56(5), 5319–5329 (2020)
5. Khezri, R., Mahmoudi, A., Aki, H.: Multi-objective long-Period optimal planning model for a grid-connected renewable-battery system. IEEE Trans. Ind. Appl., 58(4), 5055–5067 (2022)
6. Soto, E.A., Bosman, L.B., Wollega, E., Leon-Salas, W.D.: Peer-to-peer energy trading: A review of the literature. Appl. Energy 283, 116268 (2021)
7. Zhang, C., Wu, J., Zhou, Y., Cheng, M., Long, C.: Peer-to-peer energy trading in a microgrid. Appl. Energy 220, 1–12 (2018)
8. Morstyn, T., McCulloch, M.D.: Multiclass energy management for peer-to-peer energy trading driven by prosumer preferences. IEEE Trans. Power Syst. 34(5), 4005–4014 (2019)
9. Inam, W., Strawser, D., Afridi, K.K., Ram, R.J., Perreault, D.J.: Architecture and system analysis of microgrids with peer-to-peer electricity sharing to create a marketplace which enables energy access. In: *2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)*, pp. 464–469, IEEE, Piscataway, NJ (2015)
10. Tushar, W., Yuen, C., Mohsenian-Rad, H., Saha, T., Poor, H.V., Wood, K.L.: Transforming energy networks via peer-to-peer energy trading: The potential of game-theoretic approaches. IEEE Signal Process. Mag. 35(4), 90–111 (2018)
11. Tushar, W., et al.: A motivational game theoretic approach for peer-to-peer energy trading in the smart grid. Appl. Energy 243, 10–20 (2019)
12. Tushar, W., Saha, T.K., Yuen, C., Liddell, P., Bean, R., Poor, H.V.: Peer-to-peer energy trading with sustainable user participation: A game theoretic approach. IEEE Access 6, 62932–62943 (2018)
13. Long, C., Zhou, Y., Wu, J.: A game theoretic approach for peer-to-peer energy trading. Energy Procedia 159, 454–459 (2019)
14. Paudel, A., Chaudhari, K., Long, C., Gooi, H.B.: Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model. IEEE Trans. Ind. Electron. 66(8), 6087–6097 (2019)
15. Jing, R., Xie, M.N., Wang, F.X., Chen, L.X.: Fair P2P energy trading between residential and commercial multi-energy systems enabling integrated demand-side management. Appl. Energy 262, 114551 (2020)
16. Khezri, R., Mahmoudi, A.: Review on the state-of-the-art multi-objective optimization of hybrid standalone/grid-connected energy systems. IET Gener. Transm. Distrib. 14(20), 4285–4300 (2020)
17. Fathi, M., Khezri, R., Yazdani, A., Mahmoudi, A.: Comparative study of metaheuristic algorithms for optimal sizing of standalone microgrids in a remote area community. Neural Comput. Appl. 34, 5181–5199 (2022)
18. Australian Government, Bureau of Meteorology. Climate data online. http://www.bom.gov.au/climate/data/index.shtml?bookmark=200. Accessed Sept 2021
19. Khezri, R., Mahmoudi, A., Whaley, D.: Optimal sizing and comparative analysis of rooftop PV and battery for grid-connected households with all-electric and gas-electricity utility. Energy 251, 123876 (2022)
20. AGL energy. Energy price online. https://www.agl.com.au/get-connected/electricity-gas-plans/vic/comparison?zcf97o=vlx3ap&bundle=energy-nbn-mobile+plan&cidi=B100102 Accessed Sept 2021.
21. Combe, M., et al.: Optimal sizing of an AC-coupled hybrid power system considering incentive-based demand response. IET Gener. Transm. Distrib. 13(15), 3354–3361 (2019)

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