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Effects of energy sharing and electricity tariffs on optimal sizing of PV-battery systems for grid-connected houses

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A R T I C L E I N F O

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A B S T R A C T

This paper investigates the optimal sizing of solar photovoltaic (PV) and battery energy storage (BES) for grid-connected houses based on mutually-agreed energy sharing prices by considering the flat and time-of-use (TOU) tariffs. The grid-tied house with PV-BES, referred to house 1 (H1) in the paper shares electricity with house 2 (H2) whenever needed with mutually-agreed electricity tariffs. The main objective function of the study is to minimize the cost of electricity (COE) for the H1 while decreasing COE for H2. Eight different schemes are investigated with the combination of flat and TOU tariffs for buying, selling, and mutually-agreed rates, respectively. For each scheme, optimal sizing of components and COE for both houses are evaluated. Realistic hourly-arranged annual data of temperature, solar irradiation, and load consumption of two houses are used as the input data. For each scheme, the results are compared with the situation when H1 does not have PV-BES and there is no electricity sharing. Sensitivity, operational, and uncertainty analyses are provided for the scheme with the lowest COE.

1. Introduction

1.1. Background and motivation

According to the International Energy Agency report, with the increasing energy demands, carbon emissions will be increased by 70 % in the next 20 years. It is estimated that about 36 % of carbon emission is caused by buildings which consume around 40 % of electricity commercially and residentially [1]. Hence, there is a need to generate energy from renewable energy (RE) resources like wind and sun due to their zero-carbon emission ability. Among RE resources, solar rooftop photovoltaic (PV) technology has gained maximum popularity due to its eco-friendly and budget-friendly characteristics [2]. One third of Australian households had rooftop PV system by the end of June 2019 which is due to the government incentives like feed-in-tariff (FiT) as well as decrease in PV components cost [3]. In South Australia (SA), up to 30 % of the total electricity bill is decreased in residential homes by installing solar rooftop PV Systems [4].

Solar PV systems in grid-connected households tend to supply the home's load first and sell the extra generated electricity to the grid. Since the FiT rates are getting lower compared to the retail price, battery energy storage (BES) would be a great option to store the power during daytime and then supply the load during peak hours [5]. The BES is an expensive piece of technology at least for now and

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Nomenclature

COE_{H1}	H1 cost of electricity (¢/kWh)
COE_{H2}	H2 cost of electricity (¢/kWh)
CRF_{co}	components capital recovery factor
CRF_{el}	electricity capital recovery factor
C_{H1}^{el}	H1 annual cost of electricity ($)
C_{H2}^{el}	H2 annual cost of electricity ($)
C^{ma}	components annual maintenance cost ($)
C^{r}	components annual replacement cost ($)
DB	degradation of battery (%)
$DD(t)$	battery depth of discharge (%)
er	escalation rate (%)
E_{bc}	battery total capacity (kWh)
ir	interest rate (%)
L_{H1}^{an}	H1 annual electricity demand (MWh)
L_{H2}^{an}	H2 annual electricity demand (MWh)
NPC_{H1}^{el}	H1 net present cost of electricity(kWh)
NPC_{H2}^{el}	H2 net present cost of electricity (kWh)
NPC_{H1}^{tot}	H1 total net present cost ($)
NPC_{H2}^{tot}	H2 total net present cost ($)
NPC_{H1}^{co}	H1 net present cost of components ($)
N_{gen}	total number of PV units
N_{BESS}	total number of battery units
N	total number of components in the system
P_{L1}	H1 load power (kW)
P_{L2}	H2 load power (kW)
P_{gen}	production power of PV system (kW)
$P_{BESS,ch}$	power delivered to battery during charging (kW)
$P_{BESS,dis}$	power delivered by battery during discharging (kW)
$P_{BESS,in}$	battery's available input power (kW)
$P_{BESS,out}$	battery's available output power (kW)
$P_{BESS,im}$	battery's import power (kW)
$P_{BESS,ex}$	battery's export power (kW)
$P_{BESS,max}$	battery's maximum allowable power (kW)
P_{dump}	power dumped (kW)
$P_{H1}^{ex,H2}$	power exported by H1 to H2 (kW)
$P_{ex,max}$	maximum allowable export power to grid (kW)
$P_{H1}^{ex,grid}$	H1 power exported to grid (kW)
$P_{H1}^{im,grid}$	H1 power imported from grid (kW)
$P_{H2}^{im,grid}$	H2 power imported from grid (kW)
PC_{PV}^{ca}	PV system capital present cost ($)
PC_{BESS}^{ca}	battery system capital present cost ($)
PC_{PV}^{ma}	PV present cost of maintenance ($)
PC_{BESS}^{ma}	battery present cost of maintenance ($)
PC_{PV}^{r}	PV system present cost of replacement ($)
PC_{BESS}^{r}	battery system present cost of replacement ($)
PC_{PV}^{sv}	PV system present salvation value ($)
PC_{BESS}^{sv}	battery system present salvation value ($)
R_{H1_H2}	H1 and H2 agreed electricity rate for energy sharing (¢/kWh)
R_{el}	grid rate for purchasing electricity (¢/kWh)
R_{ta}	rate for feed-in-tariff (¢/kWh)
n	project lifetime (years)
SOC_{max}	battery's maximum state of charge (%)
SOC_{min}	battery's minimum state of charge (%)
SOC	state of charge (%)
$\eta_{BESS,ch}$	battery efficiency when charging (%)
$\eta_{BESS,dis}$	battery efficiency when discharging (%)

hence a proper investigation is needed to check its suitability from economic point of view [6]. Selecting non-optimized number of PV and BES will not offer maximum economic benefits. Thus, optimal capacity of components should be selected to maximise the economic and technical benefits [7].

Peer-to-peer (P2P) energy sharing system has emerged an exclusive platform for the prosumers to increase the profitability of PV-BES system. In P2P energy sharing, a prosumer can share the generated energy from PV and discharge the stored energy in BES to be used by other consumers in the community. Another major objective of the P2P sharing is to decentralize infrastructure of the power grid. It allows direct communication and encourages prosumers to consume energy from distributed energy resources (DERs) and supply the other consumers by the extra power [8]. The governments of developed countries also take great care of non-fossil fuel energy generation that making P2P a wonderful energy trading strategy [9].

Currently, the consumers use flat rate to buy/sell electricity from/to the grid. The new pricing mechanism offer the electricity rate according to the time they wish to buy/sell electricity and this is the recommended mechanism to reduce the consumption during peak hours [10]. The electricity rate varies between peak and off-peak hours in time-of-use (TOU) mechanism. To achieve the maximum economic benefits for both prosumer and consumer, it is important to investigate the optimal sizing of components when TOU rates are used. It is also important to see how TOU rates impact in energy sharing.

1.2. Literature review

Optimal sizing of PV and BES has been investigated by several studies [5–7]. However, those studies have not considered the effect of energy sharing on the optimal sizing problem. On the other side, the existing papers on energy sharing have not applied any optimal sizing for PV and BES. In [11], an incentive-based mechanism is suggested that works with TOU and proof of credit for the P2P system. P2P electricity mechanism has been discussed in [12] and the double side auction for the P2P system is viewed in detail in [13]. In [14] the concept of P2P is given under two different systems which include residential and commercial prosumers and the TOU pricing mechanisms are used for both types of prosumers. Two different BES structures are discussed in the research [15] including energy service provider owned structure and user-own structure for P2P systems. The research showed the user-own structure was far better than the battery owned structure where both systems billed by TOU tariffs.

The concept of consumer management is shown in [16] where different financial impacts are considered for P2P based model. The TOU-based billing variables used in the model and solar PV-based P2P systems are explored in detail. The network constraints are used in [17] to provide a P2P model for 12 customers to provide the most economical energy with the best quality. Upper and lower limits of constraints are decided based on TOU values. The energy management of individual users and the P2P energy trading for an improved experience of DERs by managing the decentralized markets is done in [18]. The consumer interests were implemented through network awareness and an attempt was done to achieve the customer satisfaction levels. Different aspects of P2P energy trading are shown in [19] where a comprehensive review is done of the recent research in the field. The present and future development are considered, and different aspects of P2P energy trading including networking, cost, designs, trading options, policies, and infrastructure are reviewed. P2P is found to be a hot topic for research and is a feasible solution to meet the present needs.

A game-based P2P energy sharing is shown in [20] for energy management in a community of energy buildings. A noncooperative Nash equilibrium game is used to solve the problem to promote the energy efficiency of the community. In [21], cost minimization has been discussed for all smart houses connected under P2P energy sharing where the Pareto optimal solution is obtained. In [22] a management strategy is proposed for the residential and commercial prosumers through a simulation model based on TOU to save the cost. In [23] a decentralized P2P model is obtained based on the consumer interest with TOU based billing strategy. In [24] a strategy was proposed that does not violates any network constraint and ensure TOU based P2P energy sharing.

All the above-mentioned papers have discussed the energy sharing between houses and grid. Table 1 compares the current studies for energy sharing in terms of the electricity tariff, mutually-agreed price, optimal sizing, contract feasibility, and practical factors

Table 1
Current studies summary for energy sharing and optimal sizing.

Paper	Electricity tariff	Mutually-agreed price	Optimal sizing	Contract flexibility	Practical factors			
					GC	**BD**	**RD**	**SC**
11	TOU	×	×	×	×	×	×	×
12	Flat and TOU	×	×	×	×	×	×	×
13	TOU	×	×	×	×	×	×	×
14	TOU	×	×	×	×	×	×	×
15	TOU	×	√	×	×	×	×	×
16	Flat and TOU	×	×	×	×	×	×	×
17	TOU	×	×	×	×	×	×	×
18	Flat and TOU	×	×	×	√	×	×	×
19	Flat	×	×	×	×	×	×	×
20	Flat	×	×	×	×	×	×	×
21	TOU	×	×	×	√	×	×	×
22	TOU	×	×	×	×	×	×	×
23	TOU	×	×	×	×	×	×	×
24	TOU	×	×	×	×	×	×	×
This paper	Flat and TOU	√	√	√	√	√	√	√

including grid constraint (GC), battery degradation (BD), incorporating real data (RD), and salvage cost (SC) of PV and BES. The paper considers electricity tariffs as the mechanism, which can either be flat or time-of-use (TOU) tariffs. None of the papers has considered mutually-agreed energy sharing price. Optimal sizing of the components was found in one paper. Although some papers mentioned about the impacts on grid due to overload of voltage, most of them do not consider the exact figure for power restriction to the grid. Existing papers do not discuss contract flexibility, including how easily one can enter or exit the contract and its impact on the network.

1.3. Contribution

This paper is original and novel for optimizing the capacity of PV and BES for households when they can share energy with their neighbours under a mutually-agreed TOU rate. The originality of the paper can be discussed in three aspects. First, the existing studies on optimizing PV and BES have investigated the problem without any energy sharing. It is notable that energy sharing brings more benefits to the PV and BES owner compared to solely using it in the house and selling it to the grid within a low rate. Second, the existing studies on energy sharing have not investigated optimal sizing of the PV and BES and they only developed optimal operation model with some typical component sizes which may not achieve the highest economic benefit for the system owner. Third, the existing studies have not considered all practical parameters like battery degradation, salvation value of system components, daily supply of charge of electricity, and grid constraint fixed by policy maker in their optimization model. The key contributions of this paper compared to other existing papers in energy sharing and optimal sizing of PV-BES systems are as follows:

- Development of an original model for optimal sizing model for PV-BES system under energy sharing schemes with Flat and TOU electricity tariffs for buying/selling energy from/to the grid and energy sharing rate between houses;
- Development of a novel rule-based energy management system for energy sharing between houses under TOU energy tariffs;
- Considering all practical parameters including battery degradation, salvation value of system components, daily supply of charge of electricity, and grid constraint fixed by policy maker in the optimization model;
- Applying a flexible contract between households for energy sharing to investigate different scenarios if one house wishes to cancel or extend the energy sharing contract.

In this study, eight different schemes are investigated based on the electricity tariffs for buying/selling electricity from/to the grid and energy sharing rates between houses. A control strategy is developed in HEMS according to the peak and off-peak rates for buying, selling, and sharing of the energy. The objective function aims to minimise the cost of electricity (COE) of a prosumer which is house 1 (H1) while decreasing the electricity cost for a consumer which is house 2 (H2). All constraints are considered along with real annual data of temperature, solar irradiance, and load consumption of houses. Sensitivity analyses on the grid constraint, possible load variation, and possible components cost variation are done for the best scheme with the lowest COE. Uncertainty analysis is performed by the percentage variation of temperature and solar irradiance, and COE for each house is observed.

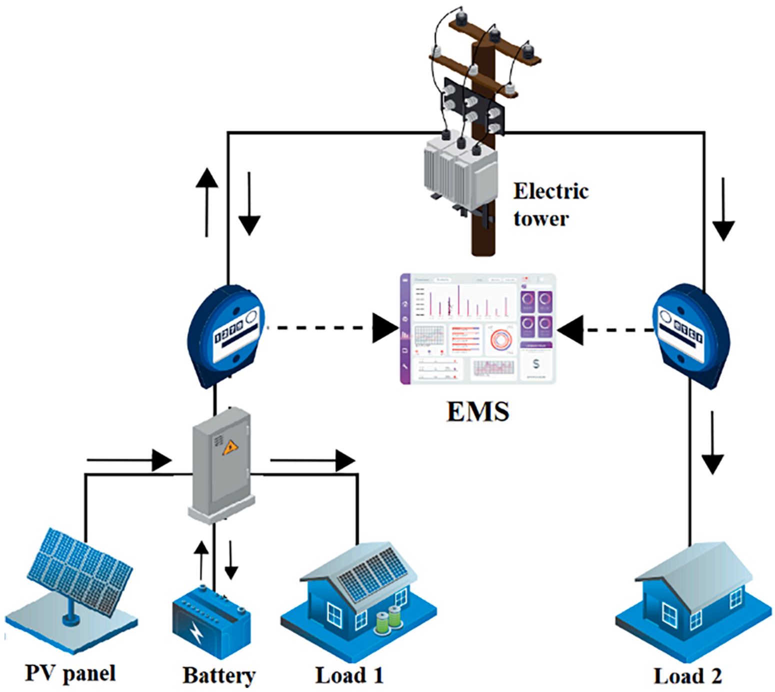


Fig. 1. System configuration showing energy sharing between the houses.

1.4. Article organization

The rest of the paper is structured as follows: Section 2 describes the operational strategies under energy sharing and different electricity tariffs. Section 3 explains the optimization model. Section 4 includes the system model and case study. Section 5 discusses the obtained results. Section 6 presents different analyses for the best scheme. Section 7 contains the conclusion of the paper and future works.

2. Operational strategy

Fig. 1 shows the system configuration which includes two houses (i.e., loads), their connection to grid, and communications between houses, PV, and BES. The main assumption for this study is that H1 willing to purchase the components considering the energy sharing possibility between H1 and H2. Electricity provider monitors the energy sharing between the houses, but the electricity rate is agreed and approved between the houses. The methodology is scalable and can be developed for multiple houses in which H1 will be the load with components for *n* number of houses and H2 will be the load without components for *n* number of houses. This study is a baseline for future projects to develop the algorithms for multiple houses. Developing algorithms for *n* number of houses is beyond the scope of this paper.

The developed rule-based EMs flowchart is shown in Fig. 2. The main benefits by rule-based EMSs are their practicality, simple understanding, ease of implementation, lower computational requirement, and the ability to update the rules [6]. In this study, EMS rules are changed based on the generated energy by the PV system and the electricity price for purchasing, selling, and energy sharing.

When the PV power exceeds the load of H1, the electricity rate is checked to determine if it is off-peak or peak time. If the PV power is smaller than the sum of needed power by H1 and available input power for BES, it will initially satisfy the load of H1 and the remaining power is delivered to the battery. In this case, there will be no power left for H2 and dump power will be zero. The grid will then satisfy H2's load demand.

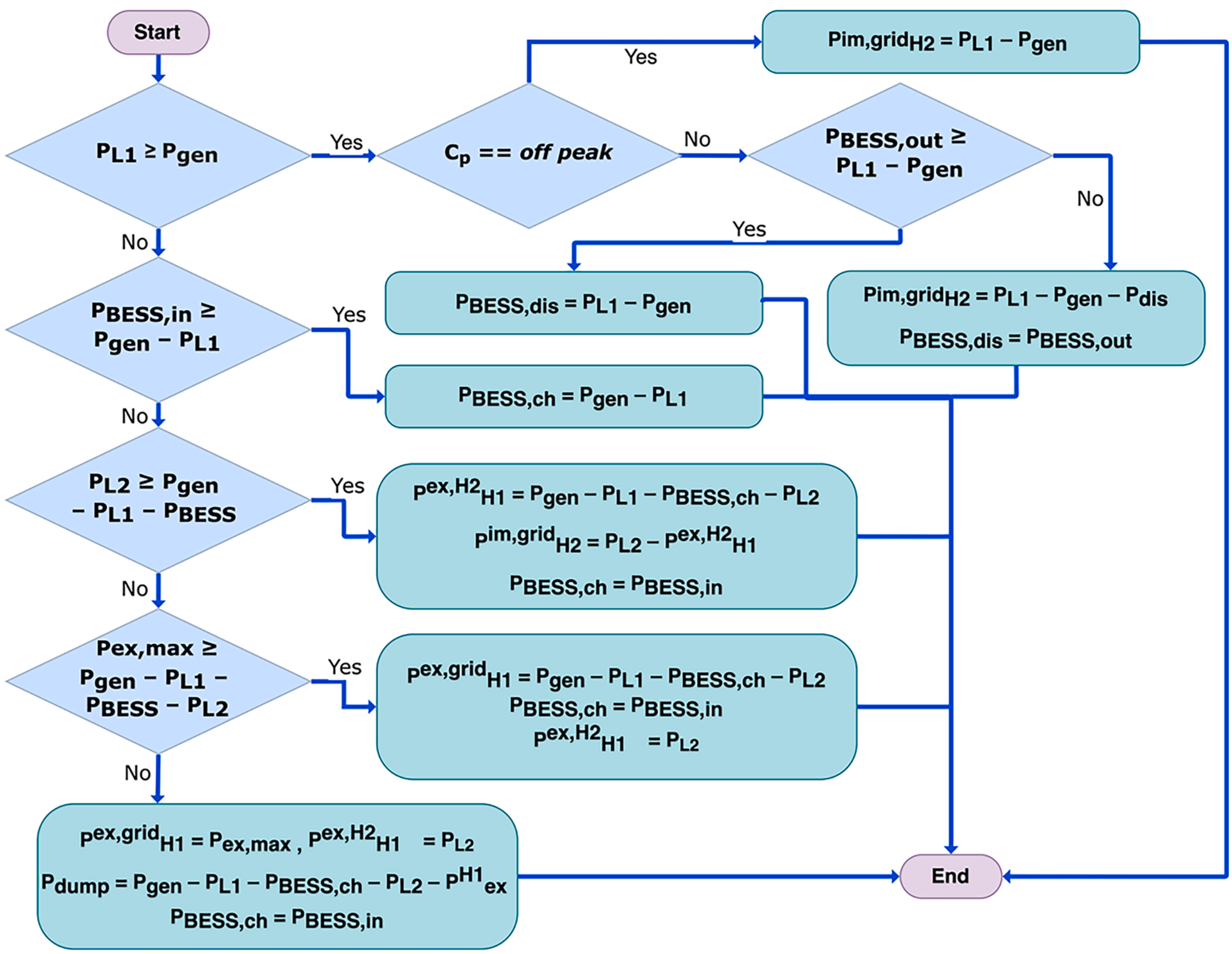


Fig. 2. Flow chart of the rule-based energy management system.

When the PV power is greater than combined power of load of H1 and available input power of battery, it will initially satisfy the load of H1, charges the battery, and satisfy the load demand of H2 (1). If the generation is high enough, it sells the extra power to grid (2) and dump the remaining power via inverter with the help of control system (3).

$$P_{H1}^{ex,H2}(t) = P_{gen}(t) - P_{L1}(t) - P_{BESS,in}(t) \tag{1}$$

$$P_{H1}^{ex,grid}(t) = \max\left(P_{ex,max}, P_{gen}(t) - P_{L1}(t) - P_{BESS,in}(t) - P_{L2}(t)\right) \tag{2}$$

$$P_{dump}(t) = P_{gen}(t) - P_{L1}(t) - P_{BESS,in}(t) - P_{L2}(t) - P_{H1}^{ex,H2}(t) - P_{ex,max}(t) \tag{3}$$

H2 buys power from grid if H1 cannot satisfy all its load demand as follows:

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

When the PV power is less than the power demand of H1, battery will satisfy its demand. If the battery is unable to fulfill its demand, then H1 buys all the required energy from the grid. In this scenario, H2's load demand is satisfied via grid. No power is shared between the houses and dumped power is zero.

$$P_{H1}^{im,grid}(t) = P_{L1}(t) - P_{gen}(t) - P_{BESS,out}(t) \tag{5}$$

For each interval of time, SOC of battery is calculated based on the SOC at previous time interval and the charging/discharging power as follows:

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

The available input power ($P_{BESS,in}$) and available output power ($P_{BESS,out}$) of BES are defined to constrain the charging/discharging power of the battery.

$$P_{BESS,in}(t) = \frac{E_{bc}}{\Delta t}\left(SOC_{max} - SOC(t)\right) \tag{7}$$

$$P_{BESS,out}(t) = \frac{E_{bc}}{\Delta t}\left(SOC(t) - SOC_{min}\right) \tag{8}$$

3. Methodology

3.1. Objective function

The main objective function of this paper is to minimize the COE for H1 by finding out the optimal PV and BES that can be used when TOU electricity rates are used. This section explains the model used to calculate the optimal component sizes. COE is the ratio of total electricity cost in a year and the total electricity consumption annually. COE of each house can be calculated by the following formula [3].

$$COE_{H1} = \frac{NPC_{H1}^{co}\ CRF_{co} + NPC_{H1}^{el}\ CRF_{el}}{L_{H1}^{an}} \tag{9}$$

$$COE_{H2} = \frac{NPC_{H2}^{el}\ CRF_{el}}{L_{H2}^{an}} \tag{10}$$

Capital recovery factor (CRF) of system components (CRF_{co}) can be calculated with the help of interest rate and project life as follows:

$$CRF_{co} = \frac{ir(1+ir)^n}{(1+ir)^n - 1} \tag{11}$$

CRF of electricity (CRF_{el}) can be calculated by considering an escalation rate and project life as follows:

$$CRF_{el} = \frac{R_r(1+R_r)^n}{(1+R_r)^n - 1} \tag{12}$$

$$R_r = \frac{ir - er}{1 + er} \tag{13}$$

Net present cost (NPC) of system components for house can be calculated with the help of components capital cost, maintenance cost, replacement cost and salvation value as follows:

$$NPC_{H1}^{co} = N_{BESS}\left(PC_{BESS}^{ca} + PC_{BESS}^{ma} + PC_{BESS}^{re} - PC_{BESS}^{sv}\right) + N_{PV}\left(PC_{PV}^{ca} + PC_{PV}^{ma} + PC_{PV}^{re} - PC_{PV}^{sv}\right) \tag{14}$$

Capital cost of system components is the cost invested at the start of the project. The present maintenance cost of the components can be calculated as follows:

$$PC^{ma} = C^{ma} \frac{(1 + ir)^n - 1}{ir(1 + ir)^n} \tag{15}$$

Components present replacement cost can be calculated as follows:

$$PC^{r} = C^{r} \sum_{t=1}^{tY<n} \frac{1}{(1+ir)^{tY}} \tag{16}$$

Components' salvation value is the value of the components at the end of the project horizon and can be formulated as follows [6]:

$$PC^{sv} = PC^{c}.\ \frac{A}{Y} \frac{1}{(1+ir)^{n}} \tag{17}$$

where, A represents the remaining lifetime of the components after project lifetime and Y represents the lifetime of the system components.

The lifetime of PV component is usually provided by the manufacturer. However, BES lifetime is calculated based on capacity degradation during battery operation. When the degradation reaches 20 %, the battery is considered to have reached the end of its life [25]. Capacity degradation of battery which is a function of depth of discharge (DOD) can be calculated with respect to SOC as follows:

$$DOD(t) = 1 - SOC(t) \tag{18}$$

To determine degradation of the battery, DOD and its associated number of cycles should be found out. In this paper, the Rainflow cycle counting algorithm was used to pull out the battery cycles data from the annual DOD. The data from algorithm was analysed and battery degradation was determined with the help of experimental model. The model was determined under various stress levels and stress factors of BES to obtain data for its lifetime via accelerated lab cycle tests. For each cycle (c) the experimental model used to determine battery degradation was calculated as a function of DOD as follows [25]:

$$BD, (c), = \frac{2, 0}{3, 300, 0., e^{-,0.0,657,6.D,OD(,t)}, +32, 77} \tag{19}$$

Annual COE for H1 with real interest can be calculated as follows:

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

where (C_{H1}^{el}) is sum of buying electricity from the grid with real TOU retail rate of grid, selling electricity to H2 with TOU rate fixed between H1 and H2 and selling electricity to the grid in TOU rate which can be written as follows:

$$C_{H1}^{el} = \sum_{t=1}^{8760} \left(P_{H1}^{im,grid}(t)\ R_{el}(t)\ \Delta t\right) - \sum_{t=1}^{8760} \left(P_{H1}^{ex,grid}(t)\ R_{ta}(t)\ \Delta t\right) - \sum_{t=1}^{8760} \left(P_{H1}^{ex,H2}(t)\ R_{H1\_H2}(t)\ \Delta t\right) \tag{21}$$

Annual COE for H2 with real interest can be calculated as follows:

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

where (C_{H2}^{el}) is sum of buying electricity from grid with TOU grid rate and buying electricity from H1 with TOU rate agreed between both the houses.

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

3.2. Net present cost

The total NPC for H1 can be calculated by adding present cost of components and its present electricity cost as follows:

$$NPC_{H1}^{tot} = NPC_{H1}^{co} + NPC_{H1}^{el} \tag{24}$$

Since H2 does not have a system component, its NPC will be identical to its NPC of electricity.

$$NPC_{H2}^{tot} = NPC_{H2}^{el} \tag{25}$$

3.3. Design constraint

Eq. (26) represents the constraint on PV panel capacity where the rating capacity of PV ($P_{gen,rate}$) is 1 kW. Eq. (27) represents the constraint for charging and discharging of battery with respect to available input and output power, respectively. $P_{BESS,rate}$ is the rating capacity of BES which is 1 kWh. The minimum and maximum SOC values of the battery are restricted by the Eq. (28). Eq. (29) is the constraint for power balance in each time interval between the houses, grid, PV, and BES. The Australian government has established a grid constraint limiting single-phase houses to not sell more than 5 kW of electricity, as depicted in the Eq. (30).

$$0 \leq P_{gen}(t) \leq P_{gen,max}, \ P_{gen,max} = N_{gen} \ P_{gen,rate} \tag{26}$$

$$0 \leq P_{BESS,im}(t), \ P_{BESS,ex}(t) \leq P_{BESS,max}, \ P_{BESS,max} = N_{BESS} \ P_{BESS,rate} \tag{27}$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{28}$$

$$P_{gen}(t) + P_{BESS,in}(t) + P_{H1}^{im,grid}(t) + P_{H2}^{im,grid}(t) - P_{H1}^{ex,grid}(t) \geq P_{L1}(t) + P_{L2}(t) \tag{29}$$

$$0 \leq P_{ex,grid}(t) \leq P_{ex,grid_{max}} \tag{30}$$

3.4. Optimization procedure

This model can be optimized in MATLAB by using the tools available in software, but PSO is used because of its ease of use and proven reliability in this type of study. The results obtained with the help of PSO is approved for the optimal sizing of the components in [26–27]. In addition, various studies in power system planning have also utilized similar methods and achieved efficient results

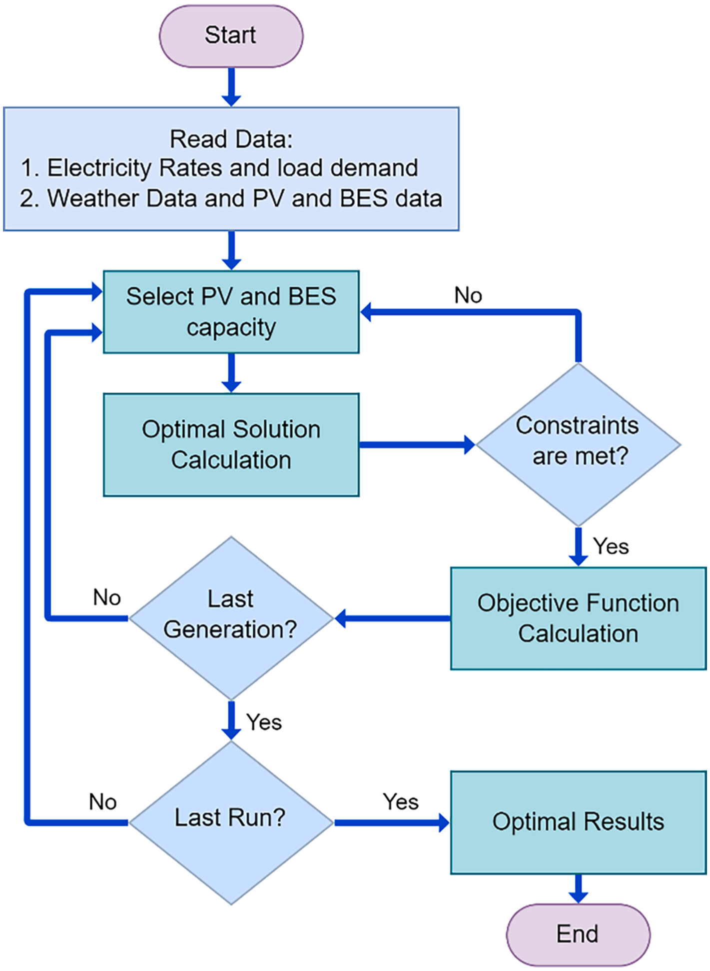


Fig. 3. Flow chart of the optimization procedure.

[1–6]. PSO depends less on initial points and has very high convergence rate. It also has high computational efficiency [28]. Fig. 3 shows the flow chart for the optimal sizing of the system components using PSO.

To achieve the optimal solution, a large number of generations and populations are selected so that PSO can explore a wide search space and ultimately attain the global solution. The total number of generation and population used in this study are 200 each meaning simulation is run for 200×200 times to achieve optimal results. All necessary data, including weather, irradiance, and load data, must be gathered before simulation. Additionally, PSO verifies the design constraints, objective functions, and operates accordingly. The simulation process for this study is executed 10 times to ensure the algorithm provides the global solution. At the start of each simulation, every particle in the swarm initializes with its own solution, where the minimum is identified as the particle's best position. The global best solution is determined from the best solution among these 10 best positions. Other parameters of the PSO algorithm, including cognitive, social, and inertia weights, are set to 2, 2, and 0.5, respectively.

4. System model and case study

The developed model in general in nature and can be used for any 2 houses if they agree on an energy sharing scheme with pre-fixed rate. Here, two grid-connected houses situated in South Australia were selected for the case study.

4.1. Data collection for optimal sizing and COE calculation

4.1.1. Meteorological data

Solar irradiance and temperature data was taken from Bureau of Meteorology of Australian government [29]. Fig. 4 illustrates the annual meteorological data. Fig. 4a shows the temperature varying from 2.2 °C to 41.9 °C. Fig. 4b shows the solar irradiance with an average value of 5.4 kWh/m^2.

4.1.2. Load data

Load consumption of H1 is taken from [3] and load consumption of H2 is taken from [30] which are shown in Fig. 5a and 5b, respectively. The load demand for H1 ranges from 0.3 kW at its lowest to 1.6 kW at its highest, while for H2, it varies from 0.19 kW at its lowest to 3 kW at its highest. The power losses during energy sharing are neglected in this study due to their insignificant and short distance between the two houses.

4.1.3. Components cost and electricity price

Table 2 shows the values for the economic data, electricity and components prices. Interest and grid escalation rates are 8 % and 2 %, respectively. Retail price, flat feed in tariff and daily supply of charge (DSOC) are taken from AGL website, one of the Australian energy providers [31]. Peak and off-peak tariff rates and all the mutually-agreed rates were reasonably assumed for the investigation of this study.

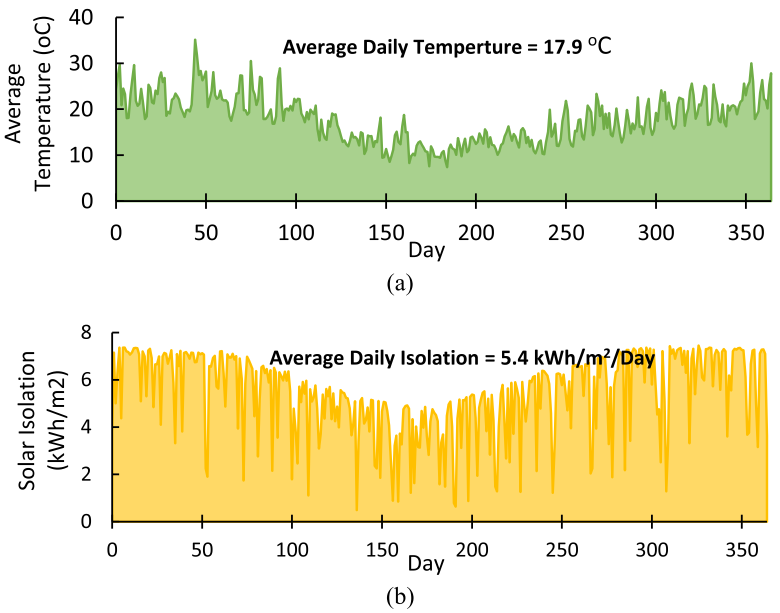


Fig. 4. Yearly meterological data in SA, (a) Ambient temperature, (b) solar irradiance.

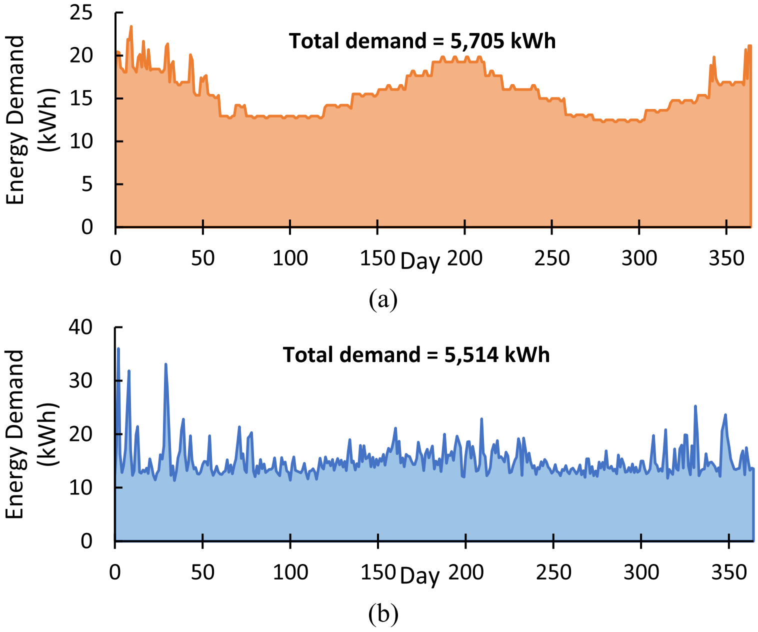


Fig. 5. Daily energy consumption in a year for: (a) H1, (b) H2.

Table 2
Economic, electricity and components prices.

Parameters	Value	Parameters	Value
Project lifetime	20 years	**Retail peak price**	0.3933 $/kWh
Interest rate	8%	**Retail off-Peak price**	0.2508 $/kWh
Grid Escalation rate	2%	**Retail flat price**	0.3388 $/kWh
Time between overhauls	10 years	**Peak feed in tariff**	0.17 $/kWh
PV overhaul cost	300 $/kW	**Off-peak feed in tariff**	0.10 $/kWh
PV O&M cost	50 $/year	**Flat feed in tariff**	0.12 $/kWh
Maximum grid export power	5 kW	**Mutually-agreed peak rate**	0.25 $/kWh
Battery SOC minimum	20 %	**Mutually-agreed off-peak rate**	0.17 $/kWh
Battery SOC maximum	95 %	**Mutually-agreed flat rate**	0.20 $/kWh
BES capital cost	350 $/kWh	**BES efficiency**	95 %
BES overhaul cost	200 $/kWh	**Daily supply of charge**	0.99 $/day
PV capital cost	1500 $/kW		

4.2. Case study in various scenarios

The second part of the case study will be done for 4 different scenarios shown in Fig. 6. The scenarios are investigated to make this study more practical and realistic. It is also to investigate the effect of the flexibility of contract between the houses on the COE and optimal sizing. In these scenarios, it is assumed that H2 might not feel comfortable to take 20 years of contract. For this investigation both houses will agree to make an initial contract for energy sharing. After the initial contract, it is assumed that H2 will extends contract of 70 % of the project life because H2 is happy with the saving in electricity prices. So, 1st contract period, 2nd contract period and no contract between houses are assumed for the investigation as shown in Fig. 6.

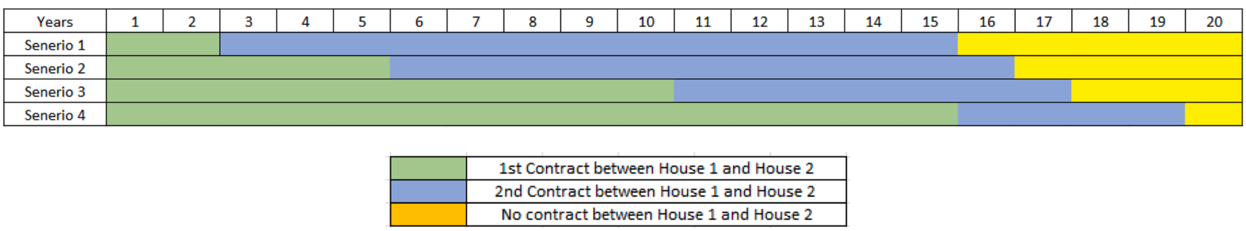


Fig. 6. Considered scenarios for the duration of P2P sharing contracts between the houses.

5. Results and discussion

In this study, eight different schemes are optimized based on the electricity tariff for buying/selling electricity from/to the grid and energy sharing rate between houses. Table 3 lists the considered schemes.

5.1. Optimal solution results and discussion

Optimal sizing of the system components and COE for both houses are calculated based on the real data for all schemes. Fig. 7 shows the system components' NPC and grid NPC along with optimal PV and battery storage for 8 different schemes. It is observed that out of 8 schemes, 6 of the schemes optimal battery size is 7 kWh, but with T-T-F and T-T-T schemes, they are 6 kWh and 5 kWh, respectively. Optimal capacity of PV varies between 10 kW and 11 kW.

The total NPC of the components ($20,749) is low across the four schemes, the grid NPC does not present an equally attractive proposition. Despite the higher NPC of components, T-T-T shows the most attractive grid NPC at $11,819. It is evident that the grid NPC becomes more appealing with a larger PV size, as this results in increased power generation and sales to the grid or H2. The lowest grid NPC is observed in F-F-F. This is due to H1′s inability to maximize earnings from selling electricity to the grid or H2 during peak hours, as the flat rate is lower compared to peak hours, resulting in lower revenue.

Fig. 8 shows the NPC and COE for both houses with and without PV-BES (normal case). Under normal case, without system components, H1 and H2 have identical NPC across the four schemes with flat-rate purchasing, as well as identical NPC across the four schemes with time-of-use (TOU) rate purchasing. This is because without system components, H1 selling electricity to the grid and selling electricity to the H2 will be 0. Similarly, for H2, no electricity is received from H1. NPC just depends on buying of electricity for all schemes in normal case. It is observed that in all the schemes NPC for H1 is lowest with PV-BES. Out of all schemes, T-T-T has the lowest NPC of $10,059.50 for H1. Additionally, for H2, it is observed that T-T-F has the lowest NPC of $22,954.50.

In the normal case, the COE does not exhibit significant differences between both houses, as it primarily hinges on electricity purchases from the grid, influenced by each house's load and DSOC. For H1, COE when electricity is bought in flat rate is 40.20 ¢/kWh and TOU rate is 41.47 ¢/kWh. For H2, COE when electricity is bought in flat rate is 40.42 ¢/kWh and TOU rate is 41.87 ¢/kWh. COE decreases significantly when PV-BES are installed. For H1, the lowest COE is 21.17 ¢/kWh in T-T-T scheme which is 48.9 % COE reduction compared to normal case, similar scheme. This is mostly because H1 can take advantage on TOU selling rate to grid which is very high and take some advantage by TOU rate selling to H2. For the same scheme, H2 COE is reduced from 41.87¢/kWh to 37.31¢/kWh.

H2 has the lowest COE of 35.95 ¢/kWh in T-T-F scheme which is 14.1 % COE reduction when we compare with the normal case, similar scheme. T-T-T is the best scheme for this study because the objective function is to minimize the COE of H1while decreasing COE for H2.

5.2. Different scenario results and discussion

For each of the 8 schemes, different scenarios results are observed to be more flexible in contract between the houses. The electricity rates for energy sharing between the houses are updated for each year of contract in Flat and TOU tariffs. Table 4 provides the summary for the rate we used to obtain the results for different scenarios. To give the benefit for H2 in energy sharing rate, if taken higher number of contract years, the formula below is obtained. The energy sharing rate varies between 2 and 20 years.

$$\textit{Energy sharing rate for year ‘}x\textit{‘} = \left(\frac{M_1 - M_2}{20 - 2}\right).(20 - x) \ + M_2 \tag{31}$$

where M_1 is rate at 2-year contract, and M_2 is the rate at 20-year contract.

Fig. 9 shows the NPC and COE of H1 and H2 for all schemes in different scenarios. H1 has the highest NPC and lowest NPC in the 1st and 3rd scenarios, respectively. H2 has the highest and lowest NPC in the 2nd and 4th scenarios, respectively. Both the houses have got the lowest COE for the 4th scenario, but the highest scenario fluctuates depending on the scheme, alternating between the 1st and 2nd scenarios. In the 1st scenario, H1 has the highest COE because while H2 pays a higher rate, which lowers COE for H1 with a smaller contract, H1 cannot take advantage of selling electricity to H2 due to no contract in the last 5 years. Over the past 5 years, despite the high electricity costs incurred from H2, its cost of electricity (COE) remains high. COE for H2 is the highest in 1st scenario because when it takes low period of initial contract, it is paying the highest energy sharing rate. Both the houses have lowest COE in 4th scenario. This is because H1 can benefit from sharing rates with H2 for 19 out of 20 years, whereas H2, having opted for a longer initial contract period, gains advantages from H1 in mutual sharing of COE.

Table 3
Different schemes based on the electricity tariff for buying/selling electricity from/to the grid and energy sharing rate between houses.

Name	F-F-F	F-F-T	F-T-F	F-T-T	T-F-F	T-F-T	T-T-F	T-T-T
Buying energy tariff	Flat	Flat	Flat	Flat	TOU	TOU	TOU	TOU
Purchasing energy tariff	Flat	Flat	TOU	TOU	Flat	Flat	TOU	TOU
Energy sharing tariff	Flat	TOU	Flat	TOU	Flat	TOU	Flat	TOU

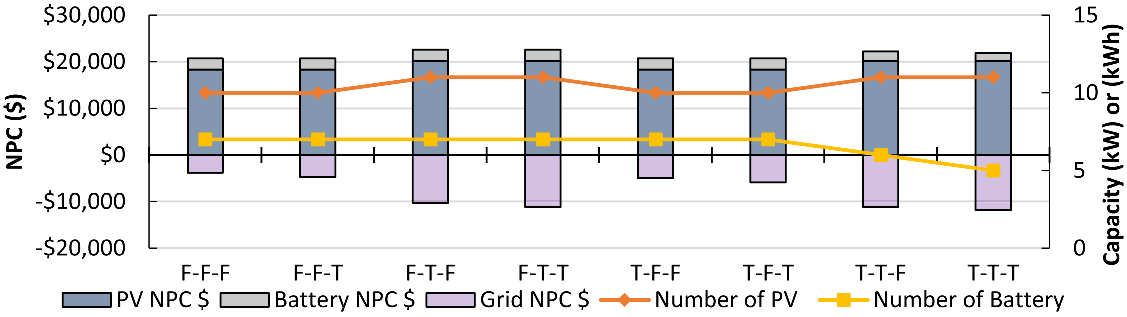


Fig. 7. Optimal capacity and NPC of components obtained for all schemes.

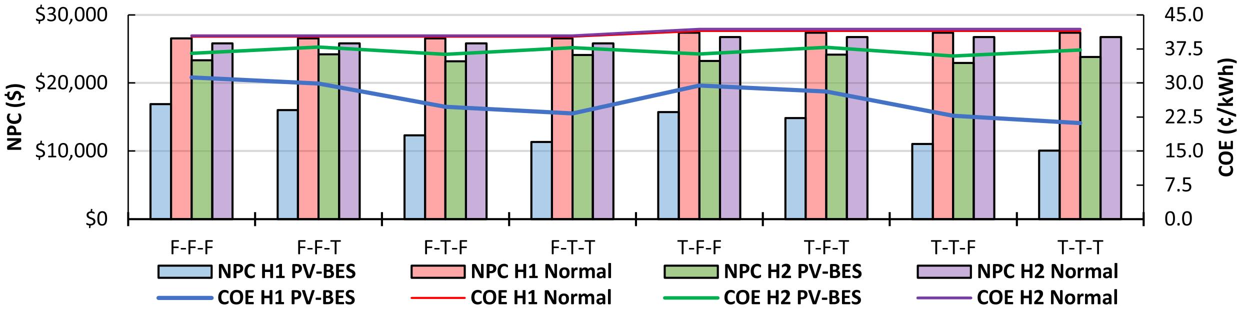


Fig. 8. NPC and COE of H1 and H2 with and without PV-BESS system for all schemes.

Table 4
P2P electricity sharing rates for Flat and TOU tariffs in different scenarios.

Case study	Summary	Years	Rate Flat	Peak rate	Off Peak rate
Normal	H1 (No PV-BES)	First contract: 0 Second contract: 0 No contract: 20	–	–	–
–	H1 with PV and without any contract (no sharing)	First contract: 0 Second contract: 0 No contract: 20	–	–	–
Scenario 1	H1 with PV with 2- and 13-years contract	First contract: 2 Second contract: 14 No contract: 4	25.00 21.94 –	30.00 26.94 –	22.00 18.94 –
Scenario 2	H1 with PV with 5- and 11-years contract	First contract: 5 Second contract: 11 No contract: 4	24.17 22.50 –	29.17 27.50 –	21.17 19.50 –
Scenario 3	H1 with PV with 10- and 7-years contract	First contract: 10 Second contract: 7 No contract: 3	22.78 23.61 –	27.78 28.61 –	19.78 20.61 –
Scenario 4	H1 with PV with 15- and 4-years contract	First contract: 15 Second contract: 4 No contract: 1	21.39 24.44 –	26.39 29.44 –	18.39 21.44 –
–	H1 with PV with 20 years contract	First contract: 20 Second contract: 0 No contract: 0	20	25	170

5.3. *TOU-TOU-TOU*

Since the T-T-T was obtained as the best scheme with the lowest COE as compared to other schemes, a deeper analysis is provided for this scheme. Fig. 10 shows the summary for all scenarios for T-T-T scheme. As shown, the best-case study by T-T-T is for a 20-year contract between H1 and H2. After that, Scenario 4 has achieved a lower COE compared to other scenarios. It can be inferred that prolonging the first contract between the customers achieves a lower COE for both houses.

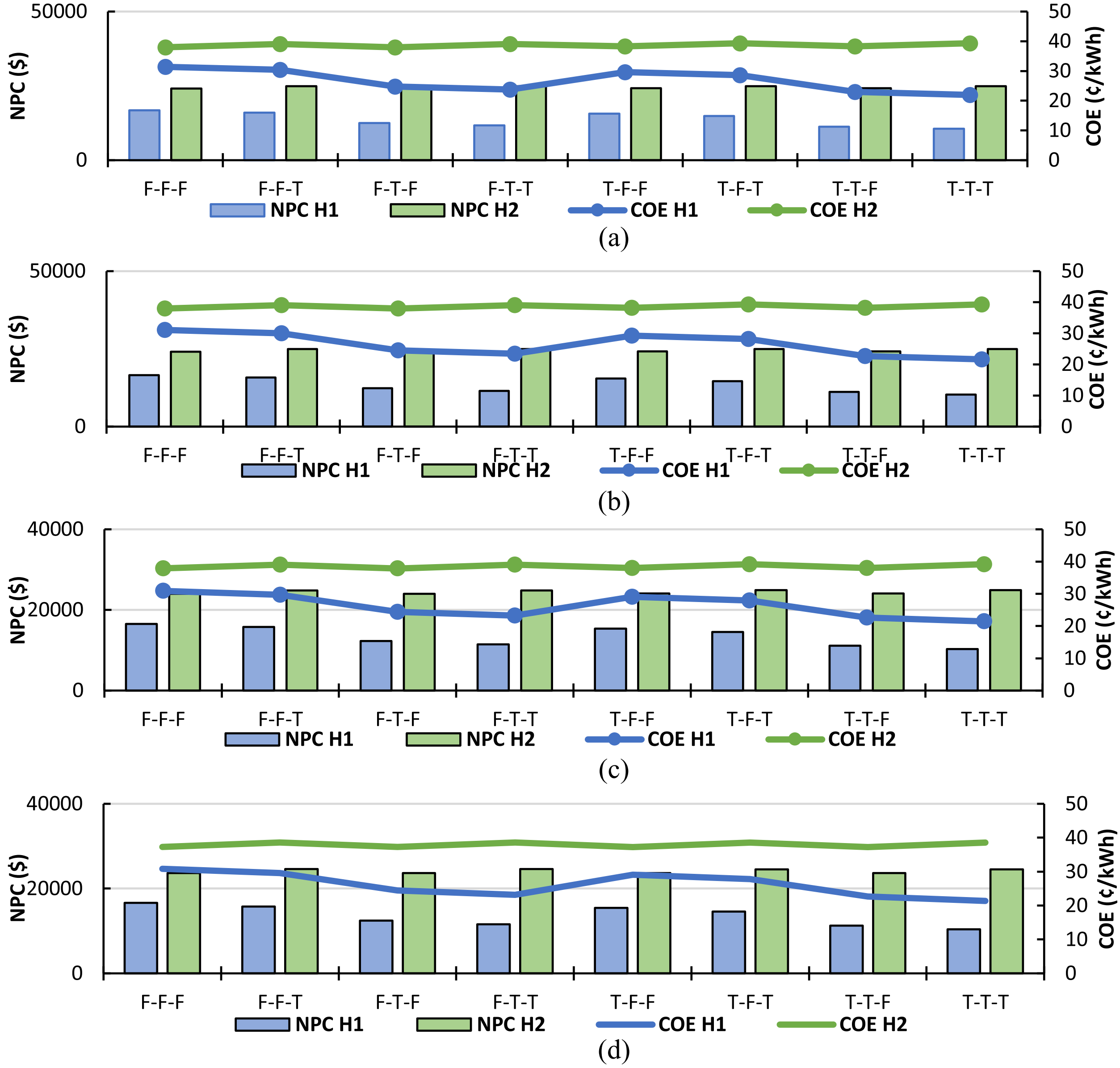


Fig. 9. NPC and COE of H1 and H2 for all schemes in different scenarios. (a) H1 with PV with 2- and 13-years energy sharing contract, (b) H1 with PV with 5- and 11-years energy sharing contract, (c) H1 with PV with 10- and 7-years energy sharing contract and (d) H1 with PV with 15- and 4-years energy sharing contract.

6. Analysis

All the analysis was conducted to determine the optimal solution for the best scheme identified, which was found to be TOU-TOU-TOU.

6.1. Sensitivity analysis

6.1.1. Effect of export power limitation

One of the most important parameters in this study is power export restriction (5 kW) set up by power networks and government. These things are temporary and might vary with the popularity of solar and energy sharing. So, it is important to see its variation effects in our study. Fig. 11 shows the results obtained when grid power export restriction varies from 0 kW to 10 kW. With the increase of power export restriction, the optimal PV size gradually increases. Optimal battery is pretty much constant with 5 kWh and 6 kWh. For H1, it can be observed that COE decreases significantly with the increase in exported power. This is because when export power

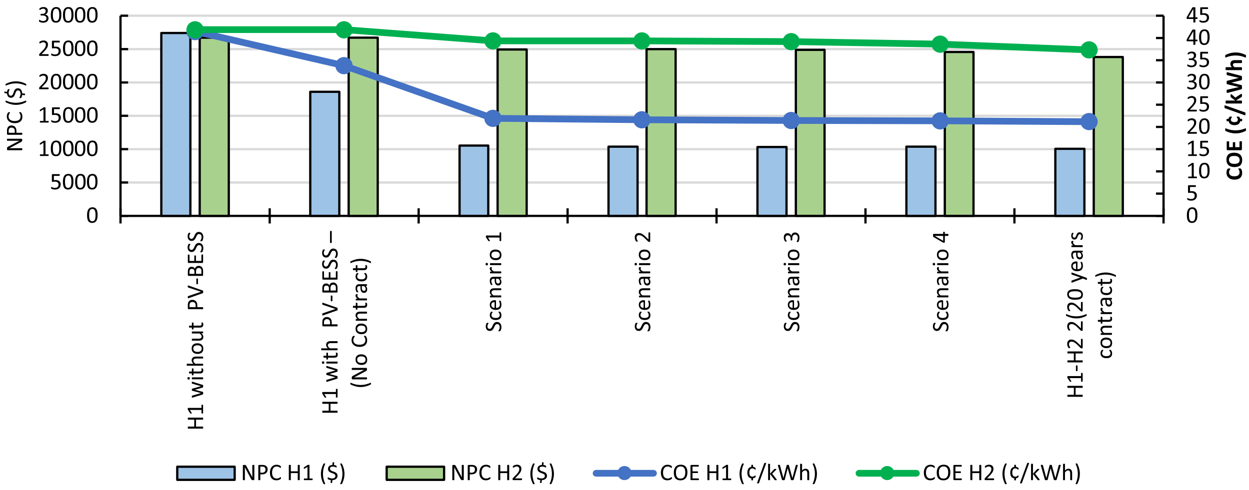


Fig. 10. COE and NPC summary for best the scheme (T-T-T) for different scenarios.

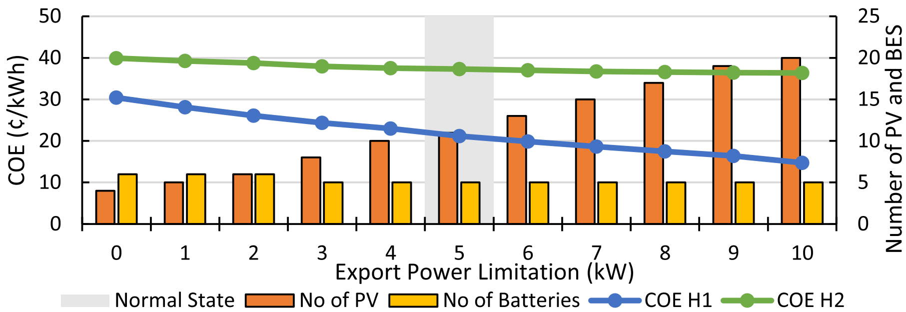


Fig. 11. Sensitivity analysis on COE when export power limitation is changed from 0kW-10 kW for H1.

limitation is increased, H1 can take full advantage of selling extra electricity produced to the grid instead of dumping electricity. Furthermore, H2′s electricity costs decrease gradually due to increased PV power generation, providing H2 with more opportunities to purchase electricity from H1 rather than from the grid.

6.1.2. Variation of H1 and H2 loads

The analysis is done when load consumption of each house varies. Optimal components size for H1 and effects on COE for each house are investigated and shown in the counterplot diagrams in Fig. 12. It can be observed that the least COE for H1 is when load consumption of H1 is lowest whereas H2 demand is the highest. This is because when load consumption of H1 is the least and H2 is the highest, H1 can take full advantage of selling electricity to H2 in agreed energy sharing rate in high price compared to the selling electricity to grid in low price. But when the load of H1 increases, it needs to satisfy its own demand and there will be less electricity to sell to H2 and less benefit to take which increases the H1 COE.

For H2 COE, it is observed that the lowest COE is when load consumption of H2 is highest and H1demand is the lowest. This is because when load consumption of H2 is highest, buying all the electricity from the grid is expensive but buying electricity in agreed energy sharing price from H1 will make the COE lower. When the load of H1 increases and that of H2 decreases, H2 cannot purchase more electricity from H1 at a lower rate because H1 must first meet its own demand. Furthermore, even though H2′s load consumption is at its lowest, DSOC remains the same as when it is highest, which contributes to an increase in COE for H2.

For optimal sizing of components, it can be observed that when load consumption of H1 and H2 are the lowest, number of PV is 10. When the load consumption of H1 and H2 increases, optimal PV size increases gradually. We can see BES has no effect on H2, this is because H2 does not get any power from the battery. The higher the load consumption of H1, the higher the optimal battery size becomes.

6.1.3. PV and battery energy storage cost variations

Fig. 13 shows the counterplot diagrams when PV-BES cost varies. For H1 it is observed that when PV-BES cost decreases, COE decreases. COE increase with the increase in load demand. More number of PV-BES needs to be installed, more components cost, and less energy is sold to H2. The highest COE is observed when both PV-BES costs and load demands are at their highest. This occurs because higher PV-BES costs lead to increased NPC of components, thereby raising the COE. Additionally, when the load demand of H1

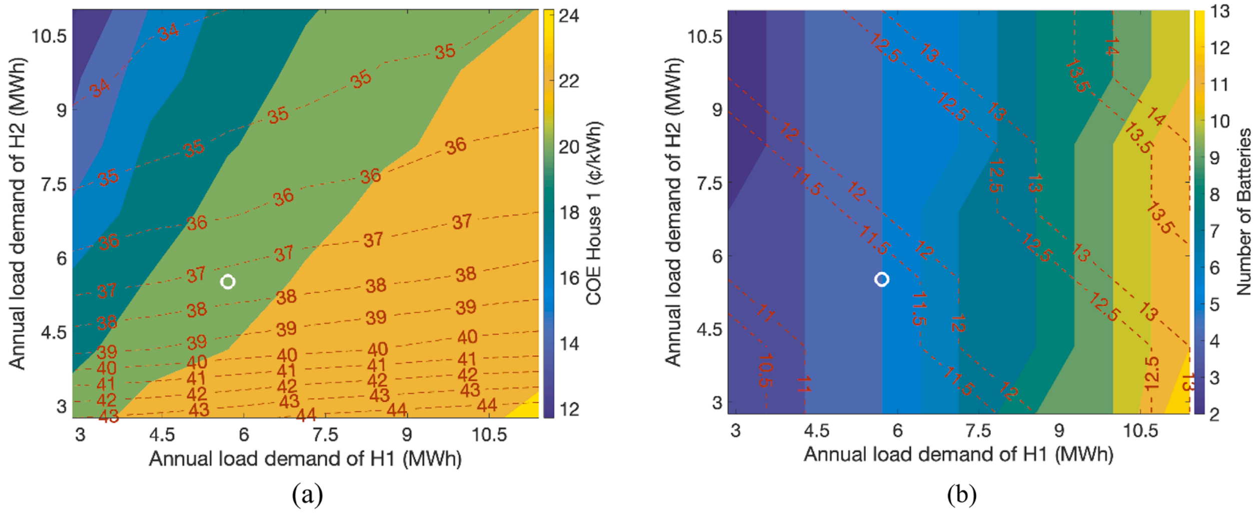


Fig. 12. Effect of houses' load demands on optimal sizing, (a) colorbar shows the COE for H1 and the red lines show the COE for H2, (b) colorbar shows the battery capacity in kWh and the red lines show the PV size in kW.

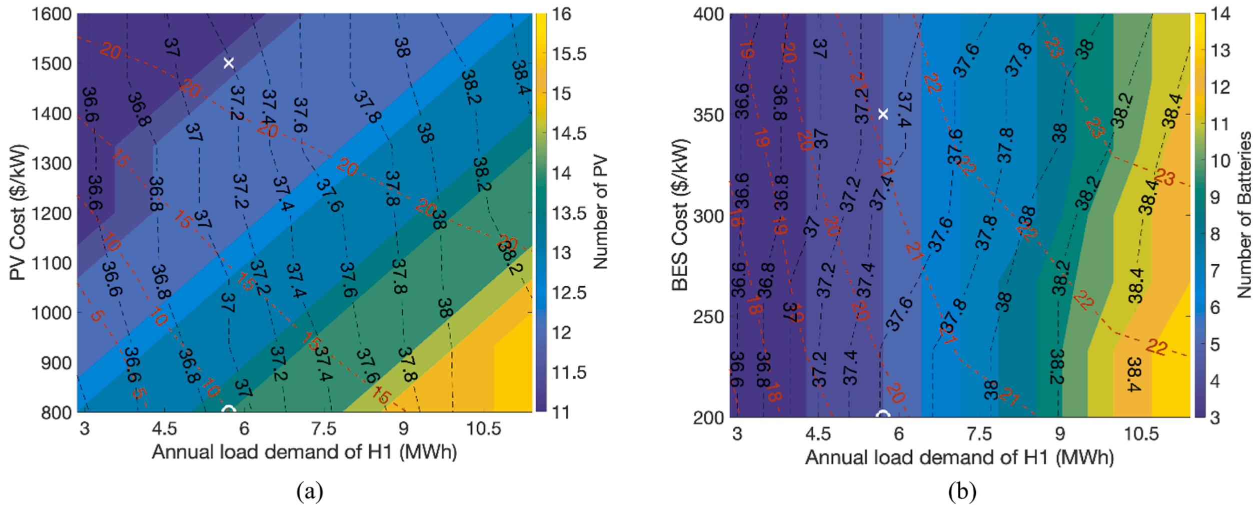


Fig. 13. Effects of load demand of H1 and cost of components on optimal sizing, (a) colorbar shows the PV size in kW, red lines show the COE for H1, and black lines show the COE for H2, (b) colorbar shows the BES capacity in kWh, red lines show the COE for H1, and black lines show the COE for H2.

increases, it diminishes the opportunities for selling electricity to the grid and H2, further contributing to the higher COE. COE does not change significantly for H2. PV-BES cost has no significant effect on COE for H2 because H2 does not have components and it has no relation with the components cost of H1. COE of H2 is affected by the load demand of H1 because the higher the load consumption of H1, the lower H2can take advantage of energy sharing rate as H1 should satisfy its own load demand which increases COE for H2.

Table 5
Grid charge effects on cost reduction and COE for both the houses.

Grid charge ($/kWh)	Energy sold to H2 by H1 (kWh)	Cost reduction for H1 (%)	Cost reduction for H2 (%)	COE of H1 (¢/kWh)	COE of H2 (¢/kWh)
0	1552.50	12.9	10.9	21.17	37.31
0.05	1552.50	9.8	9.0	21.94	38.10
0.10	1552.50	6.3	6.8	22.79	39.01
0.15	1552.50	3.3	5.0	23.53	39.77
0.20	1552.50	0	3.2	24.33	40.54

6.1.4. Effects of grid charge

In this analysis, we aimed to determine our breakeven point considering grid charges for energy transfer to houses. Grid charge will be paid equally by H1 and H2. Our breakeven point would be when grid charges 0.20 $/kWh for the energy transfer between the houses. Beyond this point, it does not make sense for H1 to share the energy as the cost would be very high. Table 5 shows the effects of different grid charges on cost reduction in% and COE for both houses.

6.2. Operational analysis

Fig. 14 shows the power flow diagram made for 2 consecutive days in summer and winter. Due to high solar irradiance, the generation of solar is high in summer whereas winter is completely opposite with the irradiance and power generation. With high energy production during the daytime, the PV system can meet the energy demands of both houses. However, during the evening and nighttime, the battery system takes over. BES can satisfy partial load demand of H1 and H1 buys additional electricity from the grid for which battery is unable to fulfill the demand. H2 buys power from the grid during this time because H1 will be unable to fulfill the demand. Fig. 14 illustrates the grid restriction of 5 kW, showing that exported power is taken into account and does not exceed this limit.

6.3. Uncertainty analysis

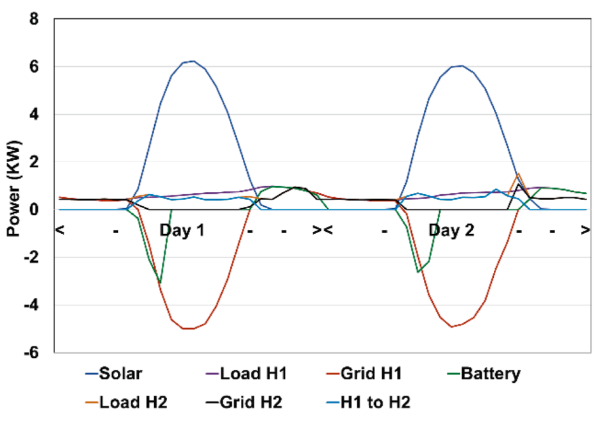
In this study, the uncertainty analysis is provided based on 10 scenarios of hourly variations. For this purpose, the real data of solar irradiance and temperature data for years 2011–2021 is taken from renewables Ninja [32]. The optimization is repeated for each scenario and optimal size of components and COE are obtained and the results are shown in Fig. 15. It is seen that uncertainties in solar irradiance and temperature do not change the optimal size of components. This means the capacities of PV and BES are intact as 10 kW and 5 kWh for all scenarios/years. COE of H1 varies between 13.14 ¢/kWh and 15.91 ¢/kWh for different years. This is because of the generated power by the PV system in each year. COE of H2 slightly varies between 37.12 ¢/kWh and 37.34 ¢/kWh which is neglectable.

7. Conclusion and future work

This study developed an optimal sizing model for residential PV and BES by considering energy sharing under TOU and Flat tariffs. Eight schemes, based on the electricity tariffs for buying/selling electricity from/to the grid and energy sharing rate between houses, were examined to achieve optimal PV-BES system. Out of eight schemes, four of them achieved optimal PV capacity of 10 kW while the other schemes achieved 11 kW. The BES optimal capacity is almost consistent of 7 kWh in all the scheme except for T-T-F with 6 kWh and T-T-T with 5 kWh.

COE for both houses significantly decreased when PV-BES is installed, and energy sharing is used. Out of all the 8 schemes observed, COE reduction is maximum in T-T-T scheme for H1. Out of all the 4 scenarios, it was observed, 1st scenario has highest COE for both the houses. It was because H1was unable to take advantage of energy sharing for last 5 years and for H2 it took a smaller number of years as an initial contract and energy sharing cost was high compared to other scenarios. Both houses have least COE in 4th scenario as H1 took advantage of energy sharing for 19 years out of total 20 years and for H2 it got advantage of less energy sharing prices for all those 19 years as well as initial contract was maximum.

Future work can be done by adding electric vehicles (EVs) for the houses. The availability of EV and its charging/discharging capability can affect the energy sharing procedure and hence the optimal capacity of PV and BES. Another potential future work is to



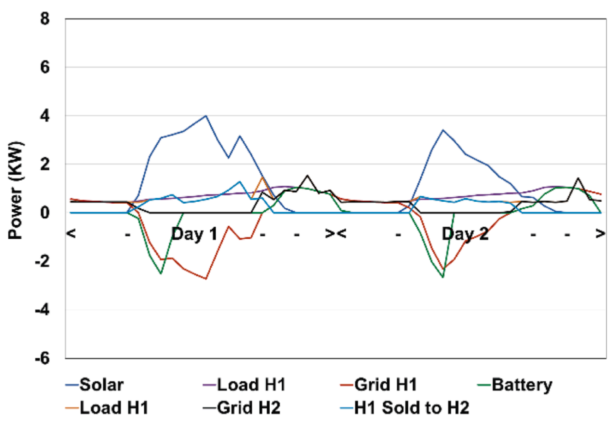


Fig. 14. Operational analysis for 2 days of: (a) Summer (b) Winter.

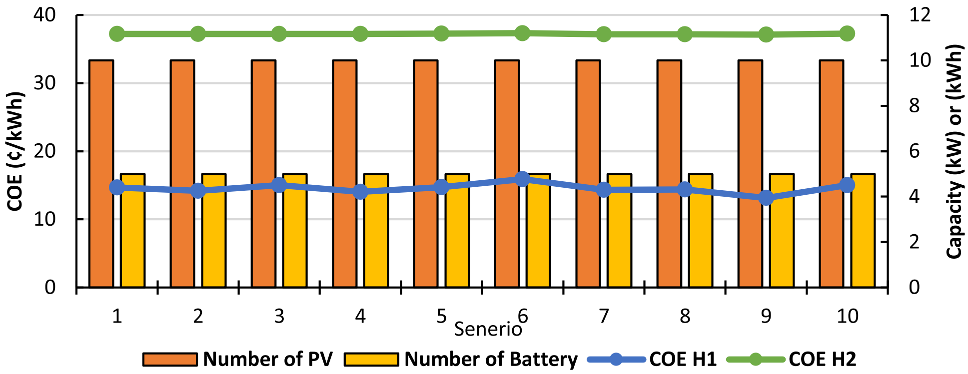


Fig. 15. Uncertainty analysis on COE and optimal sizing of components due to change in solar irradiance and ambient temperature for ten scenarios of variations.

investigate the effect of demand response programs on the optimal sizing problem by incorporating the energy sharing program.

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None.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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