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Effects of electric vehicles on energy sharing for optimal sizing of solar PV and battery energy storage

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ABSTRACT

Energy sharing for homes with electric vehicles (EVs) enhances sustainability by optimizing energy usage, reducing peak demand, and integrating renewable energy sources, thereby lowering costs and improving energy resilience. This study investigates the effects of EVs on optimal sizing problem of solar photovoltaic (SPV) and battery energy storage system (BESS) for grid-tied homes which participate in energy sharing schemes. In this paper, it is assumed that the energy is shared between two homes: home-1 as the prosumer which has an EV and intends to buy SPV and BESS, and house-2 which is a consumer. The optimization problem is formulated to achieve the minimum cost of electricity (COE) for home-1 and to reduce the COE for home-2 while taking consideration of the design constraints over the project lifespan. A rule-based energy management system is developed for different sets of configurations to compare the economic and operational results. The optimization is done by incorporating realistic annual data of the irradiance, temperature, load, and uncertainties of EV. The developed optimization technique is general in nature and can be used for any grid tied homes willing to share the electricity. Sensitivity analyses on costs of SPV-BESS, home energy demand, and grid export constraints are provided. Uncertainty analyses investigates the price of energy sharing and solar PV generation. The impact of various EV models with their respective battery capacity is also analyzed. The results show that the proposed energy-sharing methodology reduces the COE for prosumer and consumer by 1.2 ¢/kWh and 3.6 ¢/kWh, respectively.

1. Introduction

1.1. Background and motivation

Around 30 % of global energy demand is consumed by residential households [1]. To decrease this demand, installing SPV panels on-site is a practical solution. These panels allow customers to use the generated power for themselves and sell any excess back to the network at a lower feed-in-tariff (FIT). The consumer has a fewer chance of purchasing SPV due to lower FIT compared to retail price. BESS, which can be used to store energy and can be discharge in peak hours is not yet economical [2]. Electric vehicles (EVs) are expected to play a significant role in household energy consumption as internal combustion engines are phased out. Sales of EVs have been increasing in various countries and regions since 2018 [3]. According to the International Energy Agency, the number of EVs is projected to reach 130 million by 2030 [4]. In some countries and regions, home charging is expected to make up 50–85 % of EV charging because many EV owners prefer to charge their vehicles at home if they have their private space for parking [5]. 45 % of private EV owners prefer to charge EVs using rooftop SPV, 31 % prefer BESS and 14 % from grid with carbon offset. Cost is a major concern for 54 % of EV owners [6].

The widespread adoption of distributed energy resources (DERs) has drastically altered the way energy is generated, distributed, and consumed in the energy pipeline. The significant rise in prosumers, who both generate and consume energy, has led to a more decentralized and open electrical network [7]. Energy providers are no longer just responsible for selling energy, but also for renting out transmission lines for prosumers to feed energy back into the grid through net metering programs. However, some regions such as Michigan in the United States

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and Saskatchewan in Canada are starting to phase out these net metering programs. If more areas follow suit, the incentive to install SPV systems or other renewable energy systems will likely decrease. Additionally, the financial return on investment for current and future prosumers of renewable energy systems may go down, which will affect the energy market and have a broader impact on society. Achieving a low-carbon energy future requires a greater generation of renewable energy. To support this transition, new forms of compensation need to be found for residential energy prosumers [8,9]. Peer-to-Peer (P2P) energy sharing has emerged as a solution for prosumers to actively engage in the energy market. P2P allows prosumers to exchange surplus energy with their peers, resulting in increased benefits for both the prosumer and the consumer. Additionally, P2P energy trading provides more opportunities to consume clean energy and supports the transition to a sustainable future [10,11].

At the end of 2020, Australia had the highest uptake of rooftop SPV systems globally, with 21 % of homes, or 2.66 million installations, having SPV [12]. Installation of SPV in the last 5 years has been increasing steadily, with a 39 % increase in installations and a 65 % increase in capacity from 2019 to 2020 [13]. Additionally, it is estimated that 8 % of SPV systems also include BESS in 2019 [14]. However, most of these systems are integrated with flat electricity prices and the impact of TOU pricing is not widely studied. Additionally, the impact of EV on household energy usage should also be considered when investigating optimal SPV-BESS systems under TOU pricing, as EV sales in Australia grew by 90 % between 2018 and 2019 [15]. Despite a decline in overall vehicle sales by 8.4 %, the demand for EV in Australia continues to grow. This increase in demand is likely due to the availability of more affordable EVs under $60,000 [15]. With a high percentage of homes in South Australia which is 35 % having rooftop SPV systems and a trend towards more installations of SPV and SPV-BESS, it is important to consider how to optimize these systems with respect to TOU pricing mechanisms. The cost of rooftop SPV systems has reached an all-time low due to a steady decrease over the last 20 years, decreasing from around $4550 per kilowatt in 2000 to $650 per kilowatt in 2020. Similarly, the price of BESS has decreased significantly, dropping from $1430 per kilowatt-hour in 2010 to $203 per kilowatt-hour in 2020 [16]. Developing guidelines for households that already own an EV and are looking to install a SPV-BESS system would allow them to make informed decisions about system capacity. Optimal sizing is one of the most important issues for prosumers beside grid constraint, capital expenditure cost of components. Capacity optimization was researched in previous papers but different parameters impacting the sizing that includes real load and meteorological data, real cost of components, grid constraints were not considered due to which obtained optimal sizing may not be practical. It is crucial to determine the optimal size of SPV and battery components for maximum economic benefits for households. This paper aims to find the optimal sizing of components for grid connected households with EV as well as minimizing COE for prosumer and reducing COE for consumer.

1.2. Literature review

The integration of EVs into residential energy systems has garnered significant attention in recent years, particularly in the context of P2P energy trading and energy sharing among households. The concept of P2P energy trading has been explored, with various studies proposing frameworks and models to facilitate energy transactions among prosumers. This literature review synthesizes existing research on these topics, highlighting the contributions of the current study, which focuses on optimal component sizing for grid-connected households with EVs and energy sharing mechanisms.

Several studies investigated the P2P energy sharing mechanisms with flat electricity rates for homes [17–22]. The concept of energy trading between locally based energy consumers and small-scale distributed energy resources, such as offices and factories, was discussed in Ref. [17]. Game theoretic strategies for P2P energy trading were used in Refs. [18–21] as a practical and efficient way to manage energy and drastically lower energy costs. A successful bidding approach for peer-to-peer energy trading has been developed in paper [22] to address the issue of unfair trade restrictions and a lack of flexibility in recent studies. However, those studies used flat electricity rates, whereas TOU tariffs have become a beneficial alternative for residential customers in recent years. Hence, the advantage of being driving the cost down for both prosumers and consumers is limited under such structure.

The rest of studies used TOU tariff for the homes while energy sharing was applied [23–28]. However, there are shortcomings related to those studies. For example, the energy sharing between the prosumers and consumers was fixed and not changeable. However, flexibility should be applied so that each consumer or prosumer could cancel the contract at the end of the year. Grid constraints are practical and critical restrictions that were overlooked in previous studies. This consideration is especially important when applying optimal sizing. In fact, limiting power export to the grid can restrict the optimal capacity of SPV and BESS systems.

Although an energy-sharing platform was established in previous studies, the capacity of the SPV and BESS was not optimized. Most studies considered existing SPV and BESS systems and did not attempt to optimize the capacity of these components. The only paper which discussed the optimization of SPV and BESS was [25], which considered FIT rates. The findings of this study demonstrate that using SPV and BESS together offers higher economic advantages than using BESS alone. However, the study did not discuss about the impact of EV in optimization as well as do not discuss about the grid constraints on export power.

The research conducted in Refs. [18,26,27] have integrated the EVs in P2P energy sharing, highlighting the impact of flexible demands and battery storage but did not really explore the role of EVs in demand fluctuations or energy trading strategies. Such approaches are unable to capture the increased complexity of load management when EVs are a part of the equation. In fact, by not factoring the EVs' load based on its availability and required energy when arriving home, these models underestimate the total demand and energy flexibility, which results in less effective energy distribution cross the microgrid.

In summary, the literature gaps in existing P2P energy trading research include static pricing models, limited EV integration, constrained DER sizing frameworks, and ignoring practical grid constraints. Table 1 presents a summary of shortcomings in the existing research papers about energy sharing between homes. To the best knowledge of the authors of this paper, none of the existing energy sharing research papers studied the optimal sizing of components with mutually agreed electricity rate for energy sharing.

1.3. Contributions

The major contributions of this study as compared to other existing studies are as follows:

- Optimal component sizing for grid-connected household with an EV and energy sharing with a neighbor home was conducted for the first time based on an energy sharing mechanism. It considers the impact of EV integration on optimal sizing - previously not addressed in energy sharing for residential houses - which significantly affects the energy demand and electricity costs.
- TOU electricity tariffs on a mutually agreed energy sharing price between the grid tied homes. It is assumed that the energy sharing rate is between retail rate and Fit rate. This makes sure that the house with components gets benefits selling to another house rather than simply selling to the grid. On the contrary, house who intend to purchase energy also gets benefits as the energy sharing rate would be lower than the retail rate.

Table 1
A summary of current research papers in literature which cover the energy sharing between homes.

Paper	Electricity rates	Mutually agreed price	SPV/BESS	EV	Optimal sizing	Grid constraint	Contract flexibility
17	Flat	×	SPV	×	×	×	×
18	Flat	×	SPV	✓	×	×	×
19	Flat	×	SPV + BESS	×	×	×	×
20	Flat	×	SPV + BESS	×	×	×	×
21	Flat	×	SPV + BESS	×	×	×	×
22	Flat	×	SPV + BESS	×	×	×	×
23	TOU	×	SPV + BESS	×	×	×	×
24	TOU	×	SPV + BESS	×	×	×	✓
25	TOU	×	SPV + BESS	×	✓	×	×
26	TOU	×	SPV + BESS	✓	×	×	×
27	TOU	×	BESS	✓	×	×	×
28	TOU	×	SPV	×	×	×	×
This Paper	TOU	✓	SPV + BESS	✓	✓	✓	✓

- Development of separate energy management system for grid tied home with EV sharing electricity with other home under TOU tariffs.

This work also include minor contributions as follows:

- Optimization model includes all the practical parameters such as daily supply charge of charge of electricity, battery degradation, components salvation value and grid constraint set by decision maker.
- Study the effects on optimal sizing of components and COE for the home with different EVs available in the market with different battery capacity which reveals that lower the battery capacity lower the optimal components size and COE for house.
- Developing and investigating different scenarios to make contract between the homes flexible if any home wish to extend or cancel the energy sharing contract.

1.4. Article organization

The paper is structured as follows: Section 2 describes operational strategies for the home energy management system when EV is at home and when it is not. Home energy management system is the integrated system of software and hardware which uses flow chart, algorithm, and control strategies for analyzing load profile, PV and BES sizing and grid interaction. Section 3 describes methodology that includes objective function, optimization flow chart and constraints of the study. Section 4 contains the case study and data collection to obtain the results. Section 5 includes results and discussion. All the analysis that includes sensitivity, uncertainty and operational analysis is presented in section 6. Finally, section 7 discusses the conclusion and future work.

2. Operational strategies for home energy management system

The network configuration of energy sharing between the homes is shown in Fig. 1. Both homes (i.e., Load 1 and Load 2) are tied with the grid. home-1 has SPV, BESS and EV whereas home-2 does not have these components. The consideration made for this study is that energy will be shared between the homes with mutually agreed rate and home-1 will purchase the SPV and BESS accordingly. There is an agreed electricity rate (monitored by electricity service providers) for sharing the energy between the homes. Although the results are presented for this case study, the proposed energy management system is scalable and similar algorithm can be developed for multiple homes. In an extended version of this study, home-1 will be n number of homes with SPV and BESS components and home-2 will be *m* number of homes without SPV/BESS components but may own EVs. Although, this study only focuses on two homes, it is the baseline research for future similar projects relevant to developing the algorithms for a network of homes that is currently out of the scope in this paper.

In this study, a rule-based home energy management system (EMS) is developed to implement energy sharing. The flowchart for EMS is shown in Fig. 2. It is notable that rule-based EMSs are straightforward and user-friendly for implementation, facilitating clear and explicit rules for both designers and users.

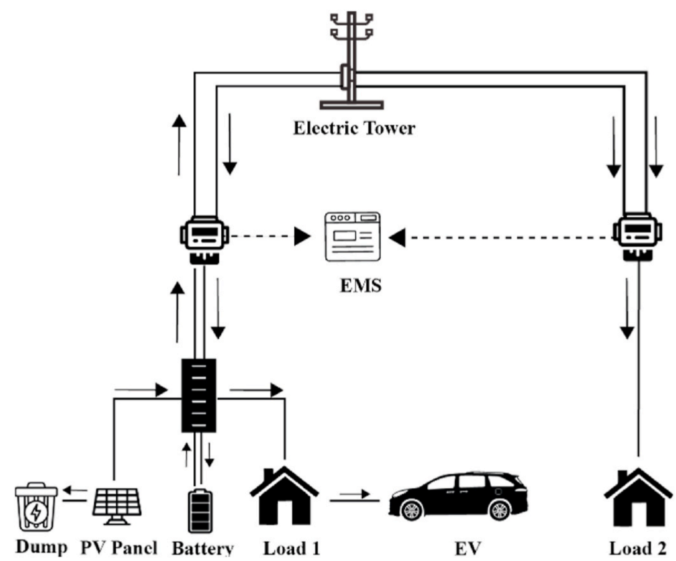


Fig. 1. Network configuration showing the energy sharing between home-1 and home-2.

Since the focus of this paper is to investigate the impact of EV on energy sharing, the EMS is divided into two parts based on the EV's availability. The first part of the EMS is used when EV is at home (home-1) whereas the second flowchart is used when EV is not at home (home-1). The energy demand for charging EV is excluded in the second part. It is notable that several past papers have discussed the equation without EV [29–32].

When EV is at home, the generated power by SPV first supplies home-1 load and then charges the EV. If there is any excess power from SPV, then it charges the BESS. Once all loads of home-1, EV charge, and BESS charge are supplied by the SPV, any excess power can be shared with home-2. Therefore, the SPV\s generated power is always first used for the loads of home-1 and its EV and BESS, and then it shares energy with home-2. Since no power is left to be sold to home-2, the export power to grid and dump power of SPV are also zero. Hence, all the load demand for home-2 will be fulfilled by grid. It is to be noted that the mathematical equations are presented in Fig. 2, and they are not present in text to avoid repetition.

When SPV power generation is greater than combined power needed for home-1, EV and BESS, it will initially satisfy demand of home-1, and hence the remaining power will be sold to home-2 as follows:

Fig. 2. Flow chart for the rule-based home EMS: energy sharing between home-1 and home-2 when: (a) EV is at home-1; (b) EV is not at home-1.

$$P_1^{ex2}(t) = P^{SPV}(t) - P^{L1}(t) - P_{in}^{EV}(t) - P_{in}^{BESS}(t) \tag{1}$$

where P_1^{ex2} represents the exported power to home-2 by home-1. Also, P^{SPV} and P^{L1} represent power generation by SPV system and load power of home-1, respectively. In addition, P_{in}^{EV} and P_{in}^{BESS} is available input power of EV and battery respectively.

If the PV generation is higher than the required power by home-2, then the excess power is exported to the grid by home-1 which is given by:

$$P_1^{ex\_GRID}(t) = \max\left(P_{max}^{ex\_GRID}, P^{SPV}(t) - P^{L1}(t) - P_{in}^{EV}(t) - P_{in}^{BESS}(t) - P^{L2}(t)\right) \tag{2}$$

where $P_1^{ex\_GRID}$ represents export power by home-1 to grid, $P_{max}^{ex\_GRID}$ is maximum allowable export power to grid, and P^{L2} is load power of home-2.

Any excess power remaining after export to the grid will be dumped via the control system of the SPV's inverter. It is notable that in most of the countries with high contribution of SPV on feeders, the export power to the grid from individual SPVs is restricted by distribution network providers. The dump power (P^{dump}) can be calculated by:

$$P^{dump}(t) = P^{SPV}(t) - P^{L1}(t) - P_{in}^{EV}(t) - P_{in}^{BESS}(t) - P^{L2}(t) - P_{max}^{ex\_GRID}(t) \tag{3}$$

Home-2 has an option to buy power from grid if the exported power from home-1cannot satisfy its full demand.

$$P_2^{im\_GRID}(t) = P^{L2}(t) - P_1^{ex2}(t) \tag{4}$$

where $P_2^{im\_GRID}$ imported power by home-2 from the grid.

When SPV's power generation is less than the combined load demand of home-1and EV, BESS satisfies the partial or total demand if there it has enough charge. If the BESS is unable to fulfill the total demand of home-1 and EV, the required power is imported from the main grid (5). For this case, home-2 buys all the electricity from the grid and power exported to home-2 or grid by home-1 will be zero.

$$P_1^{im\_GRID}(t) = P^{L1}(t) + P_{in}^{EV}(t) - P^{SPV}(t) - P_{out}^{BESS}(t) \tag{5}$$

where $P_1^{im\_GRID}$ is imported power from grid by home-1 and P_{out}^{BESS} is available output power of BESS.

In all steps, the state of charge (SOC) of BESS for each time interval is calculated by Ref. [30]:

$$S^{BESS}(t+\Delta t) = \frac{S^{BESS}(t) + \left(P_{ch}^{BESS}(t)\eta_{ch}^{BESS}(t) - P_{dis}^{BESS}(t)\eta_{dis}^{BESS}(t)\right)\Delta t}{E^{bc}} \tag{6}$$

where S^{BESS} is the SOC of BESS. P_{ch}^{BESS} and P_{dis}^{BESS} represent power delivered to and by battery during charging and discharging, respectively. η_{ch}^{BESS} and η_{dis}^{BESS} are charging and discharging efficiency of the BESS, respectively. E^{bc} is total battery capacity of the BESS.

Available input power (P_{out}^{BESS}) and export power (P_{in}^{BESS}) of the BESS are used to restrict the charge and discharge power according to the SOC of the BESS.

$$P_{out}^{BESS} = \frac{E^{bc}}{\Delta t}\left(S^{BESS}(t) - S_{min}^{BESS}\right) \tag{7}$$

$$P_{in}^{BESS} = \frac{E^{bc}}{\Delta t}\left(S_{max}^{BESS} - S^{BESS}(t)\right) \tag{8}$$

S_{min}^{BESS} and S_{max}^{BESS} represents minimum and maximum SOC of the battery.

Similarly, the SOC of EV for each time interval can be calculated by Ref. [30]:

$$S^{BEV}(t+\Delta t) = \frac{\left(P_{ch}^{BEV}(t)\eta_{ch}^{BEV}(t)\right)\Delta t + S^{BEV}(t)}{E_{bc}^{EV}} \tag{9}$$

where S^{BEV} is EV's battery SOC. P_{ch}^{BEV} and η_{ch}^{BEV} represent power delivered to EV during charging period of EV, respectively. E_{bc}^{EV} is the total battery capacity of the EV.

The available input power of the EV (P_{in}^{BEV}) is calculated at charging period to restrict the EV's charge power according to the SOC of its battery.

$$P_{in}^{BEV} = \frac{E_{bc}^{EV}}{\Delta t}\left(S_{max}^{BEV} - S^{BEV}(t)\right) \tag{10}$$

where S_{max}^{BEV} represents maximum SOC of EV's battery.

3. Methodology

This section discussed the methodology to obtain the optimal sizing of components.

3.1. Objective function

The objective function is to minimize the COE for home-1, mainly because home-1 is responsible for purchasing the SPV and BESS components in this study. Therefore, the optimal sizing problem is solved for home-1 as the prosumer. Meanwhile, home-2 as the consumer, benefits from the energy sharing by utilizing the excess energy from SPV-BESS of home-1. The rate for energy sharing between the homes is lower than the electricity rate bought from the grid. Hence, any amount of shared energy would automatically reduce the COE for home-2. The COE of home-1 can be formulated as follows [31]:

$$f = \min(\mathrm{C}_1) = \min\left(\frac{\sqcap_1^{COMP}\,CRF^{COMP} + \sqcap_1^{elec}CRF^{elec}}{L_1^{an}}\right) \tag{11}$$

It is notable that the COE of home-2 is calculated by:

$$\mathrm{C}_2 = \frac{\sqcap_2^{elec}CRF^{elec}}{L_2^{an}} \tag{12}$$

where C_1 and C_2 represent the COE of home-1 and home-2, respectively. Likewise, $\sqcap_1^{elec}$ and $\sqcap_2^{elec}$ represents NPC of electricity for home-1 and home-2 respectively. $\sqcap_1^{COMP}$ is components net present cost. In addition, CRF^{COMP} and CRF^{elec} are capital recovery factors (CRF) of components and electricity. Lastly, L_1^{an} and L_2^{an} represents annual electricity demand for home-1 and home-2, respectively.

CRF is the ratio to determine the present value of an annuity. The capital recovery factor for the system components and electricity can be calculated as follows:

$$CRF^{COMP} = \frac{r^i(1+r^i)^n}{(1+r^i)^n - 1} \tag{13}$$

$$CRF^{elec} = \frac{r^r(1+r^r)^n}{(1+r^r)^n - 1} \tag{14}$$

$$r^r = \frac{r^i - r^e}{1+r^e} \tag{15}$$

where r^i and r^e represents interest rate and escalation rate respectively. r^r is called actual rate, and n is the project life.

Net present cost (NPC) is the present value of a component which can be calculated with its capital, replacement, maintenance cost and its salvation value as follows.

$$\sqcap_1^{COMP} = N^{BESS}\left(PC_c^{BESS} + PC_m^{BESS} + PC_r^{BESS} - PC_{sv}^{BESS}\right) + N^{SPV}\left(PC_c^{SPV} + PC_m^{SPV} + PC_r^{SPV} - PC_{sv}^{SPV}\right) \tag{16}$$

where N^{BESS} and N^{SPV} represent total number of batteries and SPV, respectively. PC_c^{BESS}, C_m^{BESS} , PC_r^{BESS} and PC_{sv}^{BESS} represents capital present cost, maintenance cost, replacement cost and salvation value of BESS, respectively. Likewise, C_c^{SPV} , PC_m^{SPV} , PC_r^{SPV} and PC_{sv}^{SPV} are capital present cost, maintenance cost, replacement cost and salvation value of SPV, respectively.

The manufacturer determines the lifetime of SPV components. The capacity degradation of the battery during its operation is a measure of BESS lifetime. The end of battery life reaches when the capacity degradation is 20 % [32]. The degradation of battery can be calculated by the depth of discharge of each cycle and total number of cycles. Data for SOC of battery is obtained for each year of operation. The depth of discharge is calculated as follows:

$$BDD(t) = 1 - S^{BESS}(t) \tag{17}$$

where BDD represents battery's dept of discharge.

In this study, Rain flow algorithm method is used to extract the data and calculate number of cycles. The extracted data is analyzed under various stress factors and stress levels in lab to determine battery degradation [32]. It is calculated as a function of battery depth of discharge for each cycle (c) as follows:

$$BD(c) = \frac{20}{33000.e^{-0.06576.BDD(t)} + 3277} \tag{18}$$

where BD is battery degradation.

The total battery capacity annual degradation can be calculated as follows:

$$ABD = \sum_{t=1}^{8,760}\sum BD(c) \tag{19}$$

where ABD is annual battery degradation.

The NPC of electricity for both homes can be calculated by the following formulas:

$$\sqcap_1^{elec} = C_{home-1}^{elec} \frac{(1+r^r)^n - 1}{r^r(1+r^r)^n} \tag{20}$$

$$\sqcap_2^{elec} = C_{home-2}^{elec} \frac{(1+r^r)^n - 1}{r^r(1+r^r)^n} \tag{21}$$

where C_{home-1}^{elec} is the annual electricity cost of home-1 which is the sum of electricity buying from the grid under TOU rate, selling electricity to home-2 with agreed TOU rate, and exported electricity to grid in TOU rate. C_{home-2}^{elec} is the annual electricity cost which is sum of electricity buying from grid by TOU rate and buying electricity from home-1with agreed TOU rate.

$$C_{home-1}^{elec} = \sum_{t=1}^{8760} \left(P_1^{im\_GRID}(t)\Delta t\right) R_{tou}^{elec} - \sum_{t=1}^{8760} \left(P_1^{ex2}(t)\Delta t\right) R_{tou}^{H1\_H2} - \sum_{t=1}^{8760} \left(P_1^{ex\_GRID}(t)\Delta t\right) R_{tou}^{ta} \tag{22}$$

$$C_{home-2}^{elec} = \sum_{t=1}^{8760} \left(P_2^{im\_GRID}(t)\Delta t\right) R_{tou}^{elec} + \sum_{t=1}^{8760} \left(P_1^{ex2}(t)\Delta t\right) R_{tou}^{H1\_H2} \tag{23}$$

where R_{tou}^{elec} is the buying electricity price from grid in TOU rate. $R_{tou}^{H1\_H2}$ represents the TOU electricity rate for energy sharing between home-1 and home-2, and R_{tou}^{ta} is the selling electricity price to the grid in TOU rate.

The total NPC for home-1includes its component NPC and electricity NPC whereas the total NPC of home-2 only includes its electricity NPC.

$$\sqcap_1^{tot} = \sqcap_1^{comp} + \sqcap_1^{elec} \tag{24}$$

$$\sqcap_2^{tot} = \sqcap_2^{elec} \tag{25}$$

where $\sqcap_1^{tot}$ and $\sqcap_2^{tot}$ represents total net present cost for home-1 and home-2 respectively.

3.2. Design constraints

The mathematical form of the design constraints should be defined to solve the optimization problem accurately. Equations (26)–(28) represent the power constraints for SPV, BESS, and EV, respectively. Equations (29) and (30) represent the SOC constraints for battery and EV, respectively. Equation (31) represents the power balance constraint between SPV, BESS, EV, home, and grid for any given interval of time. Equation (32) represents the export power limitation constraint set by Australian government. Other minor constraints not shown in the equation but used in the analysis is that the flat rate is always in the middle compared with peak and off-peak rates for buying, sharing, and selling of the electricity, respectively.

$$0 \le P^{SPV}(t) \le P_{max}^{SPV} \tag{26}$$

$$0 \le P_{in}^{BESS}(t), P_{out}^{BESS}(t) \le P_{max}^{BESS} \tag{27}$$

$$0 \le P_{in}^{EV}(t) \le P_{max}^{EV} \tag{28}$$

$$S_{min}^{BESS} \le S^{BESS}(t) \le S_{max}^{BESS} \tag{29}$$

$$S_{min}^{EV} \le S^{EV}(t) \le S_{max}^{EV} \tag{30}$$

$$P^{PV}(t) + P_{in}^{BES}(t) + P_{home-1}^{im\_GRID}(t) + P_{home-2}^{im\_GRID}(t) - P_{home-1}^{ex\_GRID}(t) \ge P^{L1}(t) + P^{EV}(t) + P^{L2}(t) \tag{31}$$

$$0 \le P_{home-1}^{ex\_GRID} \le P_{max}^{ex\_GRID} \tag{32}$$

3.3. Optimization procedure

The optimal sizing of system components can be achieved with the help of multiple solvers in MATLAB, but PSO is used in this study. This is because of the nonlinearity of the BESS's SOC and battery degradation models. The degradation needs to be calculated at the end of optimization, which makes the solution of the model with conventional optimization mathematically infeasible. The PSO algorithm has been successfully used for optimal sizing in numerous research studies in the power systems [2,30–33]. Therefore, the comparison between the PSO and other optimization algorithm is out of the scope for this paper. PSO has several advantages which includes its simplicity, convergence rate, less dependent on initial points, potential to find global optima and requirement of little space [34]. Fig. 3 shows the flowchart used by PSO to find the optimal solutions in this paper. All data such as load of both homes, EV data, meteorological data, component specifications, and electricity cost are incorporated in PSO before the simulation. PSO tries

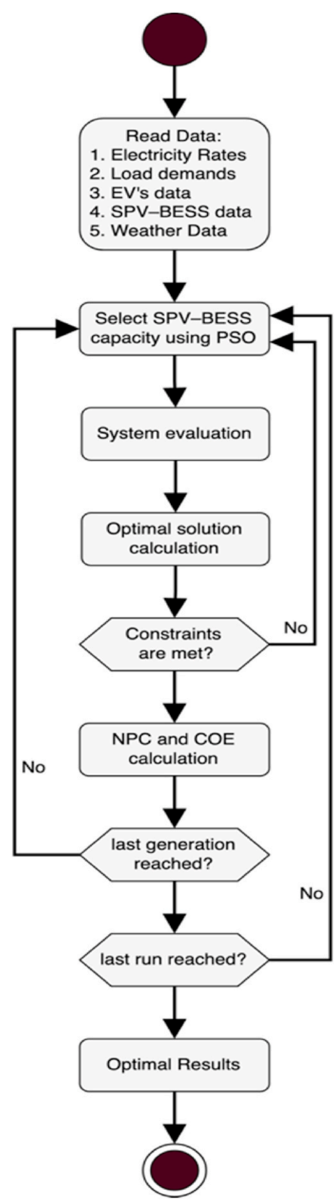


Fig. 3. PSO optimization Flow chart in this study.

the random number of each component until an optimal solution is achieved. It also checks the design constraints to achieve the valid optimal solution.

Optimal solution is ensured to be achieved when higher number of runs, population and generation are chosen [30]. Therefore, to achieve convergence, 200 generations have been selected, meaning PSO will run the optimization for 200 times in each run. Furthermore, the process is repeated for 10 times to ensure the global optimal results. It means the optimization model is executed for 10 runs and the minimum obtained COE is selected as the optimal solution. Several other parameters in PSO algorithm such as social, inertia and cognition weight are assumed as 2, 0.5 and 2 respectively.

4. Case study

The main purpose of this case study is to investigate the impacts on current COE and the saving that houses can make on COE after optimal components are obtained and energy is shared between houses. Two houses load data were taken. One of the houses has components including PV and BES and next house do not have components but willing to share electricity. Real meteorological data, component cost and electricity rate were also taken in addition to load data which is explained briefly in below section.

4.1. Data collection for optimal sizing and COE calculation

4.1.1. Meteorological data

Fig. 4 shows the annual temperature and solar irradiance data of south Australia plotted for every month for a year in box plot format. The data was taken from bureau of meteorology of Australia [35]. The ambient temperature is between 2.2 °C which is the lowest and 41.9°C being the highest with annual average of 17.9 °C. The average solar isolation is 5.4 kWh/m^2.

4.1.2. Load data

Fig. 5 shows the load data for home-1, home-2 and EV. The load data were taken from Refs. [30,36] for home-1 and home-2, respectively. The minimum and maximum load for home-1 are 0.32 kW and 1.65 kW, respectively, with an average load of 0.65 kW. The minimum and maximum load for home-2 are 0.19 kW and 2.97 kW, respectively, with an average load demand of 0.63 kW. Minimum and maximum load for EV is 0.32 kW and 6.85 kW, respectively, with an average load of 1.47 kW.

The developed methodology is general in nature and optimization can be done with any two homes with energy sharing and having EV. Two south Australian homes were taken for this study. A Renault Zoe (2020 R135) with 5 kW single-phase charging power and battery capacity of 54 kWh is taken for this study [37] and different analysis is done in later part of the paper for various EVs and battery capacities. In addition, truncated gaussian distribution is used due to uncertainties in EV SOC when it reaches home as well as arrival/departure times to/from home to model the stochastic behaviors shown in Table 2.

4.1.3. Components cost and electricity cost

Table 3 shows the components cost and time of use (TOU) electricity rates. 1 kWh/0.5 kW is the considered battery size for a unit. EV is assumed to be present initially in home. Flat FIT, retail rate and DSOC is taken from AGL, one of the reputable energy companies of Australia [38]. Other rates were reasonably assumed, and different analysis is done in the later part of the study.

4.2. Different scenarios case study

The next part of the study is done to investigate the flexibility of contract and how it effects COE with different scenarios shown in Fig. 6. Different scenarios are investigated to see how COE varies with flexible contract between the homes as both homes might not feel comfortable for 20 years of contract. For this study it is assumed that both homes agree for initial contract for certain number of years, if both is happy with the benefits, contract will be extended 70 % of the project life. COE will be calculated for each of the scenarios.

4.3. Feasibility of energy sharing

It is known that feasibility of energy sharing can be a challenge especially due to technology maturity and distribution network policies for different countries. However, the recent developments on smart meters and energy sharing platforms can assist to achieve this. Some examples of realistic energy-sharing technology platforms are provided below:

- The company SonnenCommunity offers a platform where households with SPV and BESS can share electricity directly within a local network [39]. Members contribute excess energy to a virtual pool, allowing them to purchase energy at reduced rates when needed. With Germany's robust renewable energy policies and support for decentralized grids, it serves as an ideal testing environment. The

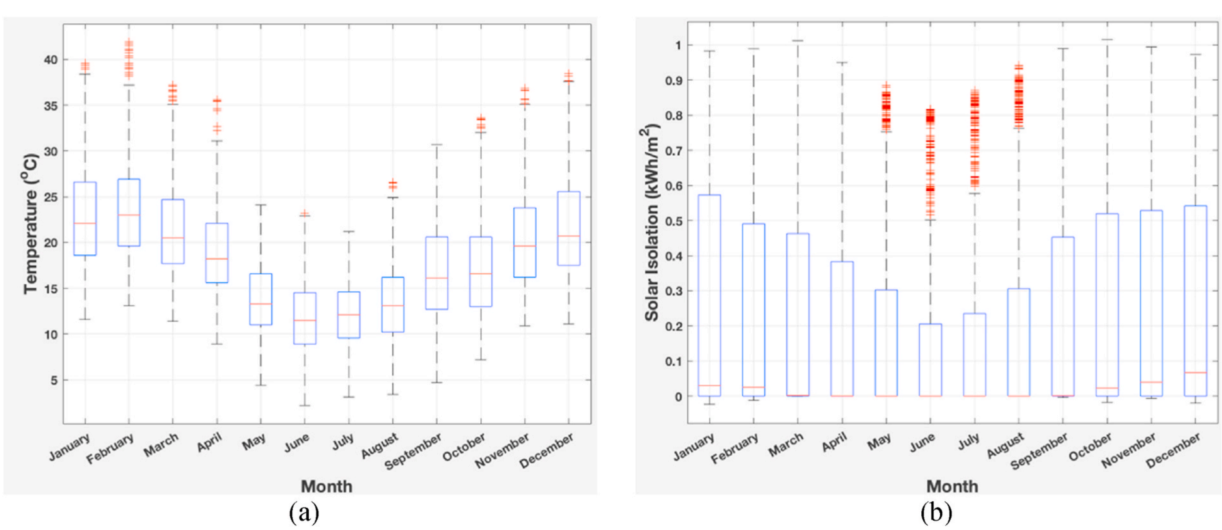


Fig. 4. The annual meteorology data of South Australia: (a) Ambient temperature; (b) Solar irradiance.

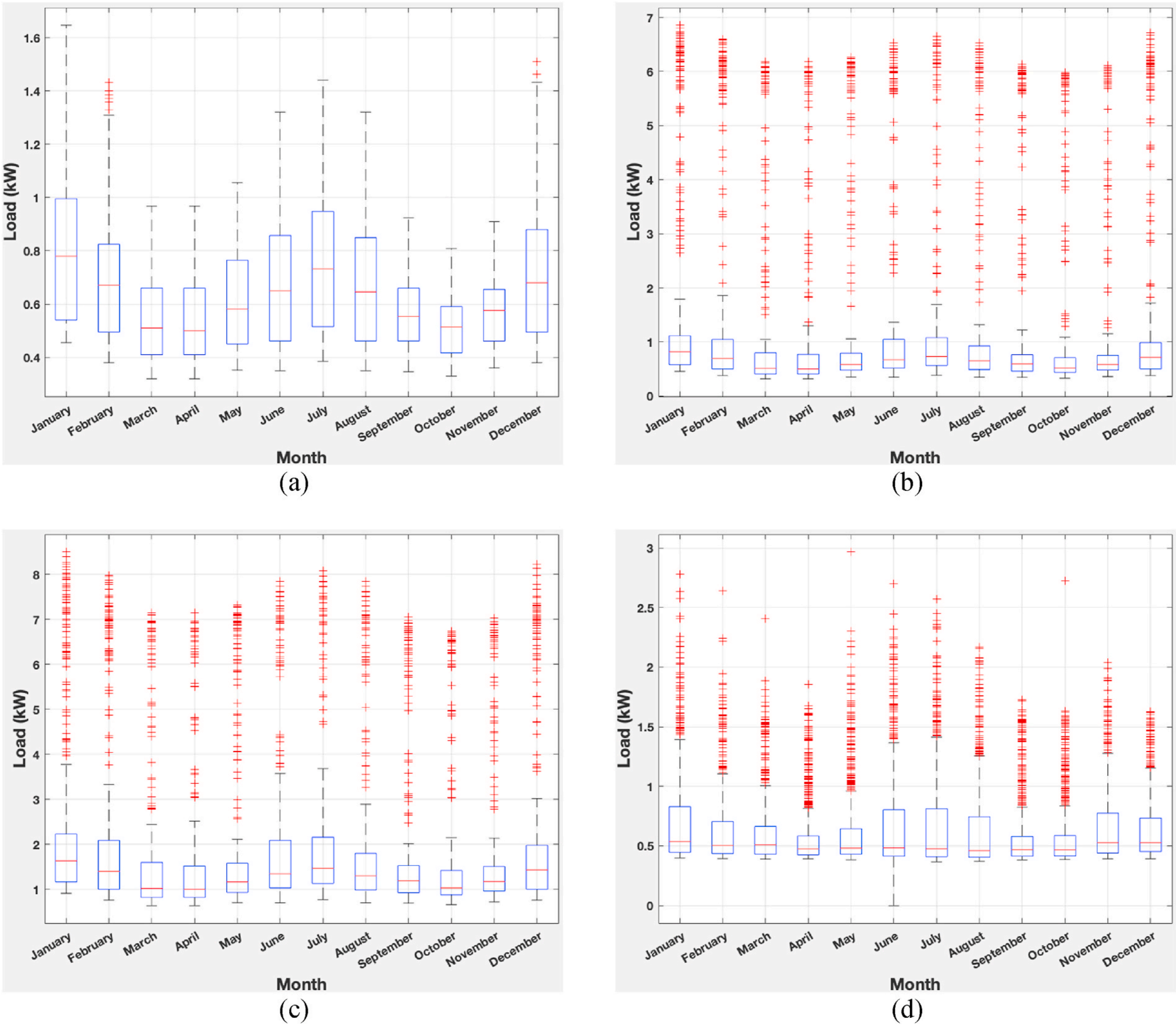


Fig. 5. Daily load consumption for a year: (a) Load of home-1, (b) Load of EV, (c) Load of home-1 with EV, (d) Load of home-2.

Table 2
Probability parameters for the uncertainties of EV.

	Mean	Standard Deviation	Min
Initial SOC at arrival (%)	50	30	20
Arrival time (h)	18	3	15
Departure time (h)	8	3	5

success of SonnenCommunity demonstrates that P2P energy sharing is both technically feasible and economically sustainable.

- Power Ledger has led the way in blockchain-based P2P energy trading. By collaborating with local energy providers, Power Ledger's platform allows households with SPV to sell surplus electricity directly to their neighbors [40]. This model has seen successful adoption across several Australian cities, enabling households to engage in direct energy trading rather than depending solely on grid buy-back rates. The achievements in Australia indicate that P2P energy sharing can succeed even in markets with established grid systems.
- New York's Brooklyn Microgrid project enables residents to trade surplus SPV energy with one another via a blockchain-powered marketplace [41]. Notably, this initiative operates in an urban setting and is in line with local grid regulations. The project illustrates that, even within tightly regulated markets, peer-to-peer

Table 3
Components, economic and electricity prices.

Parameters	Value	Parameters	Value
Project lifetime	20 years	**Retail peak price**	0.39 $/kWh
Interest rate	8 %	**Retail off-Peak price**	0.25 $/kWh
Grid Escalation rate	2 %	**Retail flat price**	0.339 $/kWh
Time between overhauls	10 years	**Peak FIT**	0.17 $/kWh
SPV capital cost	1500 $/kW	**Off-peak FIT**	0.10 $/kWh
SPV overhaul cost	300 $/kW	**Flat FIT**	0.12 $/kWh
SPV O&M cost	50 $/year	**Mutually agreed peak rate**	0.25 $/kWh
Maximum grid export power	5 kW	**Mutually agreed off-peak rate**	0.17 $/kWh
Battery SOC minimum	20 %	**Mutually agreed flat rate**	0.20 $/kWh
Battery SOC maximum	95 %	**BESS efficiency**	95 %
BESS capital cost	350 $/kWh	**Daily supply of charge**	0.99 $/day
BESS overhaul cost	200 $/kWh		

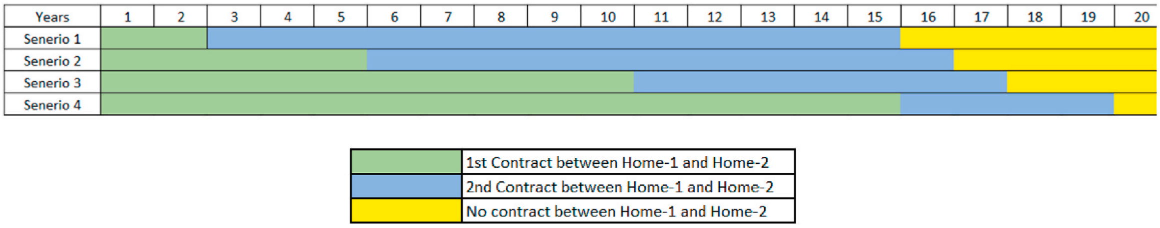


Fig. 6. Different scenarios of contract between the homes for 20 years.

energy trading can succeed through innovative grid management and decentralized technology.

The authors believe these technologies could enable the implementation of the proposed methodology for different case studies in Australia and worldwide.

5. Results and discussion

5.1. Optimal sizing and COE calculation

Optimal component and NPC results have been calculated for three different configuration and shown in Table 4. The highest number optimal components are seen when energy is shared between the homes with EV, SPV, and BESS. This is because of more energy demand overall which includes home-1, EV and home-2. COE for each configuration is shown in Fig. 7(a). The lowest COE is obtained for the 3rd configuration for the homes. This is because home-1 can take full benefit of generated power by selling to home-2. Similarly, home-2 can get benefit because of the lower energy prices compared to buying in retail rate. For the other 2 configuration, there is no energy sharing because of which the homes cannot take full benefit for themselves.

Fig. 7(b), (c), (d) shows the pie chart which contains the energy shared between homes, energy bought and sold to grid by home-1, energy bought from grid by home-2 and dumped energy. For the 1st configuration where there is no SPV and BESS, both the homes buy all the energy from the grid, no energy is shared between homes and no energy is dumped. For the 3rd configuration partial energy demand of home-2 is satisfied by home-1. Exported energy to the grid is high for home-1 compared to 2nd configuration which resulted in buying more energy from grid for home-1.

Results are presented by making 3 configurations for flat and TOU tariff which is shown in Table 5. The less optimal components are on the 2nd configuration which is because of absence of EV. COE for all three configurations is shown in Fig. 8(a). The lowest COE for home-1 is when it does not have EV. Comparing home-1 having EV with flat and TOU tariff, home-1 has lower COE under TOU tariff. This is because home-1 can take advantage of selling power to home-2 in TOU rate and sell power to grid in TOU rate which is higher than flat rate. home-2 has minimal effect on COE for all the configurations. COE for the 3rd configuration is higher for home-2 which is due to buying some electricity from home-1 in peak hours in TOU rate which is higher compared to flat rate.

Pie chart in Fig. 8(b), (c) and (d) represents the energy shared, energy bought from the grid by both the homes, energy sold to grid by home-1, and energy dumped by home-1. The maximum energy sold to home-2 is in 2nd configuration because there is no EV. When there is no EV unlike other 2 configuration, home-1 can sell extra energy to home-2 or grid. When EV is present, more energy is shared between homes in TOU tariff compared to flat tariff as well as more electricity is sold to grid in TOU tariff.

The selected EV for this study was Renault Zoe with battery capacity of 54 kWh. However, other EVs such as tesla model x, tesla model 3, BMW i3, Hyundai IONIQ and Nissan leaf with different battery capacities shown in Fig. 9 are investigated for comparison purpose [32]. As such, the optimal components are shown in Fig. 10 along with COE for the homes. The lowest COE for home-1 is achieved for Hyundai IONIQ because of its lowest battery capacity. For home-2 BMW i3 and Hyundai IONIQ has the lowest COE if home-1 uses those EV.

5.2. Different scenarios result and discussion

COE and NPC decrease significantly when energy is shared between the homes. COE is lowest in scenario 3 compared to other scenarios for home-1 shown in Fig. 11. COE is the lowest in the 1st scenario which is due to the last 5 years with no contract. In the last 5 years, home-1 cannot take advantage of the energy sharing rates between the homes. For home-2 the lowest COE is when the contract between homes is 20 years as shown in Fig. 12. This is because home-2 can take full advantage of 20 years of lower energy sharing rate from home-1 compared to buying electricity from grid in retail rate.

6. Sensitivity analysis

6.1. When export power limitation is changed

5 kW is the maximum export power to the grid that is set up by Australian government and power networks for single-phase homes. As the situation might change in the near future due to gaining popularity of renewable energy sources, there is good possibility that this restriction might vary. It is important to investigate its effect in our study which is presented in Fig. 13. The lowest COE is observed when the export power limitation is 10 kW. This is because home-1 can take full advantage of selling electricity to grid instead of dumping electricity. Likewise, with the increase in number of SPVs, the power generation increases, and home-2 can take advantage of buying electricity from home-1 in lower price as compared to the retail rate.

6.2. Changing export power limitation (with fixed SPV and batteries)

The analysis is also done when export power limitation is changed but numbers of SPV and BESS are kept the same as optimal solution which is shown in Fig. 14 home-1 shares electricity to home-2, sells to the grid and dumps the extra electricity. The highest COE can be observed when export power limitation is lowest. This is because home-1 cannot sell the electricity to grid for its benefit. When export power limitation is increased, COE for home-1 gradually decreases till the point when optimal components are fully functional, and no power will be left to be exported which is 5 kW as seen in Fig. 14. After this point COE for

Table 4
Home-1 Optimal component sizing for 3 different configurations with and without home-2 load.

Configuration	SPV (kW)	BESS (kWh)	NPC_home-1 ($)	NPC_home-2 ($)
Load 1 + EV	0	0	55164.1	26318.8
Load 1 + EV + SPV BESS	11	18	39070.1	26318.8
Load 1 + EV + SPV BESS + Load 2	12	16	37030.3	24033.9

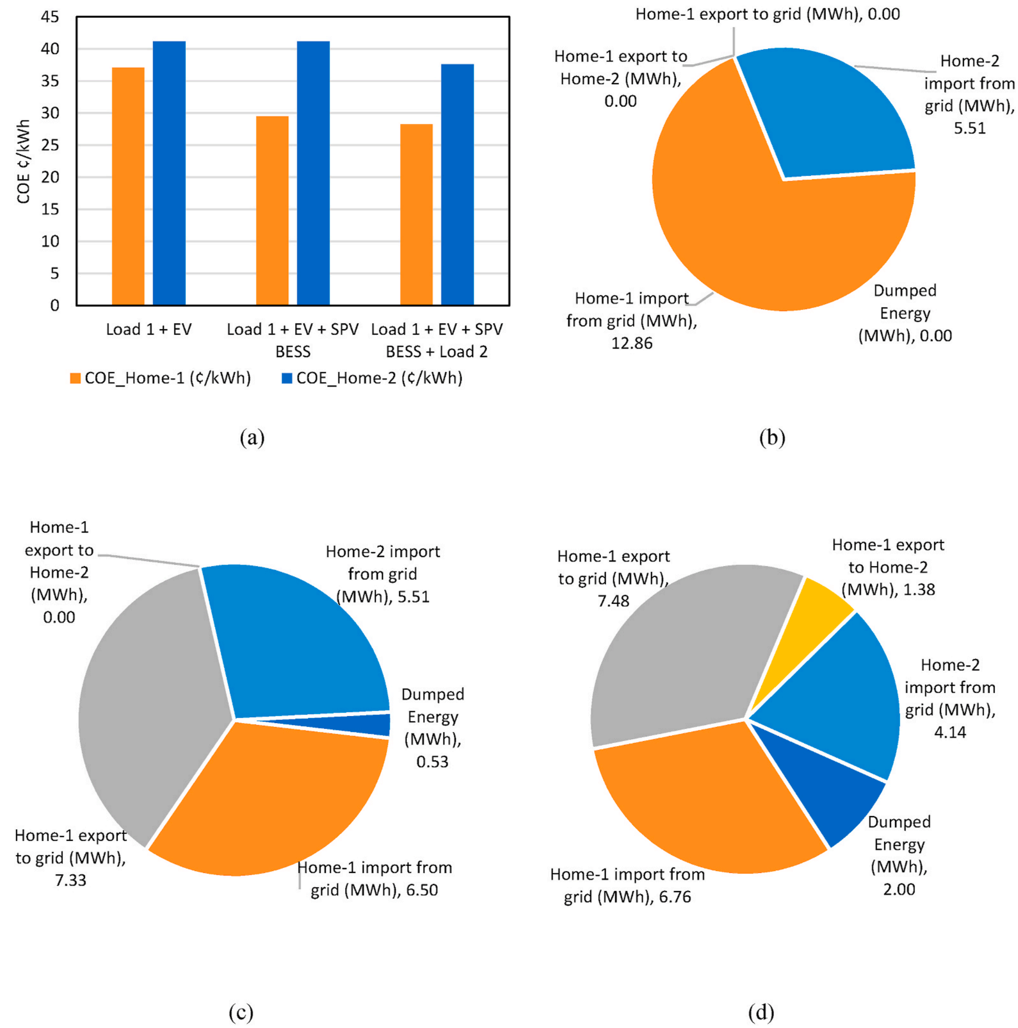


Fig. 7. COE and energy import, export of each home for different configuration: (a) COE of home-1 and home-2; (b) Energy import, export for 1st configuration; (c) Energy import, export for 2nd configuration; (d) Energy import, export for 3rd configuration.

Table 5
Home-1 Optimal component sizing for 3 different configurations with Flat and TOU electricity rates.

Configuration	SPV (kW)	BESS (kWh)	NPC of home-1 ($)	NPC of home-2 ($)
SPV-BESS-EV under Flat tariff	11	20	39462.6	23584.5
SPV-BESS without EV under TOU tariff	11	5	10059.5	23822.1
SPV-BESS-EV under TOU tariff	12	16	37030.3	24033.9

home-1 remains the same. Export power limitation does not have impacts for home-2.

6.3. Variation of load demand of both the homes

Load demand of homes may vary in the entire year; therefore, it is important to investigate its effects on COE and optimal components sizing. Fig. 15 shows the contour plot diagram of this analysis. When the loads of home-1 and home-2 increase, the number of SPVs increases to satisfy the increased demand of the homes. The number of batteries increases when load of home-1 increases which supports the load demand in peak hours whereas the number of BESS does not have impact with the change in load of home-2. It is because home-2 does not get electricity from battery.

COE of homes are the highest when load demand of both homes is the lowest. This is because of the high capital cost of components as well as DSOC. With the increase in load demand for both homes, COE decreases for home-1 shown in Fig. 15(a). This is because DSOC is fixed and does not depend on the load demand as well as more electricity will be shared between the homes. This maximizes the benefit for home-1 by selling the electricity in higher cost to home-2. The lowest COE for home-2 is when load demand of home-1 is lowest, and home-2 is highest shown in Fig. 15(b). This is because when load demand of home-1 is less, home-2 can take extra advantage by buying more electricity in a cheaper rate. The reason behind home-2 being able to buy more electricity is because the home-1 demand is less and generation is high. The cross sign (x) shows the COE for the homes of this study.

6.4. Cost variations of SPV-BESS

SPV and BESS costs are decreasing due to an increase in investment in renewable energy throughout the world. It is important to investigate its effects on COE for homes. Fig. 16 represents the contour plot diagram when SPV and BESS costs vary and its effect on COE of homes. The red lines represent COE for home-1 and dashed black lines represent COE for home-2. Cross mark (x) in Fig. 16(a) shows the SPV cost we used in this paper that is $1500/kW and dot mark (.) in the same figure shows the COE for home-1 when SPV cost is decreased to $800/kW. When SPV cost

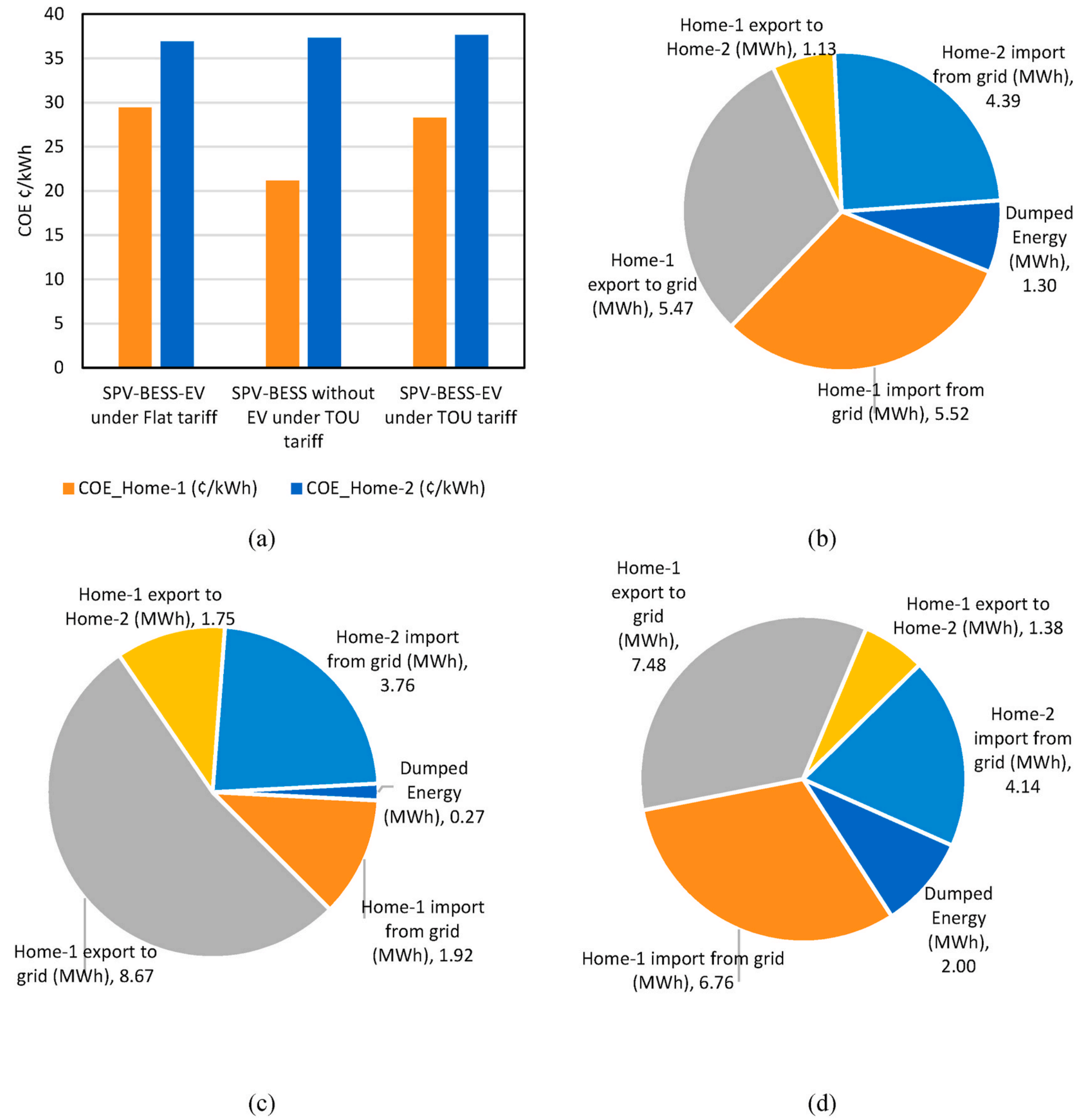


Fig. 8. COE and energy import, export of each home for different configuration: (a) COE of home-1 and home-2; (b) Energy import, export for 1st configuration; (c) Energy import, export for 2nd configuration; (d) Energy import, export for 3rd configuration.

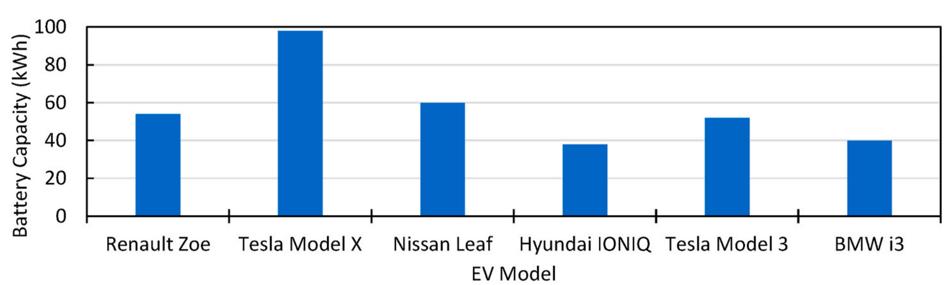


Fig. 9. EV with different battery capacity.

decreases, COE of home-1 also decreases. There is no effect on COE for home-2 when SPV cost decreases.

Cross mark (x) in Fig. 16(b) shows the battery cost used in this paper that is $350/kWh and dot mark (.) in the same figure shows the COE for home-1 when battery cost is decreased to $200/kWh. When battery cost decreases, COE of home-1 decreases but there is no effect on COE of home-2 which suggests there is no effect on COE of home-2 with component price.

6.5. *Effects on grid charge*

The electricity is shared between the homes via grid. Grid charge is not considered in this study. It is important to see the effects of grid charge if power networks decided to charge certain fees because homes are using grid for energy transfer. This charge is paid equally by both the homes. Table 6 shows the grid charge and its effect on COE and cost reduction for both homes. Breakeven point was achieved in 0.11 $/kWh

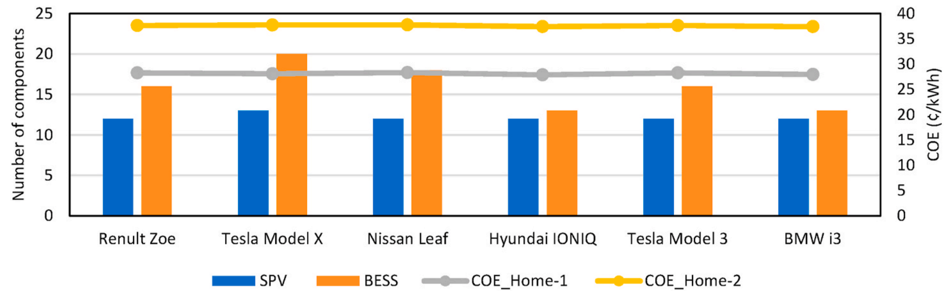


Fig. 10. Optimal components and COE for home-1 and home-2 with different EV.

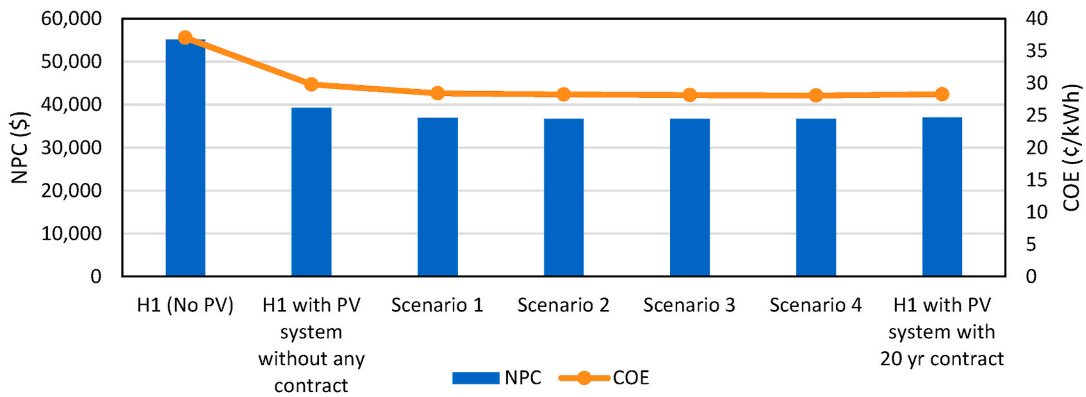


Fig. 11. NPC and COE of home-1 with various contract scenarios for energy sharing.

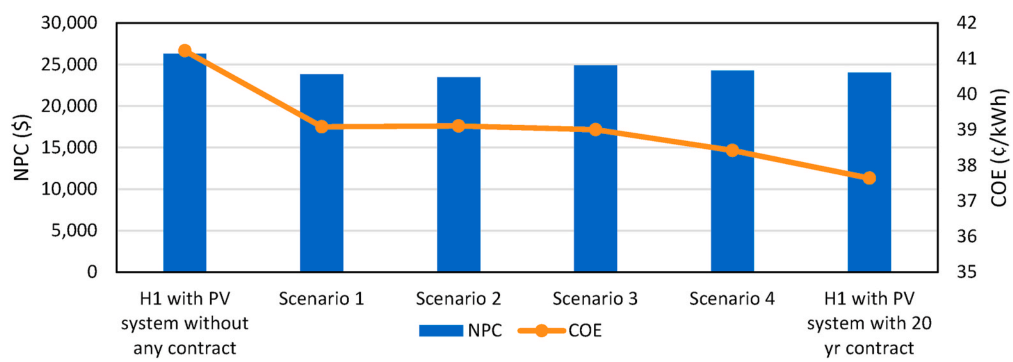


Fig. 12. NPC and COE of home-2 with various contract scenarios for energy sharing.

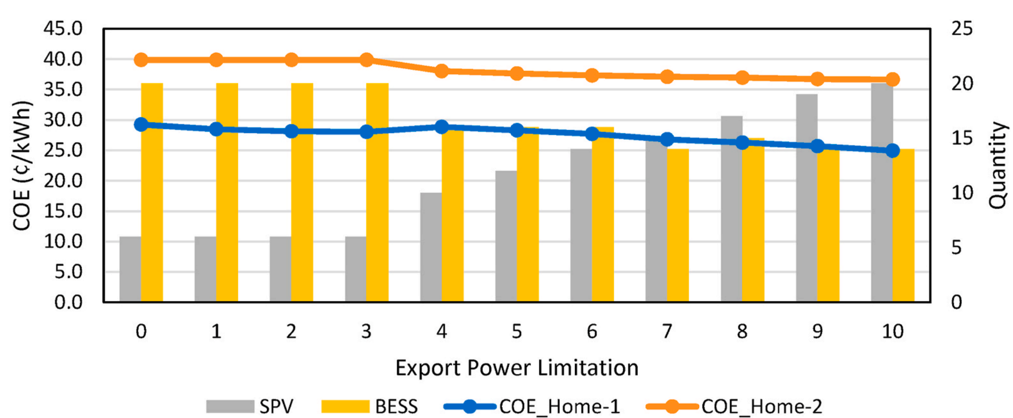


Fig. 13. Sensitivity analysis in optimal sizing and COE when export power limitation varies for home-1.

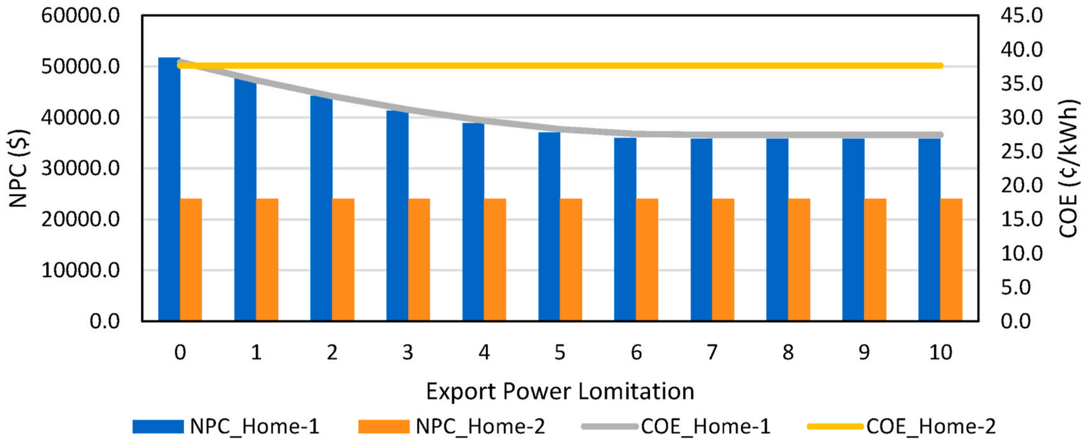


Fig. 14. Sensitivity analysis when optimal components is fixed as optimal solution and export power limitation is changed.

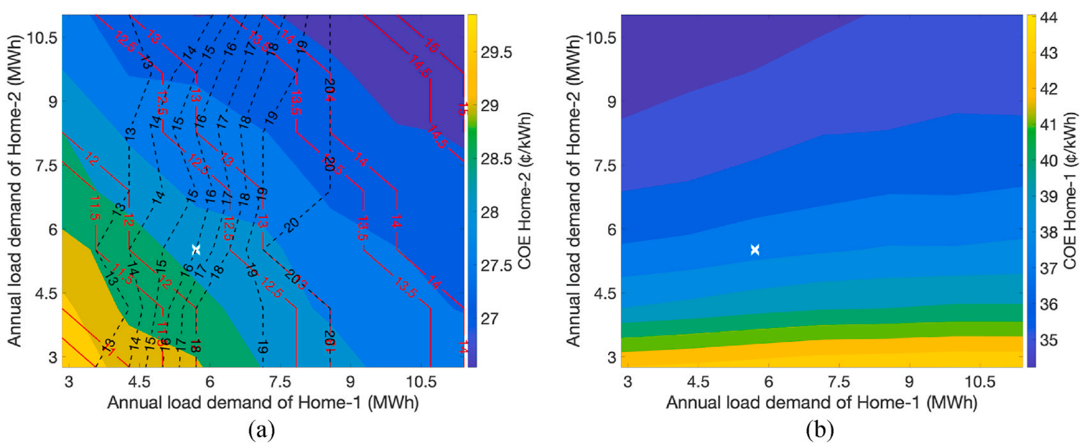


Fig. 15. Sensitivity analysis: COE represented by colour (a) Annual load demand of home-1 vs Annual load demand of home-2 (Red line represent number of SPV and black dashed line represents number of battery), (b) Annual load demand of home-1 vs Annual load demand of home-2.

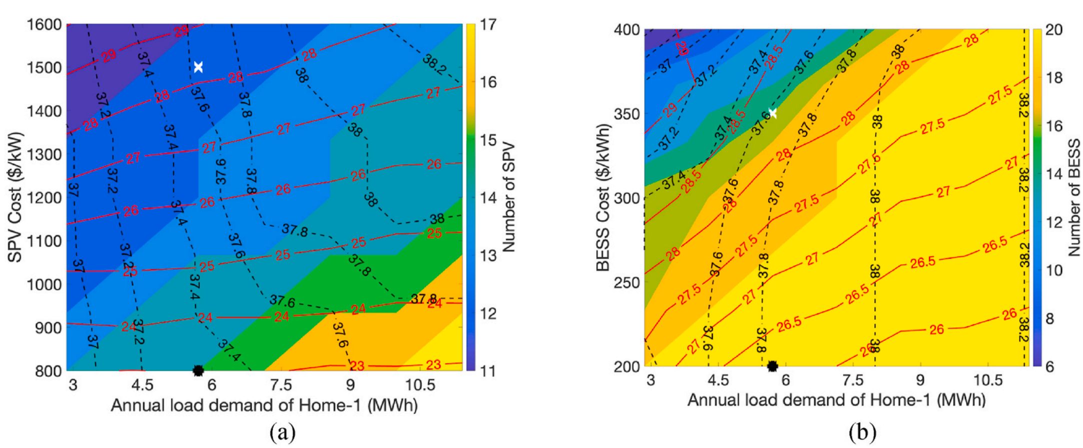


Fig. 16. Sensitivity analysis: Red line represents COE of home-1, and black dashed line represents COE of home-2 (a) Annual load consumption of home-1 vs SPV cost (Colour region represent number of SPV), (b) Annual load consumption of home-1 vs BESS cost (Colour region represent number of BESS).

in which home-1 neither makes profit nor suffer loss with energy sharing. It is important to note that if grid charges 0.12$/kWh or more, there is no benefit for home-1 to sell the electricity for home-2. Beyond the breakeven point, home-1 benefits more by just selling to the grid instead of sharing and paying the grid cost.

7. Uncertainty analysis

7.1. When the sharing rate and FIT changed

Energy sharing rate between home-1 and home-2 is assumed in a reasonable way for this study. So, it is important to see its effects on COE for both homes with other rates as shown in Fig. 17. The (o) mark

Table 6
Effects of grid charge on COE and cost reduction of both the homes.

Grid charge as a rent ($/kWh)	Energy sold to home-2 by home-1 (kWh)	Cost reduction home-1 (%)	Cost reduction home-2 (%)	COE home-1 (¢/kWh)	COE home-2 (¢/kWh)
0	1376.4	4.23 %	8.69 %	28.27	37.64
0.025	1376.4	3.15 %	7.06 %	28.59	38.31
0.05	1376.4	2.27 %	5.58 %	28.85	38.92
0.075	1376.4	1.22 %	4.03 %	29.16	39.56
0.1	1376.4	0.34 %	2.55 %	29.42	40.17
0.11	1376.4	0.00 %	1.97 %	29.52	40.41

represents the rate that we used for this study. When energy sharing rate between the homes and FIT is high, COE of home-1 is the lowest and vice versa as shown in Fig. 17(a). This is because home-1 can take advantage of high electricity sharing rate from home-2 as well as it can take advantage of high FIT rate which lowers its COE. For home-2 shown in Fig. 17(b), it is observed that the lower the energy sharing rate between homes, the lower the COE of home-2 as it is benefitted when it can buy electricity from home-1 in lowest possible cost. There is not significant difference in COE for home-2 with the change in FIT as COE of home-2 does not depend on FIT of home-1.

7.2. When solar isolation and ambient temperature changed

Fig. 18 shows the scenarios from the year 2011 to year 2021. The real data of ambient temperature and solar irradiance was extracted from renewables ninja website to find out its effect in optimal components sizing and COE of homes. The obtained results show that there is no significant difference in COE of homes as well as optimal components. COE of home-1 is in the range of 24.75¢/kWh to 26.03¢/kWh whereas for home-2, COE is in the range of 37.47¢/kWh to 37.64¢/kWh.

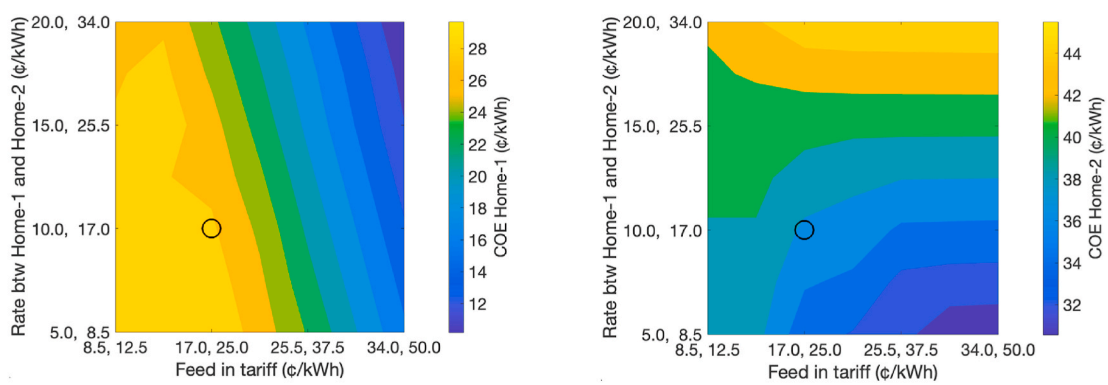
8. Operational analysis

Power flow diagram for home-1 in summer and winter for 2 consecutive days is shown in Fig. 19. It can be observed that solar irradiance is high in summer due to which power generation from solar is high whereas in winter, irradiance, and generation both are lower. Due to peak power generation during daytime, home-1 load has been satisfied by SPV and extra power is sold to the grid. In the evening when SPV cannot generate enough power to satisfy the demand, the battery gets discharged to satisfy the load demand. After the peak hours end, EV gets charged from the grid avoiding peak hours rate and increasing COE of home.

9. Conclusion

This study investigated the optimal sizing of the components for grid connected homes with EV and energy sharing mechanism between them. 12 kW of SPV and 16 kWh of BESS were found out as optimal capacities for the system components considering the TOU electricity tariffs. A separate energy management system was developed and EV's initial SOC as well as arrival and departure time were incorporated via stochastic functions in the system. Actual load data along with solar irradiance and ambient temperature is considered along with export power limitation and salvation value of components.

COE of home-1 with components and EV without energy sharing is 29.5 ¢/kWh whereas for home-2, it is 41.2 ¢/kWh. After energy sharing, the COE for home-1is reduced to 28.3 ¢/kWh and for home-2, it is reduced to 37.6 ¢/kWh under TOU tariffs. The reduction of COE for home-1 is 4.23 % and for home-2 is 8.69 %. When different EV with different battery capacities were compared, best result was found with the EV like Hyundai IONIQ with lower battery capacity. COE obtained



(a) (b)

Fig. 17. Uncertainty analysis: electricity rates between home-1 and home-2 vs FIT (a) Colour region represents COE of home-1, (b) Colour region represents COE of home-2.

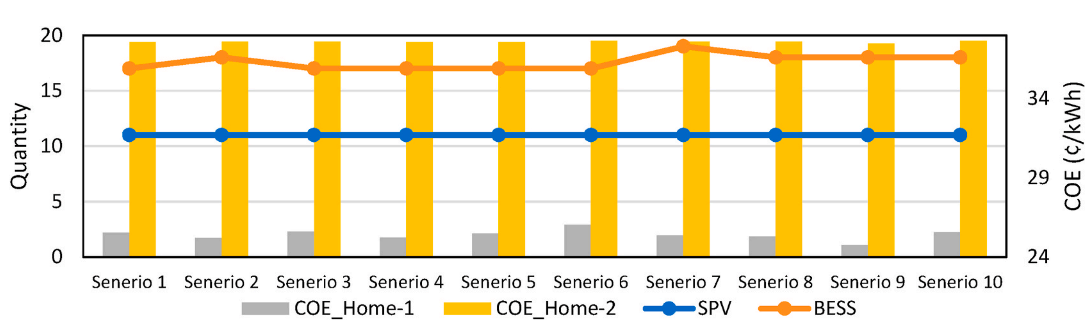
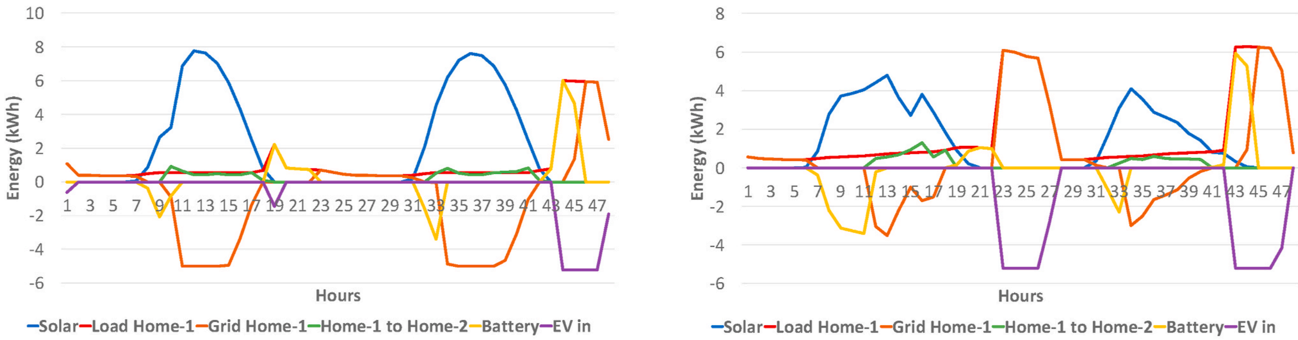


Fig. 18. Uncertainty analysis on optimal sizing and COE due to the change in ambient temperature and solar irradiance from 2011 to 2021.



(a) (b)

Fig. 19. The operational analysis for sample two days: (a) Summer (b) Winter.

when comparing with different scenarios that COE varies with different year of contract. For this case study scenario 4 has lowest COE. Sensitivity analysis done by increasing the export power limitation shows that COE decreases gradually with the increase in export power limitation. Analysis done when load demand of both the houses varies shows that COE is highest when load demand of both the houses is lowest, and COE is lowest when load demand of both house is highest. This was due to more utilization of energy sharing which benefits both the houses when demand is high whereas if demand is low, less benefits would be taken by households. Negligible change in uncertainty analysis proves the robustness of the results obtained despite the variation in solar insolation and ambient temperature.

One of the limitations of this study was the number of the homes considered for energy sharing and EV owning. In this work, it was assumed that the extra energy of SPV and BES can only be shared with one home. However, energy sharing may achieve higher profits when the home with SPV and BES can share the energy with more buildings. As another limitation, this study did not investigate the effect of EV and energy sharing on the voltage distribution network. Having EV, SPV, and BES can affect the voltage profile of distribution networks especially when the PV congestion is high. This affects the optimal sizing of SPV and BES for the new home installers. However, this work only studied the economics of energy sharing and optimal sizing.

Future studies can focus on development of an optimization problem for a greater number of prosumers and consumers by investigating their impacts on COE for multiple homes. The suggestion for future researchers who investigate on multiple prosumer and consumer would be, home-1 can be taken as a load of n number of homes with SPV and battery, and home-2 can be taken as a load of n number of homes without renewable energy systems and optimal components size could be studied. As another future direction, researchers can investigate and add the impacts of distribution network conditions and limitations to the optimal sizing problem while the energy is shared between homes with EVs. While this complicates the optimization problem, it is worthwhile to integrate the distribution network parameters to achieve a systematically economical sizing solution for energy sharing.

CRediT authorship contribution statement

Siraj Khanal: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rahmat Khezri:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis. **Amin Mahmoudi:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Conceptualization. **Solmaz Kahourzadeh:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Conceptualization. **Hirohisa Aki:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

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

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