# Optimal Sizing of Solar PV and Battery Energy for Grid Connected House Based on Energy Sharing

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# Abstract

This study examines the optimal sizing of solar photovoltaic (PV) and battery energy storage (BES) systems for grid-connected residential houses, considering an energy sharing scheme. Two houses share the energy under mutually agreed electricity rates. House 1 (H1) has the PV panels and BES whereas house 2 (H2) do not have any of those. H1 and H2 are willing to share the energy for their own benefits to reduce their cost of electricity (COE). The main objective function of the study is to minimize the COE for H1 while decreasing the COE for H2. Three studies are conducted, and their results are observed. One of them is buying, selling, and sharing energy with flat electricity rate, second with time of use (TOU) rates. Both studies do not consider electric vehicle (EV) in the system and finally the third study includes the EV integration in H1 and TOU electricity rates.

The developed methodology of the energy management system is general in nature and can be used between any of the 2 houses willing to share the energy. Particle swarm optimization (PSO) method is used to investigate the optimal sizing of system components and COE due to its high convergence rate and accuracy. Real data for solar irradiance, temperature, load consumption of each house, components cost, electricity and tariff rates are taken for the study. To show that this study also works in flexible contract between the houses, four different scenarios are conducted, and their results are obtained and analysed. Scenarios represent different years of energy sharing contract between houses. Eight different schemes are made for TOU study. To make these 8 schemes, 3 factors which are TOU buying electricity rate from grid, TOU selling electricity to grid and TOU energy sharing price between the houses are considered. Six different configurations are made to compare the results between them for EV study.

For all these studies, sensitivity analysis for 20-year contract is conducted by changing the export power to grid, variation of load consumption for each house, PV-BES cost variation and its effects in optimal sizing and COE for both houses are observed and discussed. Additionally, the operational analysis is reported, and power flow diagram is made for sample two consecutive days of summer and winter. T-T-T scheme is chosen in which first T represents TOU rate for buying electricity from grid, TOU rate for selling electricity to grid and TOU energy sharing rate between houses for all the analysis as it offers lowest COE for H1 while decreases COE for H2 reasonably.

Due to uncertain factors such as solar irradiance and temperature variations, uncertainty analysis is done for this study.

# Acronyms

| | |
|---|---|
| AC | Alternating Current |
| BES | Battery Energy Storage |
| BEV | Battery Electric Vehicle |
| CES | Community Energy Storage |
| DC | Direct Current |
| DER | Distributed Energy Resource |
| EMS | Energy Management System |
| ESP | Energy Service Provider |
| ESS | Energy Storage System |
| EV | Electric Vehicle |
| FiT | Feed-in-tariff |
| GCH | Grid Connected House |
| GHG | Greenhouse Gas |
| ICE | Internal Combustion Engine |
| IP | Identified Pricing |
| LSE | Loose Serving Entity |
| MILP | Mixed Integer Linear Programming |
| NPC | Net Present Cost |
| PBV | Purpose Built Vehicle |
| PEV | Plug-in Electric Vehicle |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PV | Photovoltaic |
| P2P | Peer-to-Peer |
| RES | Renewable Energy Source |
| RP | Retail Price |
| SAPV | Standalone Photovoltaic |
| SH | Smart Home |
| SOC | State Of Charge |
| SQP | Sequential Quadratic Programming |
| TOU | Time-of-Use |

| | |
|---|---|
| UP | Unified Pricing |
| V2G | Vehicle To Grid |
| V2H | Vehicle To House |
| WT | Wind Turbine |

# Declaration

I hereby affirm the following declarations about my thesis:

- All the research presented in this thesis was conducted solely within the College of Science and Engineering, with my own participation and without any outside assistance. I am solely responsible for the execution and originality of the presented research and analysis.
- No other academic institution has used this thesis in fulfilling the requirements for a degree or certificate. It is the result of my own research and study within the confines of the required course of study.
- Except where proper credit has been given, the contents of this thesis have not been used in any other publication. I have followed the rules of academic honesty by giving credit, where credit is due to anyone or anything that was used in the creation of this work.
- External editor has not been used to edit the work such as grammar, formatting and spacing of this research and is edited and formatted by me myself.

To the best of my knowledge and belief, the statements faithfully reflect the nature and integrity of my thesis.

Siraj Khanal
June 2023

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# Chapter 1. Introduction

## 1.1 Research Background and Motivation

The energy supply system at a global level is afflicted by fluctuations in prices, apprehensions regarding energy security, and environmental issues. Soon, humanity will be faced with two significant crises. One of the primary concerns associated with the utilization of fossil fuels is the degradation of the environment, while the other is the rapid depletion of these finite resources. The primary cause of these issues can be attributed to the substantial contribution of fossil fuels to the energy mix. At present, fossil fuels account for over 80% of the global energy supply [1]. Energy production utilizing fossil fuels accounts for a substantial proportion of global climate change, with over 75% of greenhouse gas emissions and approximately 90% of carbon dioxide emissions being attributed to this source. The energy sector must be decarbonized through the use of alternative energy generated from renewable sources [2]. By 2040, energy consumption is expected to have increased by 56%. Greenhouse gas emissions will rise if the current policy of relying on fossil fuels is maintained and energy demand is allowed to rise. Therefore, these results can't be avoided without taking action to mitigate climate change. The achievement of carbon neutrality, the mitigation of climate change, and the maintenance of global temperatures below 2 degrees Celsius, as stipulated in the Paris Agreements, are all significantly dependent on the utilization of renewable energy sources (RES). RES are widely regarded as cost-effective, environmentally sustainable, and derived from freely available resources [3]. Renewable energy has garnered significant global attention owing to its immense advantages in terms of generation and consumption.

The energy industry is currently experiencing the nascent phase of a novel industrial epoch, characterized by the production of environmentally friendly energy technology. Solar photovoltaics (PV), wind, electric vehicles (EVs), and batteries, all in their infancy in the early 2000s, are now vast industrial enterprises. These and other renewable energy companies are expected to grow substantially. Since 2000, the cost of solar PV modules has plummeted by as much as 92%. Conformity to the zero-carbon pledges, in addition to the lower price, encourages the expansion of solar PV around the world. Countries across the globe are increasingly prioritizing the expansion of renewable energy technology manufacturing in order to achieve multiple objectives, including expediting the transition to net-zero emissions, enhancing energy security, and competing in the emerging global energy market [4]. Fig. 1.1 and Figure 1.2 depict the initial energy of the entire globe and the global investment in novel energies from 2011 to 2020, respectively. China has led the world in renewable energy production for almost a decade, and its lead has only grown since 2021, when the country's wind capacity expansion began to accelerate dramatically. According to the analysis of Ember, it is projected that China will surpass Europe, the second largest wind production market, in wind power generation by 46% by the year 2022. This is despite the fact that China has just been adding wind generation capacity for the past two years [5]. The European Union aims to expedite the adoption of RES as a means of achieving its objective of reducing net greenhouse gas emissions by a minimum of 55% by the year 2030 [6].

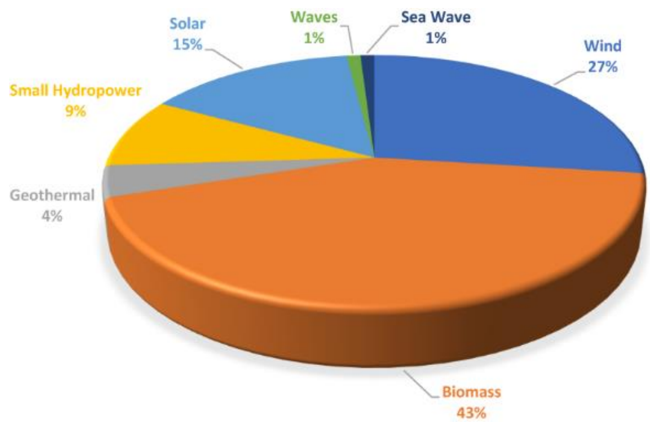


Figure 1.1 The initial energy of the entire globe [1]

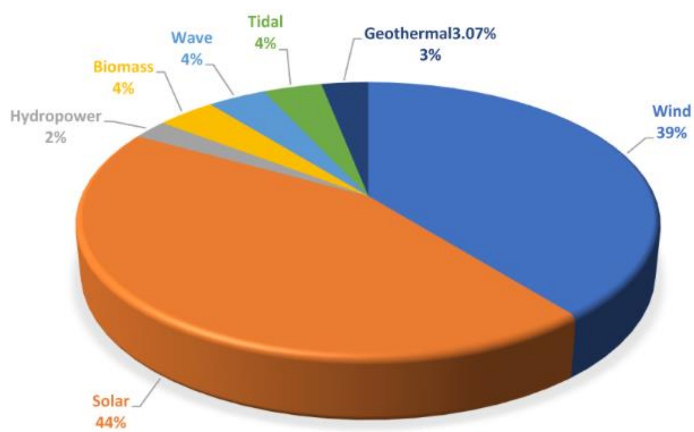


Figure 1.2 The global investment in novel energies from 2011 to 2020 [1]

The escalating global population has resulted in a corresponding increase in the demand for energy, which is anticipated to surge by approximately 25% by 2040 in comparison to present levels of consumption [7]. Australia, the sixth-largest country in terms of land area, had the world's 12th-largest economy in 2020, with a gross domestic product of US$1.331 trillion. The carbon emissions of Australia have exhibited fluctuations over time, with a recorded metric of 15.447 tons per capita in 1990, followed by a rise to 18.118 tons per capita in 2005, and subsequently a decline to 14.415 tons per capita in 2020 [8]. The Australian government increased its aim for reducing greenhouse gas emissions from 2005 levels by 2030 from 26-28% to 43% in its updated 2030 Nationally Determined Contribution (NDC) submitted in June 2022. The NDC pledge to reach zero net emissions by 2050 was codified in law with the passage of the Climate Change Act of 2022. Australia is now on a path more consistent with the Paris Agreement and has caught up to the rate of other major economies' pledged emissions reductions. Australia signed the Global Methane Pledge in October 2022 [9]. The reduction in environmental pollution is only possible if clean and carbon free energy sources are being used to produce energy.

RES such as solar, wind, and hydro power are utilized to generate electricity that is both clean and devoid of carbon emissions. Particularly important for integration with traditional energy systems is solar PV Although solar PV systems generate clean energy, there is always a discrepancy between that, and the amount of electricity used by homes. The integration of solar PV systems with the grid or battery energy storage (BES) is imperative to ensure a consistent supply of electricity, owing to the erratic nature of RES. Australian homes are progressively installing solar PV systems on their roofs. Three million or more Australian homes will have rooftop solar PV systems by 2022, according to the country's clean energy report. In 2021, the rooftop solar business added 389,577 systems and 3.3 GW of additional capacity, continuing its amazing run [10]. Due to high retail price (RP), declining PV system costs, and government incentives in the form of feed-in tariff (FiT) and rebates, PV systems have achieved such a high market penetration [11]. As of October 2020, around 21%, or 2.5 million, Australian residences will have rooftop PV systems. Australians pay wholesale prices to import electricity to their homes. After a rooftop PV system is installed, it may meet the load on its own when PV generation is high, and it can send any excess power to the grid at a FiT rate. Customers in most parts of

Australia install a BES alongside a rooftop PV system because the FiT rate is a small percentage of the RP. Rather than selling excess PV power back to the grid at a loss, homeowners who install a BES can keep it in the home for later use. In recent years, there has been a significant surge in the installation of home batteries in Australian households [12]. Numerous endeavours are being undertaken to facilitate the optimal integration of RES into the conventional energy matrix, with the aim of promoting sustainability.

The integration of RES such as PV systems and electric mobility, which encompasses EVs, into the built environment is widely regarded as crucial for achieving sustainability in the power and transportation sectors. Consequently, there has been a significant surge in the adoption of both PV systems and Evs in recent times [13]. Global warming, dwindling fossil fuel reserves, and greenhouse gas emissions are all urgent sustainability challenges that can be addressed in part by the widespread adoption of Evs. In contrast, Evs are demonstrated to produce more emissions (from source to tailpipe) in countries that rely on fossil fuels, making RES essential for getting the most out of Evs. Evs have the potential to serve as a storage system for renewable energy systems, thereby reducing their overall burden [14]. As per proposed strategies to substitute automobiles propelled by internal combustion engines (ICE), Evs are poised to assume a significant role in global residential energy usage. Fig 1.3. shows the evolution of Evs [15]. In contemporary times, novel energy technologies have been devised to address the challenge of energy scarcity.

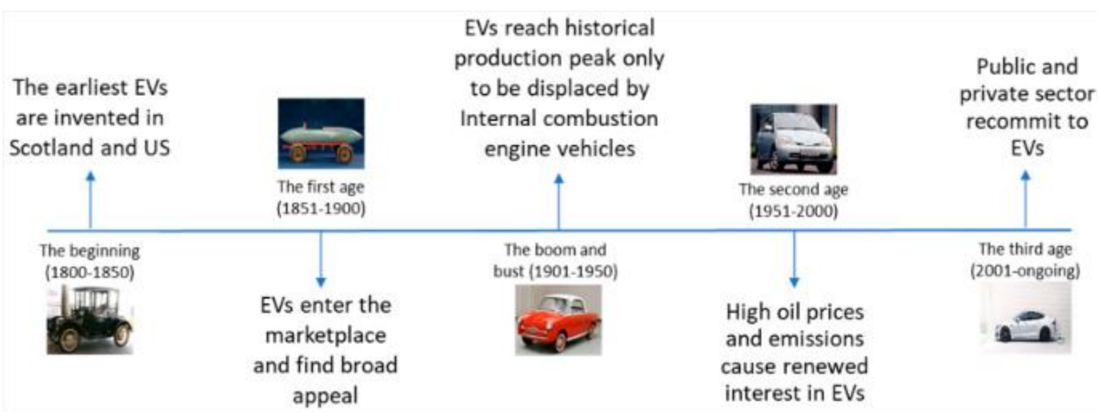


Figure 1.3 The evolution and progression of Evs for centuries [14].

In recent decades, the energy sector has experienced a significant paradigm shift from a centralized operational model to a decentralized one, due to the emergence of new distributed energy technologies and informational technologies. Due to their interdependence, the multi-energy sectors must be managed as a single unit. Consumers in the system are evolving from one type of user to another, from pure consumers to prosumers. Prosumers have the option to engage in the sale or exchange of their surplus energy output with other prosumers, or alternatively, they may choose to inject it back into the power grid. Peer-to-Peer (P2P) energy trading pertains to the direct transfer of energy between producers and consumers, and constitutes a promising novel trajectory in the advancement of the energy sector [16]. The implementation of P2P energy sharing has the potential to enhance the efficiency of the energy system, diminish the need for energy storage capacity and primary energy consumption, amplify the integration of RES, forestall the deterioration of energy quality, and mitigate the burden on the power grid by providing voltage support and congestion management for the local power grid[21]. P2P energy trading is a promising feature of the forthcoming smart grid, enabling direct energy exchange between energy consumers and prosumers within localized power networks. To better understand the various components and technologies involved in P2P energy trading, different system designs have already been proposed [17]. Through P2P energy trading, homeowners can earn extra income by selling excess energy generated from renewable sources and stored in their homes to their neighbours. P2P energy trading enables prosumers to cross-border exchange of renewable energy. In order to conduct field experiments, P2P energy trading startups in Australia, the United Kingdom, and Europe have attracted millions of euros in financing [18]. The practice of distributing excess energy from prosumers' distributed energy resources (DERs) through a community-based market presents a feasible substitute to conventional peer-to-grid (P2G) trading. This approach offers distinct benefits in relation to regional power self-consumption, self-reliance, and the return on investment for local power generation [19]. The P2P platform has the potential to mitigate expenses related to power losses and battery depreciation. Additionally, it offers added value by incorporating the unique preferences of prosumers with regards to the origin and destination of the energy they generate and consume. The envisaged P2P market platform persists in conferring benefits to prosumers by facilitating the exchange of energy with the wholesale market and other prosumers, thereby optimizing the potential of their energy assets [20]. P2P energy sharing has the potential to address several challenges in the energy sector, including minimizing power losses during battery charging, reducing energy quality losses in the power-to-X conversion process, ensuring equitable access to DER, overcoming grid infrastructure limitations, and mitigating grid import/export stress. The successful implementation of P2P energy sharing for the purpose of transitioning to low-carbon energy is contingent upon the public's preferences, level of engagement, and willingness to actively participate in shaping future energy systems. In addition to P2P energy sharing one most critical aspect that gathers the attention of the researchers and engineers is the optimal component sizing and time of use (TOU) rates in the grid connected house (GCH).

The primary goal of optimal size is to reduce the overall power system's expenditures. The literature extensively covers topics like optimal component sizing in grid-connected power systems with PV-BES [22]. About 40% of the energy used for final consumption is used by buildings. Therefore, boosting a building's energy efficiency can aid in a structural shift toward less carbon-intensive energy consumption. There has been a lot of focus in recent years on home energy management systems because of the many benefits they provide, including lower utility bills, greater efficiency in energy consumption, and fewer negative effects on the environment from carbon emissions. The implementation of a home energy management system is deemed as an optimal solution for mitigating electricity expenses and enhancing energy utilization efficacy. This system facilitates the monitoring and regulation of renewable energy production, energy storage mechanisms, and intelligent household appliances within a smart domicile [23]. The initial and crucial phase in power system planning studies is the determination of the optimal economic sizing of system components. This stage entails the process of carefully choosing and appropriately sizing power system components to effectively satisfy the power requirements and other system limitations while minimizing expenses. The optimization problem becomes intricate due to the variable nature of RES and consumer loads.

## 1.2 Research Question

The following research questions can be derived from the presented literature review:

- How to optimize the solar PV panels and BES for GCH based on an energy sharing mechanism?
- How does the TOU electricity tariff on energy sharing between the houses effects the optimal PV and BES?
- How does TOU electricity tariff effect on COE for household who owns renewable energy system share electricity based on contract?
- What would be the effects on optimal components sizing and COE if the household owns EV?
- How would different Evs with different battery capacity in a house effects optimal solution and COE of house?

## 1.3 Research objectives

The primary research goal of this study are as follows:

- To obtain optimal PV and BES solutions that are practical for households by minimizing COE based on an energy sharing scheme.
- To investigate the effects of TOU electricity tariffs in energy sharing scheme between the houses on the optimal capacity of the system components.
- To examine the effects on COE for household owning PV, BES if they are willing to sell electricity based on contract i.e., number of years.
- To develop the energy management system and optimization technique if EV is bought by house owner and observing its impact on optimal sizing and COE.
- To investigate the variations of COE for households with different Evs and different battery capacity.

## 1.4 Contributions

The main problem that has been addressed in this thesis is optimal sizing of electrical system components (PV and BES) of houses based on energy sharing in urban areas. This masters by research thesis considers the renewable energy system optimization for Australian GCH. As a result, the load for central heating is included in the system's overall load and is not segregated. The key contributions for this thesis are as follows:

- The study presents a novel approach to determining the ideal dimensions of PV and BES systems. Specifically, the investigation incorporates energy sharing methods between two households, marking the first instance of such an analysis. The model of the system is designed in such a way that households intending to acquire PV, and BES systems can contemplate the energy sharing with H1 right from the beginning of the project. The developed model incorporates the practical parameters such as actual data, grid constraint, battery degradation, and salvation value.
- An agreed-upon price is applied to the shared energy between the homes. In the primary scenario, it is presumed that this price is between the FIT and RP, so that a household with PV and BES can benefit from selling energy to H1 rather than selling energy back to the grid at a low price. On the other hand, the other household that purchase electricity from the home with PV and BES can do so at a discounted rate relative to the retail tariff. Then, a sensitivity analysis is performed to determine the effect of various mutually agreed-upon prices on the optimal size.
- Optimization of PV-BES system for a grid-connected household under energy sharing with Flat and TOU electricity tariffs for buying/selling energy from/to the grid and energy sharing rate
- Development of novel rule-based home energy management system for grid-tied house sharing energy with another house. Ideal system components size and COE is investigated when EV is owned by the house under TOU electricity tariffs. Also, examining the implications of several Evs with varying battery capacities on the optimal PV, BES, and COE of the house.

## 1.5 Thesis outline

The subsequent sections of this dissertation are categorized into the following chapters:

Chapter 2 provides literature review about renewable energy system and BES sizing that is optimal for residential households. Optimal sizing review is done for different aspects and scenarios. The first review is done for the optimal components sizing of GCH with flat and TOU rates. The second review pertains to P2P energy sharing between consumers and prosumers, with and without Evs.

Chapter 3 examines the effects of energy sharing and electricity tariffs on the optimal size of PV-battery systems for GCH. Initial section of this chapter presents the operational strategies for the energy management system. Next section describes optimization model, system model and case study. Optimal solution results are discussed and finally sensitivity, operational and uncertainty analysis is done for the best scheme obtained from the optimization.

Chapter 4 calculates energy-sharing-optimal solar PV and BES capacities for grid-tied houses with Evs. The first half of this chapter established a revolutionary rule-based home energy management system for Evs at home and away. The case study is done with different configuration that includes electricity tariffs and components with and without EV and obtained results are discussed. Finally, sensitivity analysis is done for export power limitation, load variation, and PV-BES cost variation as well as uncertainty analysis is done for temperature and irradiance variation.

Chapter 5 provides the conclusion of the key findings from the overall study. This section has the summary that our research objective has been fulfilled. Additionally, it provides a general conclusion and guidelines to the household interested in energy sharing.

Chapter 6 includes the future work that can be continued taking this research as a base study for future research purposes. The recommendation is clear and subtle and opens the door for new perspectives of energy sharing.

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# Chapter 2. Literature Review

## 2.1 Review on Optimal Sizing for Grid Connected Households

The integration of a renewable energy system that includes storage capacity has emerged as a highly popular trend among residential consumers seeking to attain sustainable and cost-effective electricity. This approach to generating electricity alleviates the strain on power grids. Notwithstanding the existence of various photovoltaic (PV) and battery energy storage (BES) initiatives, it has been underscored that significant efforts are still necessary to achieve the optimal and strategic execution of the grid connected house (GCH). The literature review presented in this section focuses on the performance of the PV-BES system, as well as the economic and technical indicators that demonstrate an upward trend. Several parameters are prioritized to ensure their fulfillment, including technical and economic feasibility information, design limitations, tariff, energy administration, and distribution, to attain optimal profitability. The objective of this review is to illustrate that the utilization of optimal battery sizing and integration in the system has yielded favourable outcomes, such as enhanced self-sufficiency, cost-effectiveness, and increased return on investment for consumers.

### 2.1.1 Background and overview

Some background of optimal sizing of systems in connection with GCH is shown in this section. The review in [1] indicates that there has been a significant increase in global electricity demand, which has been characterized by a rapid growth trajectory. It has been studied in [2]the demand for electricity has increased by approximately 6% in the year 2021 alone. In 2021, the demand for electricity in China has increased by 10%, representing half of the global increase observed. The development of a counter product to meet the demands has been perceived as attainable through the utilization of grid-connected households that have implemented diverse strategies to generate renewable energy. The article in the reference [3] has conducted a review of the renewable ground coupled heat concept, with the aim of assessing the effects of elevated voltage levels across various sectors. This has posed challenges not only for the network itself, but also for the operators managing it. Effective sizing and design strategies can help to alleviate the adverse effects associated with a renewable household system, such as the PV system, which has been identified as a systemic challenge for the GCH. The optimal sizing issues reviewed in [4], discussed the impacts of various factors to achieve a technical and economic system for GCH in a rooftop installed PV system. In [5] genetic algorithm based strategy is proposed to solve the optimal sizzing problem with a Pareto optimal solution based on cost and pollution minimization and maximization of renewable based energy. Research in [6] had been conducted for the optimal sizing based on the calculation of PV battery by enhancing the economic factors to achieve self-sufficiency.

Systematic energy management in GCH had been studied in various research to evaluate the PV-BES systems. Input data, design constraints, objective functions, pricing programs, software tools and algorithms are important parameters of optimal sizing of PV-battery GCH.

a. Input data

The optimal sizing of PV battery GCH depends on the several pieces of input data depicted in fig. 2.1. Technical data is collected based on the required loading and generation data of grid and PV-BES.

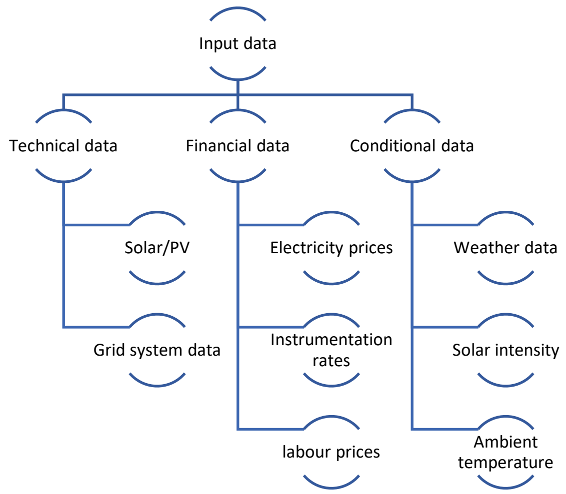


Figure 2.1 Input data for optimal sizing of Battery PV system.

On the other hand, financial data is based on the capital cost and running cost including the interest and inflation rates of electricity. Conditional data represents the weather condition if they are suitable for PV generation, overhead lines, or ambient temperature of the specific place under consideration.

b. Objective functions

Objective functions play an important role in optimal sizing of PV and BES. Algorithms are developed to maximize or minimize the objectives to achieve the optimal solutions. The main objective functions in optimal sizing for PV and BES for GCH are financial objective functions that are minimized and the technical objective functions, such as efficiency, sizing, and product life that are maximized.

c. Constraints to obtain optimal sizing.

The optimal sizing is based on different type of constraints that might include the load and generation power balance. In the case of South Australia there is a restriction limit to export rooftop solar generation that is 5KW for single phase and 30KW for 3 phase power [7]. Similarly, State of charge constraints are taken in consideration for the battery charging and discharging factors.

d. Electricity cost and optimal sizing

To obtain a Pareto optimal sizing solution, it is necessary to properly manage each objective function so that other objectives may also be attained. The cost is an important objective function to manage GCH sizing. The cost objective function is based on some technical terms including consumer rate, tariffs, capital costs, and flat price.

e. Software tools and algorithms

Today the artificial intelligence is doing best role in optimal sizing of GCH. When it comes to the sizing and optimization of grid-connected systems, a wide variety of algorithms, such as particle swarm optimization (PSO), genetic algorithm, ANT colony optimization, artificial neural network, and multi-objective optimization approaches, play a significant role. Moreover, these algorithms are run in the software tools like, HOMER [8], MATLAB [9], TRNSYS [10], retscreen [11], HYBRID2 [12], ihoga [13] to get optimal sizing of grid connected systems.

### 2.1.2 Review on Existing Studies and Technical Challenges

Research in [14], indicated the optimal sizing of the PV, wind turbine (WT) and BES in the aspect of GCH. The study has divided the optimal sizing and planning aspects categorically into three.

- Grid connected system configuration without BES.
- Grid connected system configuration with BES.
- Standalone system

Studies for the optimal sizing had been on the constraints of objectivity, designing, algorithm, function, tariffs, I/O data, method, and the origin which had been applied. The system with PV-WT-grid was the most economically advantageous design for tonsley buildings chosen as case study, according to numerical data after optimization.

a. Battery Storage System Modelling

In different studies batteries are considered as an important storage backup in a renewable system. In [15] a new method for lead acid battery is proposed based on different characteristics that have been optimized. The battery storage capacity is improved. Moreover, internal resistance, and temperature of external environment are taken in account for this model. Different experiments were performed in the research to meet the model needs. The closeness of the actual and theoretical cycle charts shows that this model accurately captures the behavior of a temperature-compensated lead-acid battery.

The validation of model with respect to experimental data is given in [16] where battery cycles are simulated to get best results. The two different PV systems are taken for the comparison by having a same battery model to check its flexibility. The results obtained from different simulations are than compared and validity of model is checked. The CIEMAT model utilized was deemed to be more than sufficient, and both batteries' discharge tests demonstrated its efficacy.

b. PV System Modelling

The study in [17] had been made to identify the simplified simulation models for the PV system and network automation. The current voltage measuring model had been reviewed to study the PV modules in the open circuit condition of voltage. This study compares simulation results with the data set supplied by the manufacturers. Additionally, experimental evidence supports the method's validity for long-term simulation.

In [18] the optimal sizing of PV for standalone systems is done through the artificial neural networks technique. The proper sizing of PV systems has been greatly simplified by artificial intelligence. For sizing PV systems of any kind, the suggested methodology relies on artificial neural networks. The result shows that highly accurate BES sizing can be carried out based on experimental data.

c. Optimal sizing of PV-BES

Optimal sizing of PV-BES is done in [19] that focuses on mixed integer linear programming (MILP) methodology. The recently created MILP optimizes both under demand tariffs and time of use (TOU). Peak grid consumption for the entire year was decreased for the residential case under demand tariff optimization from 6.08kWh to 2.25kWh. Peak grid use in the commercial case decreased from 450.03kWh to 348.6kWh over a year. Moreover, different studies were performed to optimize the dispatch of the system in [20]. The findings of the research improve the economic feasibility for consumers under various rate structures, particularly those that pose challenges for PV systems, such as non-coincident TOU structures, charges based on peak demand, and reduced rates for exporting energy to the grid. The energy scheduling was studied in [21]. The economic perspective of PV battery optimal sizing system is taken in consideration. In the end, the PV and BES combination boosts the profitability of BES, which almost certainly increases the adoption of BES. Table 2.1 comprehensively shows the literature done on PV and BES optimal sizing and outcome are described after table.

Table 2.1 Showing the literature on optimal sizing of PV-BES

| Ref. No | Decision Variable | Applied Methodology | Objective Function | Important Constraints for a feasible solution | Region |
|---|---|---|---|---|---|
| [22] | PV-BES | MILP | To minimize electricity cost | Not specified | Aus. And Germany |
| [23] | PV-BES | PSO | Maximize energy autonomy, power autonomy, lifetime capital cost, and simple payback period. | Battery aging | Netherlands and the US |
| [24] | PV-BES | MATLAB Based | Minimize the Reverse power | Battery state of charge | United Kingdom |
| [25] | PV-BES | Mutation adaptive differential evolution | Loss of load probability Levelized cost of energy (LCE) | Life cycle of PV | Not mentioned |
| [26] | PV-BES | ASHRAE model in MATLAB software | Energy cost | Net present value | Australia |
| [27] | PV-BES | Simulation model | Reducing feed-in peaks | Not specified | Australia |
| [28] | PV | HOMER | Minimize costs in the life cycle | Not specified | Australia |
| [29] | PV array | HOMER | To get best inverter size | Not specified | Saudi Arabia |
| [30] | Battery | MATLAB | Reduce the annual net payment for electricity and cost of battery | State of charge | South Australian |
| [31] | PV | MILP | Reducing losses and cost of energy | ESS limits by the rated power | Saudi Arabia |
| [32] | The capacity of PV | HOMER | Minimizing net present cost | Technical factor | Saudi Arabia |
| [33] | Battery | Battery dispatch model | Net present value of the project is maximized | Not specified | USA |

The outcome of [22] show that small-scale PV-BES in Australia can successfully reduce peak loads and may soon be a financially viable option. While stand-alone PV systems are now more cost-effective in Germany, installation rates are anticipated to rise due to a result of the anticipated decline in battery prices. BES can successfully lower PV peak power in Germany, and distribution grid operators have been given estimates of peak reduction. This paper proposes an integrated approach that first derives optimally configured PV and battery systems using a MILP and then evaluates their impact on grid planning aspects such as peak feed-in and peak demand for case studies in Australia and Germany. Developing a MILP model to determine the optimal power demand and supply ratios with the goal of minimizing the TOE and TCOE of the Hybrid Power System. The multi-objective optimization technique provided in [23], offers an effective way to establish the ideal size of PV-BES during the preliminary design stage, considering a variety of design elements and numerous objectives. The proposed method is used to determine the optimal capacity of a PV system and BSS for two residential load profiles in the Netherlands and Texas, US, to investigate the impact of meteorological conditions on the relative scale of PV and battery. A method that uses probability to calculate the ideal PV panel and BES size for household energy usage was introduced in [24]. This tool is intended to assist in choosing the best PV capacity and BES size combination for residences, and for both transformer and feeder systems. None of these papers investigated the effects in results by considering grid constraints and other constraints that includes battery degradation and components salvation value which is done in this paper.

The study in [25] discovered that a lead-acid battery-based standalone photovoltaic system (SAPV) system had a lower life cycle cost, fitness function and levelized cost of energy. This study introduces a multi-objective optimization approach called Mutation Adaptive Differential Evolution (MADE) for the purpose of optimizing the configuration of off-grid Solar Photovoltaic (SAPV) systems. The readings were satisfactory despite the greater loss of load probability. Lead-acid battery and PV module counts that are ideal were also established. Overall, the research indicates that a SAPV powered by lead-acid batteries might work well in practical situations. The study in [26] discovered that the ideal size of a grid-connected renewable energy system is influenced by the system's needed contribution to the annual energy consumption. The dimensions of solar panels necessary for diurnal energy generation remain consistent, as plug-in electric vehicles are unable to serve as a substitute for solar panels, given the lack of solar radiation during nighttime hours. The solar irradiance profile utilized in this investigation was estimated employing the widely recognized ASHRAE clear sky model. The purpose of this tool is to provide an estimation of the monthly average hourly global sun radiation on horizontal surfaces. A Plug-in electric vehicle (EV) with a high state of charge can, however, lower the daily cost by providing electricity during times when electricity prices are high. The economic analysis of PV-BES in [27] reveals that cost considerations will have a significant impact on the ideal system configurations. Simulation software is designed to provide a virtual environment that can be explored and interacted with, aiming to closely replicate the real world. Small-scale PV systems with high rates of self-consumption will ultimately be more advantageous as feed-in tariffs become less crucial. These 3 papers have given clear understanding of how BES and PV systems working together will be the most cost-effective and profitable strategy but do not have clear instructions about the load data used, whether it is taken from actual household or just assumption. These are made clear in the proposed research with real data and TOU rates.

According to the study in [28], a 6 kW PV system can cut homeowners' electricity costs by more than half in all cities for both low and high price scenarios. The system produces 56%–61% of the energy required for home use and feeds electricity back into the grid. The simulation and optimization of the system were conducted using HOMER software, with inputs including global sun irradiation statistics as a solar energy resource, the prices of PV devices, batteries, converters, and grid power pricing, as well as the sale-back tariff for economic analysis. Depending on available solar resources in the area, the investments in the PV system generates a return of 12.3 to 16.3 percent, and its grid integration lowers carbon dioxide emissions. Net present cost and irradiance both have linear relationships, as do yearly carbon dioxide emissions and irradiance. The study in [29] found that the most effective arrangement for providing electricity to Makkah city during peak load periods of 2200 MW involves utilizing a 2200 MW PV size and a 2200 MW inverter size. This configuration ensures that there is no unmet load or surplus electricity. Due to discrepancy among generation and demand patterns, the study in [30] discovered that a net zero emission home without a local BES exports two-thirds of the PV-generated electricity to the grid, resulting in an annual payment of $1,078.50. However, if the yearly payment rate is less than $80/kWh/yr, employing a local BES is economically advantageous because it greatly minimizes energy interchange with the grid and related net payments. The determination of the ideal battery capacity involves the minimization of an objective function that represents the annual net payment. This payment is influenced by several factors, including load and photovoltaic (PV) generation patterns, battery cost and specifications, as well as the retail price (RP) and feed-in-tariff (FIT) of grid power. The analysis also revealed that, in the South Australian context, the BES had already passed the economic breakeven point. The study in [31] suggests a MILP-based method for allocating and sizing a BES system in a power system with PV farms included. MILP is frequently employed in the field of system analysis and optimization due to its inherent flexibility and robustness. MILP offers a highly effective approach for addressing intricate and extensive problems, exemplified by its successful application in domains like industrial symbiosis and process integration The ideal BES size and allocation reduces operational expenses and load shedding by 3.24%. The BES system offers a benefit due to its ability to charge during the daytime when energy is readily available and discharge during the nighttime when the energy cost is relatively higher. This impedes the system from diminishing the power output produced by the PV cells. All these papers have found optimal solution of PV-BES for maximum system efficiency and reducing COE for houses significantly but necessary constraints such as battery degradation and grid restrictions which is important to reduce high voltage in grid during peak sunlight hours because of overwhelming production of energy are not considered.

The research in [32] examines three optimization methods and builds three hybrid microgrid systems in Yanbu, Saudi Arabia. The PV/biomass system using the generalized predictive control optimization method is the most cost-effective with a net present cost of $319,219 and a levelized cost of electricity of $0.208/kWh. The paper recommends additional investigation into new optimization algorithms and microgrid topologies and says that hybrid microgrid systems are a cost-effective choice in regions with substantial solar radiation. Two situations with various energy capacity but comparable battery power ratings are discussed in [33]. The battery dispatch model is a methodology employed to ascertain the optimal allocation of resources for serving various applications and determining the most opportune timing for their provision. Its primary objective is to maximize the economic yield of a battery system during its operational lifespan. Due to brief demand spikes, the load profile only needs a small amount of energy to reduce demand. The best option in the first scenario simply needs 1.5-hour battery, however in the second, the model is forced to specify 4-hour batteries, adding a lot of extra energy capacity that is not necessary. In comparison to the best case in the first scenario, the slightly increased power rating enables it to do more demand charge reduction, however, it fails to truly justify the increased energy capacity. Both papers have provided economical solution for the households, whether the solution is feasible or not if it wants to take part in peer-to-peer energy sharing between the houses is not clear as well as whether the proposed solution will still be feasible if it joins network of houses is also not clear. These are considered in this paper and optimization of components is done for maximum economic benefits of households.

d. Technical Challenges

Although the studies revealed in the literature review that there are many advantages. PV system under goes degradation problems as discussed in [34] and they should be taken in consideration to avoid any energy losses. However, it has been indicated the issue of pricing in the PV-BES based GCH such that there are many pricing methods implied like TOU and flat pricing in various countries [35]. The step method had been implied rarely. Pricing mechanisms such as energy management must be considered as a systematic approach to overcome the price fluctuations in the grid-connected household method to accommodate the consumers as well as encourage the alternate system by applying such method of pricing. Another challenge in the way of optimal sizing of PV system is uncertainty in weather conditions. there are certain conditions when the sun gets behind the clouds and solar intensity decreases so, the output of the solar panel decreases as well leading to less output [36]. The combined PV- BS has reduced this problem but, a lot of attention is required to overcome it.

### 2.1.3 Recent Development and Trend

a. Consumer guide

As reviewed in [37], suggesting that guidance needed to be provided to the clients for the proper selection of PV-BES solutions with the maximum abilities. The guide should be developed to familiarise the consumer with the allowed area for PV and BES and the import export of the energy. For sourcing power from the main grid, a fixed power rate could be utilized. The recommendations can be created depending on the available rooftop space and residential households' typical daily electricity use. This has been observed in typical households' everyday energy consumption rises, and the PV system's aggregated power rises as well.

b. Multi objective optimization

The paper [38] presents a study on the development of a hybrid PV-WT generating system equipped with a battery bank, intended for an off-grid residential property located in Tehran, Iran. For optimal system scaling, the genetic algorithm with PSO and multi objective methods had the objectives of maximizing system reliability and minimizing total current cost. The PV/WT/BES system was determined to be the optimum option with reduced costs and better results for all levels of loss of power supply probability after three different scenarios were considered. Three Pareto fronts were produced for the three systems because of the multi objective PSO approach's simultaneous optimization of cost and reliability. The suggested method produced a levelized cost of energy of 0.508 with a variation of 7–10%.

### 2.1.4 Potential Direction for Future Research

a. Demand response management

In the ideal sizing of a PV-BES for GCH, demand responsiveness has been reviewed in [39] as a significant factor. Solar insolation, load consumption, and energy rate forecasts had been critical for providing relevant insights for demand response actions. Demand response solutions have efficiently reduced the capacity of the PV and batteries, lowering the system's cost.

b. Electric Vehicles role in optimal planning

EV charging may also occur at residential locations; however, this has an impact on the PV-BES system, potentially disrupting its sizing. For the charging of PV-BES at home it should be sized accordingly to avoid instant discharge of the battery. As in the evening times there isn't any available PV generation so, larger batteries are required to charge EV at homes. However, If the PV-BES is grid connected, it would work more efficiently, and the sizing can be done more effectively.

### 2.1.5 Conclusion on the review

The impact of optimal sizing of the renewable energy system has been observed among the grid-connected household users with the self-reliant BES which has indicated that the sustainable, reliable, and self-sufficient system in an economic pattern system. A self-sufficient system proves to have a better and timetabled pattern of electricity generation, efficient battery usage and lower expense.

This section provided an overview of the various research that have been conducted on the topic of optimal PV battery sizing. This was done to investigate different objective functions and their constraints, different optimization algorithms were studied, and the software tools were discussed in detail. The methodologies of different studies were taken into consideration. Guidelines for the consumer and the role of optimal sizing in PV-BES are done in this section.

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## 2.2 Review on optimal sizing and P2P energy trading with and without an EV

### 2.2.1 Background and overview

The concept of P2P energy trading enables individuals to engage in direct exchange of electricity with one another, as opposed to solely relying on their respective utility providers. When a result, households may have lower electricity bills and less of an impact on the grid when they alter their electrical usage to coincide with local renewable generation [1]. Over the past several years, there has been a rise in the utilization of demand-side distributed energy resources (DERs). DERs are systems that contain variable demands, energy storage systems (ESS), and distributed generators that are connected to residences, buildings, microgrids, or distribution networks [2]. The global energy market is witnessing significant shifts because of an increased demand from consumers for alternative energy sources and battery storage systems to curb emissions of greenhouse gases. Rooftop solar PV panels in Australia captured 4.5 GW of solar peak capacity in 2015, with 1.4 million homes (or 15%) equipped with them. This has led to Australia becoming the world leader in the installation of household solar PV systems. [3]. The proliferation of P2P market platforms across multiple industries has levelled the playing field for small vendors compared to more established businesses. Popular P2P services include Uber for transportation, Airbnb for lodging, and eBay for sales [4]. Modern solutions to the problem of climate change and global warming have been made possible by technological developments. The introduction of Evs has significantly altered the transportation industry, a key contributor to climate change.

To secure a sustainable future, we must urgently address pressing concerns such as climate change, dwindling fossil fuel supplies, and greenhouse gas (GHG) emissions. The transportation industry is a major source of the increasing harmful emissions, hence electrifying this sector is considered as a possible remedy. More than a century has passed since EV technology reached its commercial zenith in the early 1900s. Previously, Evs were restricted to golf carts and delivery vehicles due to the prevalence of fossil fuels, the development of internal combustion technology, and the ease of operation of internal combustion engines (ICE) [5]. As per the "Global EV outlook" report by the International Energy Agency, it is anticipated that the aggregate count of Evs will attain 130 million by the year 2030 [6]. Evs offer several benefits over ICE vehicles. These advantages include decreased road noise, pollution, and vibration, as well as reduced maintenance costs and technical inspections. Additionally, Evs require fewer oil changes and can recover energy through the regenerative braking system.

Additionally, Evs have a high tank-to-wheel efficiency and offer high torque at moderate speeds. Due to the finite nature of oil reserves and strict import regulations, electricity is also less expensive than fossil fuels [7]

Tesla's CEO, Elon Musk, has stated that the company plans to manufacture 20 million Evs annually by the year 2030. This is over fifty times as much as Tesla manufactured in all of 2019. Musk added that he anticipated more than 30 million Evs to be produced yearly by the market by 2027 [8]. During the period of 2020 to 2025, General Motors has planned to allocate $35 billion towards the development of electric and autonomous vehicles, which is more than twice the amount that will be spent on gas and diesel vehicles. New, high-paying jobs will be generated by the investments. This includes converting our existing assembly operations in Factory ZERO and Spring Hill, Tennessee to produce only Evs [9]**.** Kia has also revealed its four primary business objectives for the year 2030. The company's goal for the year 2030 is to achieve the sale of 1.2 million battery electric vehicles (BEVs) on an annual basis, as well as the sale of 4 million vehicles annually, with over 2 million of those being eco-friendly models. Furthermore, the company endeavours to integrate connected car functionalities and self-driving technologies into every novel automobile, and to position itself as the foremost brand in the worldwide purpose-built vehicle (PBV) industry [10]. Moreover, Audi plans to be a pioneer in sustainability, social responsibility, and technology by the year 2030. Audi's new business strategy, "Vorsprung 2030," aims to hasten the automaker's electric transformation, which had been scheduled for 2026. In addition, Audi's production of ICE vehicles will'be discontinued completely somewhere around 2033 [11]. The global community is currently undergoing a shift towards the electrification of the transportation industry, and scholars are actively exploring strategies to optimize its potential benefits. Evs are currently being regarded as a potential storage solution for peak hour usage.

The integration of EVs into the smart grid is a crucial aspect of future energy systems, as they possess the ability to store electrical energy within their batteries during periods of low demand and subsequently discharge this energy into the grid during peak hours [12]. A study focuses on evaluating the advantages of P2P technology when integrated with unidirectional EV chargers, commonly referred to as V1G, as well as with chargers that have the capability to transfer EV battery energy to either the household (V2H) or the power grid (V2G) was conducted. Engaging in P2P trading utilizing V1G technology has the potential to result in an upsurge in communal energy, minor enhancements in microgrid autonomy, and improvement in household expenditures. The integration of P2P technology with V2H technology yields significant benefits. At the local level, the electricity grid is impacted by two notable factors in the process 41imulay decarbonisation, namely the widespread adoption of embedded renewable generation, particularly PV systems, and the increasing electrification of transportation. PV systems and Evs have the potential to create a mutually beneficial relationship, as EV batteries can effectively store excess power generated by nearby PV installations. The traditional energy system does not offer any motivation for households to engage in power trading with their electricity supplier unless PV and EV technologies are integrated within the same meter. For an EV to utilize excess energy from a neighbouring source for charging purposes, a payment scheme would need to be established that falls above the supplier's feed-in tariff (FiT) but below the retail electricity price. This mutually beneficial transaction would result in advantages for both parties involved. The exchange of energy described is commonly referred to as a P2P trade. In addition to generating economic advantages, communities that engage in P2P trading have the potential to attain ecological benefits and alleviate pressure on the distribution grid [1]. A P2P trading system has been posited as a potential solution for ameliorating the effects of EV recharging on the electrical grid during typical business hours. Similar to various P2P shared economy enterprises, the aforementioned trading platform facilitates the interconnection of two distinct market participants: electricity “producers” (i.e. vehicles possessing an excess of energy in their batteries) and electricity “consumers” (i.e. vehicles requiring energy to complete their daily journeys) [13]. Moreover, attaining the optimal size for the grid components holds great importance. The achievement of functionality and sustainability in P2P energy sharing networks necessitates the consideration of EV optimization strategies.

Prior research has demonstrated that P2P energy sharing networks, which incorporate BES systems, can yield substantial cost reductions for prosumers residing in each community. However, these studies have not considered the most efficient BES sizing for various ownership structures, nor have they explored the interplay between P2P energy sharing and energy storage sizing. Despite the considerable research conducted on determining the ideal energy storage capacity and enhancing the efficiency and longevity of BES, the substantial initial investment and ongoing expenses associated with BES implementations continue to pose a challenge to their economic viability. Hence, it is imperative to ensure appropriate power and energy sizing to enable P2P energy sharing with BES to be economically feasible, taking into account the life cycle cost encompassing both capital and operational expenditures [14]. With the widespread adoption and deployment of EVs, it is anticipated that two significant effects will be observed on the power grid. Evs impose a substantial burden on the power grid during charging due to their high energy consumption. The aforementioned phenomenon can result in significant issues, including the need for a substantial capacity to accommodate the heightened peak demand, leading to the underutilization of power plants during hours of low demand [15]. One potential strategy for addressing this issue is to optimize the charging schedule of Evs through coordinated efforts. Evs have the potential to make a great contribution to the power grid. In particular, these devices have the potential to function as ESS, wherein they accumulate electrical energy within their battery units during off peak hours and subsequently discharge the stored energy to the power grid during peak hours [16]. By utilizing the services of an aggregator, a collective of EV consumers can establish an energy trading market. This market enables everyone to engage in the buying and selling of energy through the aggregator, thereby enhancing the overall performance of the system, including social welfare, while also improving their own personal benefits. If Evs are integrated into load scheduling in a suitable manner, they can be leveraged to enhance overall satisfaction with respect to load demands and/or decrease electricity costs by utilizing their stored energy for residential appliances. Efficient scheduling of energy trading has the potential to enhance the overall social welfare of power systems, regardless of whether they are collaborative or non-collaborative in nature. The enhancement of social welfare is amplified when the energy reserves of EV users are harnessed to meet the peak load demands of other customers. Furthermore, with the escalation of wholesale electricity prices, energy trading assumes a greater significance in improving the adverse consequences of the augmented wholesale electricity price. [12]

### 2.2.2 Review on Existing Studies and Technical Challenges

There is multiple research which has developed a methodology for optimal sizing for single GCH with EV. But none of the papers has developed a method to find out optimal components sizing for the households with mutually agreed energy sharing. This section has reviewed multiple papers and is divided into 3 parts:

a. Optimal sizing for single GCH with Evs.

Table 2.2: Literature on optimal sizing for single GCH with Evs.

| Ref. | Applied method | Objective Function | Constraint Considered | Optimal sizing | PV | BES | Region |
|---|---|---|---|---|---|---|---|
| **[17]** | MILP | This paper aims to analyse the collaborative assessment of multiple microgrid DERs and examine the potential for bidirectional energy trading using Evs. | The power that can be produced by DER devices. | ✓ | ✓ | ✓ | Belgium |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **[18]** | Smart Control Algorithm | Aims to explore the advantages of integrating PV generation, household battery storage, and EV equipped with V2G technology to mitigate peak grid load and enhance power quality. | Capacity of the battery and EV | ✓ | ✓ | ✓ | Not specified |
| **[19]** | Techno-economic energy system model | Offer a unique strategy for optimizing the energy costs of grid-connected households hosting Evs subject to power export limits. | Loss of BES capacity and revenue from battery salvage | ✓ | ✓ | ✓ | Australi a |
| **[20]** | Rain flow Alogrithm | Aims to offer pragmatic recommendations for households that are connected to the grid, possess Evs, and are subject to TOU electricity pricing. The objective is to determine the most suitable capacity of solar PV and battery storage systems that can be employed to reduce the cost of electricity. | Limitations on power consumption for the SPV, BSS, and EV, as well as the restrictions on the SOC for the battery and EV. | ✓ | ✓ | ✓ | Australi a |
| **[21]** | Energy manageme nt system | Propose a hybrid optimization algorithm for managing energy storage at PV-integrated EV charging stations, one that switches between deterministic and rule-based modes of operation according to the allocation of electricity pricing bands. | The ESS capacity and its degradation mode | ✓ | ✓ | ✓ | Singapor e |
| **[22]** | Simulation and Mathemati cal model | Reduce the discrepancy between the reference curve and the summed load curve of all charging events with your proposed optimized EV charging model for regulated markets. | The maximum acceptable charging power is a function of SOC and temperature of the battery | ✓ | ✓ | ✓ | China |
| **[23]** | HOMER | proposes an algorithm for microgrid planning that aims to optimize the utilization of renewable generation while accommodating EV charging demand. | Base load and EV loads should be considered together. | ✓ | ✓ | ✓ | Korea |
| **[24]** | MILP | Propose a method for optimal DC microgrid planning for Evs Supply Infrastructure, customizing to source connection technical configurations and converter kinds and topologies. | Maximum and minimum voltage | ✓ | ✓ | ✓ | Italy |
| **[25]** | MATLAB | Objective of this study is to present a technique for reducing fluctuations in power consumption over a given period, thereby enhancing the efficiency of power infrastructure utilization. | EV charging demand and utilizing SQP to optimize EV charging commencement time | × | × | ✓ | Not specified |
| **[26]** | Monto Carlo Simulation | Aims to explore the most efficient dimensions for rooftop PV systems, WT)\, and BSS in a smart home that incorporates PEV and takes into account both V2H and home-to-grid operations. | Restrictions on BES functionality during power trade and demand fluctuations, | ✓ | ✓ | ✓ | Not specified |

The paper [17] presents a proposed system for managing the energy consumption of a building. This system is designed to optimize the distribution of power among the various components of the microgrid over a 24-hour period, considering dynamic pricing signals. The system considers the variability of PV energy generation and the probabilistic nature of EV charging patterns. The study examines the potential for bidirectional energy trading by EV and analyses various systems abilities to sell energy back to the grid. The present study introduces a methodology based on MILP to address the issue at hand. MILP model of the EMS configuration is provided to investigate the cooperative evaluation of several microgrid DER components. The methodology considers the unpredictability of PV energy and the probabilistic nature of the charging patterns of Evs. This study examines the bidirectional energy trading potential of Evs and evaluates various systems abilities to sell energy back to the grid. This study is unique in its integration of the previously mentioned operational capabilities into a unified EMS under dynamic pricing-based Demand Response methods. The primary uniqueness of this paper lies in the utilization of a MILP framework .The paper [18] discusses the increasing trend towards electrification in the automobile industry and the potential for Evs with V2G capability to provide bidirectional energy transfer and grid support. The paper talks about study that has already been done on how to handle peak loads at home using PVs and batteries or PVs and Evs. In the paper, converters are used to connect energy sources (PV, EV, and battery) to the home's shared AC bus. A smart meter-connected controller collects the house's load state (power usage pattern). Setting charging and discharging thresholds using established algorithms and battery and EV capacities. Real solar insolation data to calculate PV power generation in the examined period. The proposed study involves an examination of the lithium-ion battery's capacities ranging from 2 to 8 kWh. Additionally, the integration of the EV into the system will be achieved through the implementation of a rule set that determines the Evs mode of operation. The study's findings suggest that employing domestic battery storage in households equipped with a V2G-capable EV and PV generation can effectively reduce peak loading on the electricity distribution grid by up to 37% in practical scenarios. The integration of Evs and domestic storage offers an extra degree of freedom, which can lead to further reductions in peak grid load. The scholarly article presents a sophisticated smart control algorithm that effectively manages the various components of the system to mitigate peak grid load and enhance power quality. The paper suggests that the proposed system can be used to provide grid support services and reduce the need for additional grid infrastructure. Both papers missed the comparison of how the proposed system will be affected when different Evs with different battery capacity enter the system which is analysed in this paper.

The paper [19] examines the growing significance of Evs in the realm of household energy consumption on a global scale, as nations strategize to substitute traditional ICE automobiles.

The study emphasizes that the cost of EV charging is a primary concern among individuals who own Evs. In certain countries/regions, the percentage of EV charging events that occur at home can range from 50% to 85%. This is attributed to the fact that individuals are more inclined to charge their Evs at home, particularly if they possess private parking accommodations. Approximately 50% of private EV owners exhibit a preference for utilizing renewable energy derived from household rooftop PV systems and battery storage, or alternatively, grid electricity that has been sourced from green energy or carbon emission offset mechanisms, for the purpose of charging their Evs. This paper presents a new approach for optimizing energy costs in households that are connected to the grid and have Evs, while also considering constraints on power export. The approach integrates practical EV charging patterns, power export constraints, BES deterioration, and battery recovery income into a comprehensive techno-economic model of the energy system. The study showcases the outcomes of cost optimization for four distinct system configurations, utilizing contemporary TOU tariff and authentic load and PV generation data pertaining to households in South Australia. This study employs techno-economic modelling, a methodology employed to optimize energy expenditures in households incorporating Evs and renewable energy sources. The study performs a sensitivity analysis on the annual energy cost by manipulating several factors, including the daily household load demand, PV/BES capacity, power export limits, and PV/BES cost. The results indicate that optimally sized PV and PV-BES systems can reduce the AECs of households with gasoline-powered vehicles by 6.71 and 10.38 percent, respectively.

The paper [20] delves into the subject of optimal planning for solar PV and BES systems in households that possess Evs and are subject to TOU electricity pricing. The objective is to reduce the expenditure on electricity while ensuring adherence to predetermined design limitations throughout a 20-year duration of the project. This study presents pragmatic recommendations for households connected to the grid and utilizing TOU energy pricing. The aim is to determine the most suitable PV and BES capacity to accommodate an EV already in use. The optimization technique is universally applicable and can be implemented by any household that possesses an EV. The study employs authentic data pertaining to solar insolation and temperature, in addition to household electricity demand and electricity prices, specifically in the region of South Australia. The study employs an innovative rule-based approach for home energy management to examine the most advantageous dimensions of two distinct system configurations: The two concepts under consideration are (1) PV-EV and (2) PV-BES-

EV. Stochastic functions are utilized to integrate the EV's initial state-of-charge, as well as its arrival and departure times, into the energy management system (EMS). The present study conducts sensitivity analyses on several key factors, including the FiT, grid constraint, electricity demand, and available rooftop area. These analyses aim to examine the potential variations in the cost of electricity and the capacities of PV and BES systems. The study additionally employs the rain flow algorithm to derive information pertaining to the deterioration of battery capacity and computes the net present value of electricity exchange. The average price of fuel in SA for 2020 was 134.7 ¢ were as the COE with TOU pricing comes to 45.03 ¢/kWh. Considering the average Australian travels 11,100 km/year and the average car consumes 11.1 L/100 km, the average fuel consumption per passenger vehicle comes to 1,232.1 L/year. This totals $1659.6/year in fuel for the average passenger vehicle in 2020. With the SPV-BSS system in place for homes, which own an EV the COE drops to 33.48 ¢/kWh, bringing the cost to $508 per year to run the Renault Zoe. It can be concluded that it is viable economically to run an EV in a SPV-BSS-EV system as compared to an ICEV. The cost dropping from $1659.6/year to $508/year on average after implementing an EV in a SPV-BSS-EV configuration, a difference of $1151.6/year. Both paper 4 and paper 5 do not give clear instruction whether the proposed methodology of EMS is extendible to n number of houses if those house wants to share energy with other household or take part in P2P energy sharing which is made clear in this paper.

The paper [21] presents a hybrid optimization algorithm designed for managing energy storage in EV charging stations integrated with PV systems. The Energy Management System (EMS) holds significant importance within the realm of electric vehicle (EV) charging stations and smart cities. The utilization of EMS contributes to the enhancement of energy storage system (ESS) operations by employing a dynamic strategy that alternates between deterministic and rule-based approaches, guided by the allocation of electricity price bands. To reduce EV charging station operational costs, the algorithm switches between deterministic and rule-based modes depending on energy pricing band allocation. The system categorizes real-time electricity prices into price bands, calculates PV power from solar irradiation data, and optimizes the running cost of EV charging stations integrated with PV and ESS. The research outlined in this manuscript aims to enhance the efficiency of the ESS by optimizing the charging and discharging power, as well as the power imported from the grid. This optimization is based on the allocation of price bands within the real-time wholesale electricity price. The hybrid algorithm under consideration exhibits robustness in its ability to adapt to various types of EV load modelling procedures. The proposed research lacks consideration of the constraints related to the state of charge (SOC) as well as the battery's salvation value. The paper [22] discusses the development of Evs as a solution to environmental problems and energy shortages. However, the lack of EV charging facilities is a bottleneck that restricts the rapid growth of Evs. Two sources are used in the report; one examines the effects of fast charging stations on distribution networks, while the other assesses the financial worth of solar-powered battery switching stations. The present study puts forth an enhanced EV charging framework that considers the time-of-use pricing and state-of-charge curve. Additionally, the article introduces a heuristic approach for resolving the optimized model. This study presents numerical simulations of an optimized charging model and conducts a comparative analysis of the charging performance between a typical charging pattern and the optimized charging pattern in various scenarios. The efficacy of the proposed approach has been confirmed through the simulation outcomes of both individual Evs and multiple Evs. The proposed research would have been clearer if the analysis were done with different Evs in the market with different battery capacities and time it would take to charge each of different battery capacities Evs.

The paper [23] centres on two significant technologies that aim to mitigate greenhouse gas emissions in the power system, namely Evs and renewable generation. A microgrid planning algorithm incorporating EV charging demand is proposed to maximize renewable generation at the lowest cost. The research offers a microgrid planning algorithm with EV charging demand to maximize renewable generation at the lowest cost. The algorithm employs a sustainable generation-tracking EV charging strategy and HOMER energy software to determine the most advantageous blend of power sources for a microgrid. HOMER makes use of an exhaustive search technique that simply computes the NPCs of all candidate solutions and selects the one that has the smallest NPC as the best possible answer. The study additionally examines various controlled and uncontrolled EV charging scheduling strategies. Simulations have been carried out to assess the efficacy of the proposed algorithm. The findings indicate that the microgrid created through the implementation of the algorithm leads to a reduction in both investment costs and carbon emissions. Necessary constraints such as grid constraints and battery degradation are not considered. Grid constraints are necessary to take into consideration to mitigate overload of voltage in the grid on any given point of time.

The paper [24] discusses the need for proper management of Evs to reduce possible malfunctioning of distribution systems. The incorporation of EV charging stations with ESS and PV panels is a viable option for shading systems in parking areas. The establishment of an

EV Supply Infrastructure has facilitated the implementation of a modular framework that enables the provision of mobility and grid services through a microgrid structure. The existence of indigenous direct current (DC) sources, such as PV systems and EV batteries, promotes the establishment of DC microgrids. These microgrids possess a shared DC link and have the capability to regulate the connection to the alternating current (AC) low-voltage network of the local distributor. The research presents optimal DC microgrid planning for EV supply infrastructure. For each DC microgrid setup, two primary pieces are devised and deployed in a two-step open-loop framework. The initial component involves a problem in mixed-integer linear programming, wherein the aim is to minimize the overall expenses of microgrid over its lifespan while adhering to appropriate limitations. The subsequent section entails a reliability assessment, wherein a rule-based curtailment is executed utilizing a multi-state matrix methodology. The impact of anticipated energy deficit on overall expenses is assessed across varying degrees of energy storage integration.

The paper [25] examines the increasing apprehensions regarding carbon footprints and greenhouse effects, which have prompted the creation of Evs as a means to mitigate carbon emissions produced by conventional petrol and diesel-based road transportation systems. The proliferation of Evs may potentially result in a significant strain on power systems in the coming years. The paper describes coordinated EV charging strategies for reducing the potential impact on power systems caused by EV charging load, and it highlights much research that have analysed this impact. The article additionally introduces optimal techniques for charging and discharging that aim to minimize charging expenses or maximize profits from discharging, specifically in the context of V2G systems. The present study puts forth a methodology aimed at optimizing the demand of power systems in response to the load generated by EV charging. The aim is to reduce fluctuations in power consumption over a period to enhance the efficiency of power system assets. The present study puts forth a methodology aimed at optimizing the demand of power systems in response to the load generated by EV charging. The employed methodology utilizes the Sequential Quadratic Programming (SQP) algorithm for the purpose of resolving the Quadratic Programming problem. The SQP algorithm is executed utilizing the optimization toolbox with conventional settings in the MATLAB software. The findings indicate a gradual reduction in demand profile fluctuations as the penetration levels of Evs increase from 10% to 50%. The article additionally outlines the optimal techniques for charging and discharging to minimize charging expenses or maximize profits from discharging, commonly referred to as V2G. The proposed methodology does not consider PV, it would have been great to see the optimization of power systems due to increasing power load by EV with PV integration.

The paper [26] explores the most efficient dimensions for renewable energy sources (RES), such as rooftop PV panels, WT, and battery storage systems, within the context of a smart home (SH) that incorporates a plug-in electric vehicle (PEV). The analysis considers both vehicle-to-home and home-to-grid operations. The study presents a proposition for a home EMS that operates on a set of rules. The system utilizes Monte Carlo simulations and particle swarm optimization to determine the most suitable sizes of renewable resources and BES. A Monte Carlo simulation is a computational technique employed to estimate the likelihood of different outcomes in situations involving uncertain variables. Monte Carlo simulations are utilized to elucidate the ramifications of risk and uncertainty within prediction and forecasting models. The objective is to minimize the annual cost of household electricity. Input data is generated considering the probabilistic characteristics of wind speed, irradiance, temperature, load, electricity rate, and PEV availability. This study presents an optimal sizing approach for rooftop PV, WT, and BES systems in a SH with PEV integration. The proposed method employs a rule-based algorithm with a multiple classifier system and PSO to determine the near-optimal component sizes. The performance of the SH is evaluated through its operation, and the cost of the system is calculated based on the determined sizes. Additionally, sensitivity analyses are conducted to investigate the impacts of maximum daily electricity export, rate of battery charge and discharge, as well as the maximum capacities of PV, WT, and BES in their optimal sizes. The simulations demonstrate that the implementation of PV and BES technologies will result in substantial yearly cost savings and a decrease in the LCOE. Furthermore, the integration of WT will yield further reductions in both annual cost and LCOE. The study additionally conducts sensitivity analyses to evaluate the effects of various factors such as the maximum daily electricity export, rate of battery charge and discharge, and maximum capacities of PV, WT, and BES on their optimal sizes. According to the analyses conducted, it is feasible to completely remove BES from the energy system of an SH that utilizes PEV, resulting in a decrease in the yearly electricity expenses. The proposed method does not consider grid constraints that most of the countries have, so that grid would not overload due to increasing efficiency of renewable energy and household capacity to sell electricity back to the grid.

b. P2P energy sharing between households without Evs.

Table 2.3 Literature on P2P energy sharing between households without Evs.

| Ref. | Applied method | Obj. Function | Constraint Considered | Approach | Optimal sizing | PV | BES | Region |
|---|---|---|---|---|---|---|---|---|
| **[3]** | MILP | Aim is to maximize household energy savings by considering real-world constraints and market signals. | Sensitivity of input parameters | Trading | ✓ | ✓ | ✓ | Not specified |
| **[27]** | Elecbay | Enable a significant integration of sustainable energy sources into the electrical power system. | The energy trading should not cause any security issues in the Microgrid | Game theory | × | × | × | Not specified |
| **[28]** | OpenDSS | Examine the effects of peer-to-peer energy trading on the operational performance of networks, specifically in relation to voltage regulation, power quality, and network congestion. | Study postulates that the rationality and self-interest of all participants in the local energy trading platform are presumed, although this may not necessarily reflect the reality of the situation. | Blockchain-based distributed double auction trade mechanism | × | ✓ | ✓ | Ireland |
| **[29]** | Coalition game model | Encourage prosumers to take part in energy trading on the smart grid, you should propose a game-theoretic method to P2P energy exchange. | Trading is a theoretical model and has not been implemented in a real-world setting | Game theory | × | × | ✓ | Not specified |
| **[30]** | M-leader and N-follower Stackelberg game | Study proposes a new game-theoretic framework for facilitating peer-to-peer energy trading among prosumers within a community microgrid. | The paper assumes that all prosumers are rational and have perfect information about the market. | Game theory | × | ✓ | ✓ | Singapore |
| **[31]** | Value at Risk tool | Examines bidding strategies for residential buildings in P2P energy trading. | The trading of energy in residential microgrids through P2P mechanisms is subject to certain limitations, including inflexibility and inequitable trading constraints. | Bidding | × | ✓ | ✓ | China |
| **[32]** | Numerical Simulation | Optimize the financial gains of proprietors of decentralized energy resources with due consideration to the convenience of end-users and the unpredictability of solar PV systems. | Empirical investigations utilizing simulated residential consumers may necessitate additional validation and enhancement in authentic field settings | User Centric P2P energy trading | × | ✓ | ✓ | Australia |
| **[33]** | CPLEX 12.6.1.0 | Acquire a solution that is socially optimal, which entails maximizing the overall benefits of all households that are involved in the process. , | Optimization of costs within a microgrid through the implementation of peer-to-peer energy trading among SH. | ECO trade | × | ✓ | ✓ | Canada |
| **[34]** | GAMS Software | Tackle the issue of energy sharing within the microgrid of P2P PV prosumers and enhance the efficacy of utilizing locally produced sustainable energy. | The suggested model assumes a continuous variable load shifting paradigm and a set price for energy purchase from the main grid. These assumptions may not always be accurate and may affect the proposed mode's correctness | Two stage trading approach | × | ✓ | ✓ | China |
| **[35]** | Not specified | Aims to investigate the potential benefits of P2P energy trading as a viable | Potential impacts of PTP energy trading on various stakeholders | Virtual net metering | × | ✓ | × | Australia |

solution to address the misalignment between the economic value of distributed energy technologies.

Most of the existing paper has not found optimal sizing for P2P energy sharing except a few like paper [3]. This paper has found optimal solution of components for P2P energy sharing. This study utilizes MILP for P2P energy trading Most of the existing paper follow game theory approach or trading mechanism to reduce the electricity cost between the houses unlike this paper which has completely different approach that is mutual energy sharing fixed TOU rates to reduce electricity cost. Paper [27]elucidates the utilization of Elecbay, a peer-to-peer energy trading platform, for enabling the exchange of energy directly between energy consumers and prosumers within localized power networks. The four-layer system architecture model that has been proposed can serve to classify and delineate the fundamental components and technologies that are integral to P2P energy trading. The utilization of the proposed bidding system in P2P energy trading can facilitate the simulation of P2P bidding activities between energy consumers and prosumers via the energy trading platform “Elecbay” by means of game theory. Game theory examines strategic decision-making, comprising a vast array of principles and strategies. On the “Elecbay” software interface, peers (either energy sellers or energy buyers) trade energy with one another. Energy vendors list their excess energy over a thirty-minute period for sale. Energy purchasers peruse the available products and then place orders. After orders are placed by peers, Elecbay, DSOs, and energy suppliers either approve or reject them. Each order’s acceptance or rejection is determined by network constraints, such as voltage excursion, thermal saturation, etc. After the acceptance or rejection of an order, each peer generates or consumes the quantity of energy specified in accepted orders. The distribution network provides delivery of energy. Elecbay is the supplier of energy balancing services. Smart meters document the actual energy generation and consumption of each peer. The simulation results indicate that P2P energy trading can mitigate energy exchange between the Microgrid and the utility grid, while also balancing local generation and demand. This suggests that P2P energy trading has the potential to enable a significant integration of renewable energy resources into the power grid. The paper [3] proposes an optimization model for rooftop PV systems with battery storage in the context of P2P energy trading. The study indicates that households can save up to 28% by using a large PV-battery during weekdays. However paper [28] proposes that a moderate degree of peer-to-peer trading does not exert substantial effects on the operational performance of the network. As per  the paper [28],a centralized double auction mechanism lacks robustness due to the potential failure of the auctioneer, which could result in the complete breakdown of the trading process. The auctioneer may conspire with others to change the outcome. The blockchain-based distributed double auction presented in the study allows any peer to function as the auctioneer, and the blockchain mechanism assures that each peer behaves legitimately.  Blockchain eliminates the need for a third party to authenticate a transaction between two parties. Encryption and distributed consensus system protect blockchain transaction records. The OpenDSS distribution network simulator is chosen for this objective due to its open-source nature and its specific design for detailed 52imulate52 of three-phase low voltage networks. Additionally, it possesses the capability to interface with Python or MATLAB software, further enhancing its versatility. Contract flexibility is not discussed in this paper i.e., how easy it is to enter the network and get out of the network and what would be the consequences for the network due to frequent in and out of the house in the network.

The paper [29] presents a motivational psychology framework that can be utilized to design a P2P energy trading technique within the context of a smart grid. The utilization of the motivational psychology framework has proven to be a successful approach in promoting the active involvement of prosumers in peer-to-peer energy trading. This application contributes to the sustainability and overall benefits of the electricity network.  The authors offer a coalition game model for peer-to-peer energy trading that considers prosumers' preferences and desire to collaborate. The model is evaluated using simulations, and the results show that the proposed approach can help prosumers reduce their electricity cost and carbon dioxide emissions. The paper [30] presents a noncooperative game theoretic model for ascertaining the electricity cost in peer-to-peer energy exchange among prosumers within a community microgrid.  The present model conceptualizes the pricing competition among sellers as a non-cooperative game, wherein each seller endeavours to optimize their profit by determining the electricity price. The dynamics of the interaction between sellers and customers can be represented using a Stackelberg game framework, where the sellers serve as leaders and the buyers behave as followers. The sellers might be considered as the various leaders, while the purchasers can be seen as the varied followers. The Stackelberg game establishes a connection between the evolutionary game and the non-cooperative game. The cost of electricity is determined based on the equilibrium price that is reached after the iterative algorithm converges. Simulations show that the proposed model can handle P2P energy trading in a small community microgrid with PV and ESS. Neither of these papers has investigated optimal sizing on components and paper 4 has missed PV. The effects of using RES in the network would give more information to the reader for best solutions.

The paper [31] presents a bidding strategy consisting of two stages for P2P energy trading within residential microgrids among small household entities. The objective of the proposed methodology is to establish equitable competition within the market, provide economic advantages for stakeholders, and attain self-reliance in the microgrid. In addition, the paper presents a trading price forecasting model and a risk analysis instrument aimed at assisting individuals in enhancing their decision-making abilities during the bidding process. The research utilizes the value at risk (VaR) methodology, a quantitative approach that estimates the potential maximum loss on an investment within a particular time frame and with a predetermined level of confidence. The efficacy of the proposed approach has been validated via case studies involving numerous households participating in a residential microgrid. The paper [32] presents two user-centric pricing techniques for residential microgrid P2P energy trading: Unified Pricing (UP) and Identified pricing (IP) strategies. The IP system identifies each energy transaction with a separate time based on consumers offer, while the UP strategy uses a centralized market pool to set the market clearing price at regular intervals. The primary purpose of the research is to optimize the financial benefits that owners of decentralized energy resources receive, considering both the needs of end-users and the unpredictability of solar PV systems to the greatest extent possible. The auction algorithm solves energy allocation in community microgrids to maximize social welfare. The proposed methods are tested using 15 simulated residential users in numerical studies. Neither of these papers has used practical real time data for the load of house to find the real solution and contract flexibility is not clear in the research. This paper uses real time data with practical assumptions as well as flexibility of contract is discussed in detail.

The paper [33] presents an algorithm called ECO-Trade, which aims to optimize energy costs in a P2P energy trading system among SH within a microgrid. The algorithm is designed to achieve near-optimal results. The algorithm is founded upon a multi-objective optimization problem which endeavours to minimize the aggregate cost of all households participating in the trading process. The study employs authentic datasets to assess the efficacy of the suggested algorithm and contrasts it with the optimal model. The findings indicate that the ECO-Trade algorithm produces optimal solutions within a short time frame, rendering it a feasible approach for addressing real-world issues. The article additionally tackles the issue of inequitable cost allocation by guaranteeing Pareto optimality. The problem instances were solved using CPLEX

12.6.1.0. Like most of the other P2P energy sharing papers, this paper also has not investigated optimal components sizing.

The paper [34] proposes an internal pricing mechanism based on dynamic pricing for demand response in microgrids of P2P prosumers. The pricing mechanism that has been proposed aims to enhance the utilization of renewable energy generated within the local vicinity, while concurrently decreasing the overall cost of energy. It introduces a model for energy sharing among P2P prosumers in microgrids, which is based on demand response and pricing mechanisms. The proposed methodology employs a dual-phase trading strategy, wherein the energy sharing service provider (ESP) serves as a mediator between the prosumers and the primary grid. In the first stage, the ESP purchases energy from the main grid and sells it to the prosumers at a fixed price. In the second stage, the ESP buys excess energy from the prosumers and sells it back to the main grid at a dynamic price based on the real-time market price. Necessary constraints such as grid constraints, energy sharing constraints, battery degradation and salvation value and its effects to prosumers in the network is not clear in the paper which is made clear in this paper.

The pricing mechanism for P2P transactions, as proposed in the paper [35]utilizes the disclosed preferences of P2P participants to ascertain both the traded quantity and the prevailing market price. The objective of this research is to examine the possible advantages of P2P energy trading as a feasible approach to mitigate the discrepancy between the economic value of distributed energy systems. The reservation price at which marginal buyers and sellers are prepared to trade is used to set the P2P market price for all trades in a 30-minute period. This approach bears a close resemblance to the revealed preference approach that is employed by the Australian Energy Market operator (AEMO) within the wholesale market for the purpose of ascertaining a market clearing price and quantity. This approach is deemed advantageous due to its ability to facilitate effective dispatch while simultaneously mitigating market distortion. Moreover, it guarantees that all individuals involved in trading are either in a superior position or in an equivalent position as they would have been if they had not taken part. One of the main disadvantages of trading mechanism in P2P energy sharing is when there are less participants in the network, then the cost fluctuates a lot. Buyer and seller both will be unknown for the cost they will buy or sell. It will vary depending on the demand for electricity. Therefore, mutually agreed rate for energy sharing might be potential solution for this problem which is investigated in this research.

c. P2P energy sharing between households with Evs.

Table 2.4 P2P energy sharing between households with Evs.

| Ref. | Applied method | Obj. Function | Constraint Considered | Approach | Optimal sizing | PV | BES | Region |
|---|---|---|---|---|---|---|---|---|
| **[1]** | Supply-Demand Ratio | Focus on the complementarity of P2P with embedded PV generation and Evs when examining the benefits of P2P energy trading in a grid-connected microgrid community of dwellings. | The55imulateon assumes all households are rational and operate in their own self-interest, which may not be true. | Trading | ✓ | ✓ | ✓ | United Kingdom |
| **[2]** | multiagent-based simulation framework | The objective of this study is to establish a systematic index system for the assessment of P2P energy sharing mechanisms, considering both economic and technical aspects. | Generalizability of the findings to other contexts and mechanisms may be limited | Trading | × | ✓ | ✓ | Great Britain |
| **[12]** | Energy Control System | Aims to examine the conduct of consumers within the power system by utilizing a non-cooperative game model. | Assumptions made in the paper may not hold in real-world scenarios and could affect the effectiveness of the proposed solutions | Non cooperative game model | × | ✓ | ✓ | South Korea |
| **[13]** | FEATHERS Model | Proposes the development of a peer-to-peer energy trading system that facilitates the exchange of electricity between two groups of Evs. The system aims to mitigate the impact of charging on the power grid during peak business hours. | The system assumes that all Evs have the same battery capacity and charging rate, which may not be the case in reality | Trading | × | × | ✓ | Belgium |
| **[35]** | MILP | Aims to explore the feasibility of utilizing flexible loads to consume renewable energy, particularly in the face of unpredictable power supply in the local market. Additionally, this research seeks to propose a peer-to-peer market framework and trading mechanism that can facilitate the consumption of stochastic generation by flexible loads within the local community. | The model implies that all dispersed generating and flexible loads are smart grid-connected, monitored, and managed by ICT. Not always. | Bidding | ✓ | ✓ | ✓ | England |
| **[36]** | CvaR Condition | Proposes a comprehensive | The proposed coordinated | Not specified | × | × | ✓ | Not specified |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | al Value at Risk | strategy for the integration of V2G services with energy trading, aimed at a load-serving entity that possesses both wind and thermal generating units and caters to a load with substantial EV penetration. | approach is based on certain assumptions and simplifications, such as the normal distribution of wind power ramping rate and the quadratic cost function for thermal units. These assumptions may not hold true in all scenarios and may affect the accuracy of the simulation results | | | | |
| **[37]** | MATLAB | Conducts an economic analysis of the advantages offered by algorithms in comparison to conventional vehicles that ICE. The comparison is made through the application of a NPV assessment | The algorithms proposed in the paper are based on a forecast of future electricity prices, which may not always be accurate | Not specified | × | ✓ | ✓ |

The paper [1] emphasizes the significance of decarbonizing the power grid and the role of P2P energy trading in accomplishing this objective. The paper concentrates on the advantages of P2P trading for households with PV and EV ownership and models P2P energy sharing for a local microgrid of 50 PV and EV owning households at varying penetrations. The paper assesses the level of energy autonomy achieved by microgrids and quantifies the economic benefits for households. The findings indicate that P2P trading can effectively reduce households' reliance on grid electricity and generate financial savings. The study models P2P energy sharing in a microgrid of 50 households with PV and EV ownership at different levels of adoption. The authors evaluate the benefits of P2P in conjunction with V1G, V2H, and V2G chargers. The utilization of community energy storage (CES) is also being contemplated as a substitute for energy storage in EV batteries. The paper [2] assesses the efficacy of diverse P2P energy sharing mechanisms utilizing a simulation framework that is based on multiagent systems. A multiagent system (MAS) is comprised of numerous autonomous agents that engage in interactions, negotiations, and cooperation to accomplish their own objectives. The use of MAS is widely regarded as appropriate for the execution of modelling and simulation activities in the field of power engineering, owing to its adaptable and expandable framework. The assessment criteria comprise economic and technical parameters, and the suggested methodologies were implemented to model and assess three extant P2P energy sharing mechanisms catering to domestic consumers in present and future scenarios of the United

Kingdom. The assessment criteria comprise of three economic indices, namely value realization, willingness to participate, and equality, as well as three technical indices, namely energy equilibrium, power uniformity, and self-reliance. They are standardized and put together to show the general performance. The paper mentions that Evs are one of the demand-side resources that can be controlled through direct control in a centralized coordination framework. My study is first to optimize PV and BES systems for energy sharing between two households. FiT and retail price are fundamental assumptions. PV and BES households benefit from selling electricity to H1 rather than the grid at a lower rate. The focus of this study is cantered on the optimal sizing of PV-BES, the establishment of mutually agreed energy sharing arrangements between households, the provision of contract flexibility, the utilization of real-time data, and the implementation of time-of-use rates for the purchase, sale, and sharing of energy.

The study in the paper [12] examines a hierarchical pricing structure for electricity consumers within an electrical grid. The study postulates that customers exhibit substantial load demands and does not account for scenarios wherein the aggregate demand of the power grid is negative. The present investigation offers an all-encompassing characterization of the payoff function of a customer, predicated on a multi-tiered billing structure. The paper further provides a set of equations that accurately represent the base rate, penalized rate, and wholesale price of electricity. The present study develops a non-cooperative game-theoretic model to examine the conduct of consumers within the power system. In the non-collaborative approach, we consider the energy scheduling problem as a non-cooperative game involving self-interested customers. Each customer independently decides on their load scheduling and energy trading strategies to maximize their individual profit. To address the issue of unfairness between heavy and light customers in the non-collaborative approach, implementing a tiered billing scheme is suggested. This scheme would allow for the regulation of electricity rates based on customers' varying levels of energy consumption. The present investigation ascertains the existence and uniqueness of Nash equilibrium in the game, which are essential attributes of non-cooperative games. The manuscript additionally presents numerical instances to demonstrate the efficacy of the suggested hierarchical pricing system. In conclusion, the study posits that the suggested approach has the potential to incentivize consumers to curtail their electricity usage during periods of high demand, thereby enhancing the overall efficacy of the power grid. It distinguishes itself by incorporating various factors such as mutually agreed energy sharing between houses and considering real life constraints such as grid constraints, battery degradation and salvation value of components. The paper [13] introduces a novel peer-to-peer energy trading mechanism that facilitates the exchange of electricity between two distinct groups of Evs. This system is designed to mitigate the adverse effects of charging on the power grid during peak business hours, while also providing economic benefits to all participating users. This study presents a proposition for the creation of a peer-to-peer energy trading framework that enables the transfer of electrical power between two distinct clusters of electric vehicles. The primary objective of the system is to reduce the adverse effects of charging activities on the power grid during periods of high demand, particularly during peak business hours The present system employs an activity-based framework to anticipate the day-to-day schedule and travel patterns of a simulated population residing in Flanders (Belgium). The drivers are initially categorized into three groups, but the system concentrates on the two pertinent groups: those who finish all their daily trips with surplus energy in their batteries and those who require charging their vehicle during certain scheduled stops within their daily trips. The drivers could optimize their energy expenditure in both temporal and spatial dimensions, considering the prevailing electricity rates of the grid and their individual mobility limitations. Customers with spare battery power can sell it to others who need it during their daily commutes at a price set by an aggregator, who also considers the demand for charging services in the area. The suggested trading system has the potential to cut these drivers' energy costs by as much as 71% during certain time periods and geographical areas. This study first optimizes PV and BES systems for energy sharing between two residences. A grid-tied home that shares electricity is also getting a rule-based home EMS. This paper also compares the effects of different Evs with different battery capacities in houses and networks.

The [35] paper discusses the increasing use of DER in the modern distribution system. From the supply perspective, PV and wind power are exchanged via a centralized electricity market or reused by vendors, which may give rise to issues such as voltage regulation, network losses, and gridlock. Evs and ESS have the capability to adapt their energy consumption patterns to meet the requirements of the system on the demand side. The paper additionally notes that current demand-side response initiatives are executed via intermediaries such as agents or aggregators. The article presents a P2P market framework and trading mechanism aimed at incentivizing the utilization of stochastic generation by adaptable loads within a given locality. The paper analyses and quantifies the uncertainty of PV generation and defines the flexibility characteristics of loads. The consumption properties of flexible loads against PV generation are analysed. The paper also proposes Cumulative Expected Deviations to measure the PV uncertainty to be balanced by reserve capacity. This paper distinguishes itself by incorporating various factors such as mutually agreed energy sharing between houses and contract flexibility.

The paper [36] proposes a method for coordinating V2G services with energy trading for a load-serving entity (LSE) that owns both wind and thermal generating units and serves a load with significant EV penetration. The aim is to optimize the anticipated profits of the LSE while simultaneously mitigating trading risks arising from market and wind-related uncertainties. The study proposes that the management of trading risks can be improved through the synchronization of stochastic supply scheduling with responsive demands. The research utilizes the CvaR tool for risk assessment. Conditional Value at Risk (CvaR), also referred to as expected shortfall, is a measure used to assess the level of tail risk present in an investment portfolio. CvaR is calculated by averaging the losses that occur beyond the VaR cutoff point in the distribution of potential returns. These losses are extreme and are given weights in the calculation. CvaR is a valuable tool utilized in portfolio optimization to enhance risk management strategies This paper considers the responsive demand of EV owners in the context of unidirectional V2G services. The present study suggests the synchronization of V2G services with energy trading as a means of mitigating trading risks. The utilization of V2G services as an aggregated load is leveraged to mitigate associated risks through enhanced flexibility. The article proposes that the adoption of unidirectional V2G technology is a promising initial measure towards the complete implementation of V2G, as it necessitates no additional hardware beyond the conventional EV charging station. It has not investigated the optimal components solution that is needed for maximum efficiency for household which is done in this paper. Additionally, it also has not clearly mentioned that it has used real time data of houses and Evs for its simulation and results.

The paper [37] explores the notion of plug-in hybrid electric vehicles (PHEVs) as a potential remedy for mitigating the transportation industry's reliance on petroleum. The drive system of such a vehicle consists of an electric motor, an ICE, a battery, and a device for connecting the vehicle to the utility grid. During most of the usage, the vehicle operates in an all-electric mode. The research presents two algorithms to solve peak load rise and grid overload if PHEVs are widely deployed without control. Both systems employ dynamic programming to discover the car owner's economically ideal choice depending on future electricity prices. The first algorithm optimizes charging time and energy flows, reducing daily electricity cost without increasing battery degradation. The second algorithm uses vehicle-to-grid support to profit from ancillary service marketplaces. The paper assumes Optimal charge control works best in a deregulated, market-based power industry with day-ahead and spot market prices. If grid support is considered, auxiliary services should be priced by capacity rather than energy generation. Although grid constraints are considered, SOC constraints and BES degradation are not considered. Comparison with different PHEVs existing in the market would have made research clearer. These factors are considered and applied in this paper.

d. Technical Challenges:

The intricate matter of reconciling local power and energy demand in Microgrids featuring a substantial integration of renewable energy resources poses a formidable challenge that necessitates meticulous deliberation [27]. The scholarly article referenced as [3] presents a significant contribution by introducing an optimization framework that incorporates practical limitations and market indicators. This model presents a prospective resolution to the current predicament by optimizing energy conservation in households. Additionally, it examines the impact of input parameters' sensitivity on the optimal solutions. The present analysis holds significant importance in tackling the challenge of determining the optimal parameters that can lead to the highest possible savings. Through comprehending the various factors that impact outcomes, scholars and professionals can make informed judgments and refine the system to attain superior outcomes.

Apart from the need to maintain a balance between power supply and demand, it is imperative to establish a mechanism that efficiently manages transmission and distribution losses. Maximizing the efficiency of the microgrid system is contingent upon minimizing energy losses during delivery to consumers. It is imperative to meticulously address this aspect in order to mitigate inefficiencies and enhance the utilization of sustainable energy resources [30].

Additionally, a crucial factor to contemplate in microgrids pertains to the identification of the market clearing price and energy distribution within a peer-to-peer marketplace. Developing an equitable and lucid mechanism for ascertaining prices and distributing energy in a decentralized marketplace poses a formidable undertaking [32]. Efficient mechanisms for price discovery and energy distribution can facilitate the establishment of a sustainable and economically viable microgrid ecosystem.

Through a systematic approach to addressing multiple facets, researchers and professionals can achieve notable advancements in the realm of microgrids featuring substantial integration of RES. The present study advocates for a comprehensive strategy that considers the enhancement of energy conservation, the management of transmission and distribution inefficiencies, and the implementation of equitable market frameworks, thereby fostering microgrid systems that are both more sustainable and more effective.

### 2.2.3 Recent Development and Trend

The emergence of P2P energy trading and optimal sizing has brought to the fore the necessity for additional investigation into the economic and societal implications of these trading systems, alongside the creation of more effective and protected P2P energy trading frameworks [27]. To tackle these challenges, several advancements have arisen.

A significant advancement in the field pertains to the utilization of MILP in the context of building EMS for smart buildings that are connected to the grid. The systems are designed to efficiently regulate and manage the distribution of energy throughout the building, considering a range of constraints. The integration of P2P energy trading functionalities into these EMSs facilitates the effective engagement of buildings in regional energy markets, allowing for the exchange of surplus energy with nearby buildings or the power grid. The utilization of this approach is optimized to achieve maximum energy utilization and cost savings, thereby contributing to the economic advantages of P2P energy trading [17].

Another recent development pertains to the utilization of authentic smart-metering data for the purpose of incorporating PV uncertainty in P2P energy trading systems. PV systems are susceptible to fluctuations caused by meteorological factors, resulting in indeterminate power generation. P2P energy trading platforms can make use of real-time smart-metering data to make precise predictions about PV generation and adapt energy trading strategies in real-time. The incorporation of PV uncertainty management into P2P energy trading improves the dependability and effectiveness of the process, guaranteeing the most advantageous employment of sustainable energy resources [38].

The exploration of the potential for bidirectional energy trading functionalities of Evs in P2P energy trading systems is currently receiving considerable interest. Evs can operate as energy consumers and energy storage devices, allowing for bidirectional power flow. The incorporation of Evs into P2P energy trading has the potential to enable the exchange of surplus energy produced by Evs to meet the energy demands of the local community or to put the excess energy back into the power grid. The integration of Evs not only improves the efficiency of their usage but also contributes to the enhancement of flexibility and stability in P2P energy trading systems [12].

The rise of peer-to-peer energy trading highlights the importance of examining the economic and societal implications, developing efficient platforms, and integrating advanced techniques such as MILP-based EMS, PV uncertainty reduction, and bidirectional EV energy exchange. Through the consideration of these factors, scholars and professionals in the field can realize the complete capabilities of P2P energy trading, fostering a more environmentally conscious and distributed energy environment.

### 2.2.4 Potential Direction for Future Research

The paper [3] suggests numerous data analytics and optimization improvements. Advanced data analytics can simulate dynamic phenomena such as weather and human behaviour. These methods help researchers understand the complicated dynamics of these occurrences, improving predictions and decisions. The study also recommends using a sophisticated method such as the Alternating Direction Method of Multipliers (ADMM) to locate optimal or near-optimal solutions for large-scale instances within a reasonable runtime. ADMM can parallelize and converge faster by decomposing optimization problems into smaller subproblems. These approaches can improve data analytics and optimization, leading to better models, algorithms, and results in a variety of applications.

As posited in paper [28], the subject of interest concerns the analysis of the potential impacts of peer-to-peer energy trading and regional electricity trading mechanisms on the governance, operation, and planning of electricity distribution grids. The aim of the upcoming study is to perform a thorough analysis of the effects of various peer-to-peer energy trading mechanisms on the utilization of network assets, reliability, and power quality. The aim is to enhance the understanding of the implications of these mechanisms. Additionally, it emphasizes the necessity of expanding simulations to encompass community microgrids on a larger scale and utilizing optimization algorithms to enhance results. Through the utilization of these algorithms, scholars can attain superior outcomes concerning energy management and resource allocation within the microgrid framework.

In accordance with the discourse presented in paper [1], forthcoming investigations concentrate on the advancement of P2P market mechanisms that consider the intrinsic uncertainties linked to the generation of renewable energy and the prediction of energy demand, with the aim of tackling forecasting uncertainty. By considering these uncertainties, it is possible to develop trading mechanisms that are more resilient and precise, thereby guaranteeing the effectiveness and dependability of energy transactions in peer-to-peer markets. Furthermore, in paper [35], it is proposed to investigate the influence of P2P consumers who possess energy storage or demand response technologies. Comprehending the interplay between said technologies and P2P energy trading can yield valuable perspectives on the possible advantages of incorporating storage and demand response mechanisms to enhance grid stability, congestion management, and cost optimization. The examination of the distribution of local use of system fees among purchasers and vendors is imperative in guaranteeing equity and economic effectiveness in P2P energy transactions.

The paper [17] highlights the significance of accounting for the fluctuation in the accessibility of RES. Developing an EMS framework that considers the variability in RES availability facilitates improved strategic planning and informed decision-making to enhance energy efficiency and mitigate the effects of intermittency. The paper suggests that additional research is necessary to tackle physical obstacles such as overvoltage and congestion in power networks, as well as peer-to-peer energy sharing. Innovative systems and tactics can seamlessly integrate P2P energy trading while maintaining power grid stability.

#### 2.2.5 Conclusion on the review

To sum it up, the literature review consists of three parts. The first part of the literature review was single GCH with EV, energy trading within a singular grid-connected household that possesses an EV centre around the optimization of solar power consumption, the reduction of dependence on the grid, and the potential facilitation of energy exchange with neighbouring participants is reviewed. The initiative fosters self-reliance, the utilization of sustainable energy sources, and the effective incorporation of EV charging infrastructure into the domestic energy framework.

The second part of the literature review shed light on P2P energy trading without EV. Different studies were kept under review to explore how P2P trading is beneficial and how the true potential of renewable energy can be harnessed. The current system facilitates the ability of individuals who possess RES, such as solar panels or WT, to generate excess electricity and transmit it to other network participants who may require additional power. The adoption of a decentralized approach enables individuals to assume the dual role of energy producers and consumers, thereby fostering sustainability and diminishing dependence on conventional energy grids. By utilizing secure digital platforms, individuals could engage in negotiations pertaining to energy prices and transactions, thereby promoting equitable and transparent exchanges. Moreover, different trading approaches have been identified in the literature that includes game theory, non-cooperative game model, two stage bidding strategy and many more.

The third part of the literature review focuses on P2P with Evs. P2P energy trading utilizing Evs possesses the capacity to transform the energy sector by enabling individuals to engage in the energy market, encouraging the adoption of renewable energy, and cultivating a more sustainable and decentralized energy infrastructure. The benefits of peer-to-peer energy trading that incorporates EV are numerous. The cost efficiency of P2P trading is attributed to the elimination of intermediaries, which results in reduced transaction costs. This has the potential to offer buyers cheaper electricity prices. The optimization of energy resources can be achieved through the practice of prosumers selling their surplus energy, thereby enhancing the efficiency of their renewable energy investments and mitigating wastage. Purchasers could procure renewable energy resources, which may result in a significant decrease in their carbon emissions. The utilization of P2P trading can potentially aid in the balancing of the electricity grid through the redistribution of excess energy from regions with a surplus to those with a higher demand. This can result in a reduction of stress on the infrastructure of the grid. The decentralization of the energy system through P2P trading fosters energy resilience, as it enables local energy independence. This facilitates the development of self-reliant communities, particularly in situations of power outages or emergency scenarios.

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# Chapter 3. Effects of Energy Sharing and Electricity Tariffs on Optimal Sizing of PV-Battery Systems for Grid-Connected Houses

***Abstract*:** 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 the houses are evaluated. For optimization PSO is chosen for this study due to its ease of application and proven reliability in similar research. The results obtained using PSO are satisfactory for achieving optimal component sizing. The PSO algorithm exhibits a high convergence rate and is less reliant on the initial starting locations. In terms of calculation, it is also highly efficient. PSO also considers the design constraints and objective function and adjusts its approach accordingly Realistic hourly-arranged annual data of temperature, solar irradiation, and load consumption of two houses are used as the input data. For each scheme, results are compared with the situation when H1 does not have PV-BES and there is no electricity sharing. The results for different scenarios in each of the schemes are observed to make the study more practical. Sensitivity, operational and uncertainty analyses are shown for the scheme with the lowest COE.

***Keywords:*** battery storage, energy management system, energy sharing, electricity tariffs, optimal sizing, solar photovoltaic

**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 (%) |

## 3.1 Introduction

### 3.1.1 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 water waves, wind, and sun due to their zero-carbon emission ability. Among RE resources, solar rooftop 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]. It is estimated that in 2050, rooftop PV systems to increase about six folds in Australia.

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, 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 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 DER and supply the other consumers by the extra power [8]. The government of developed countries also takes great care of non-fossil fuel energy generation that making P2P a wonderful energy trading strategy [9].

Currently, the consumer uses 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 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 impacts in energy sharing.

### 3.1.2 Literature Review

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 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 has been 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 3.1 compares the current studies for energy sharing in terms of electricity tariff, mutually agreed price, optimal sizing, contract feasibility, and practical factors including grid constraint (GC), battery degradation (BD), incorporating real data (RD), and salvage cost (SC) of PV and BES. The electricity tariff is the mechanism considered in the paper that might be the flat or TOU tariffs. None of the paper has considered mutually agreed energy sharing price. Optimal sizing of the components was found in one paper. Although some paper mentioned about the impacts on grid due to overload of voltage but most of those papers do not consider the exact figure for power restriction to the grid. Contract flexibility is not discussed in the existing papers that how easy is it to get in and out of the contract and its impact in the network.

Table 3.1: Current studies summary for energy sharing.

| 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 | √ | √ | √ | √ | √ | √ | √ |

### 3.1.3 Contribution

To the best of authors' knowledge, none of the existing studies has investigated optimal sizing of components considering mutually agreed flat or TOU rate between the houses. 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 optimal sizing model for PV-BES system under energy sharing 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 rate 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 is seeking to minimise the COE of a prosumer which is H1 while decreasing the electricity cost for a consumer which is H2. All constraints are considered along with real annual data of temperature, solar irradiance, and load consumption of houses. Sensitivity analyses on grid constraint, possible load variation, and possible components cost variation are done for the best scheme with the lowest COE. In addition, operational analysis for two summer days and two winter days is done. Uncertainty analysis is performed by the percentage variation of temperature and solar irradiance, and COE for each house is observed.

### 3.1.4 Article Organization

The rest of the paper is structured as follows: Section 3.2 describes operational strategies for the HEMS under energy sharing and different electricity tariffs. Section 3.3 explains the optimization model including objective function, design constraints and solution approach. Section 3.4 includes system model and case study. Section 3.5 and 3.6 presents and discusses the obtained results. Section 3.7 presents different analyses done for the best scheme which includes sensitivity analysis, operational analysis, and uncertainty analysis. Section 3.8 contains the conclusion of the paper and future works.

## 3.2 Operational Strategy

The configuration of the system is shown in fig. 3.1. The figure shows two houses (i.e., loads), connection with the grid, and the connection 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 and can be a part of future research.

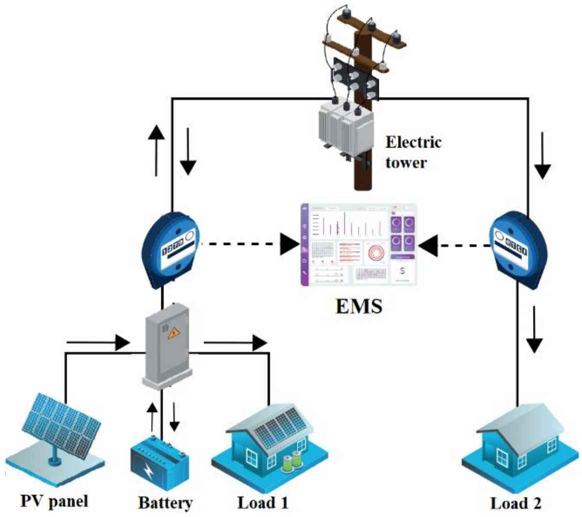



Figure 3.1: System configuration showing energy sharing between the houses.

The developed rule-based ems flowchart is shown in fig. 3.2. 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, the rules of the EMS 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 is greater than load of H1, the electricity rate is checked whether 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 remaining power charges the battery. In this case, there will be no power left to sell for H2 and dump power will be zero. H2 load demand will be satisfied by the grid.

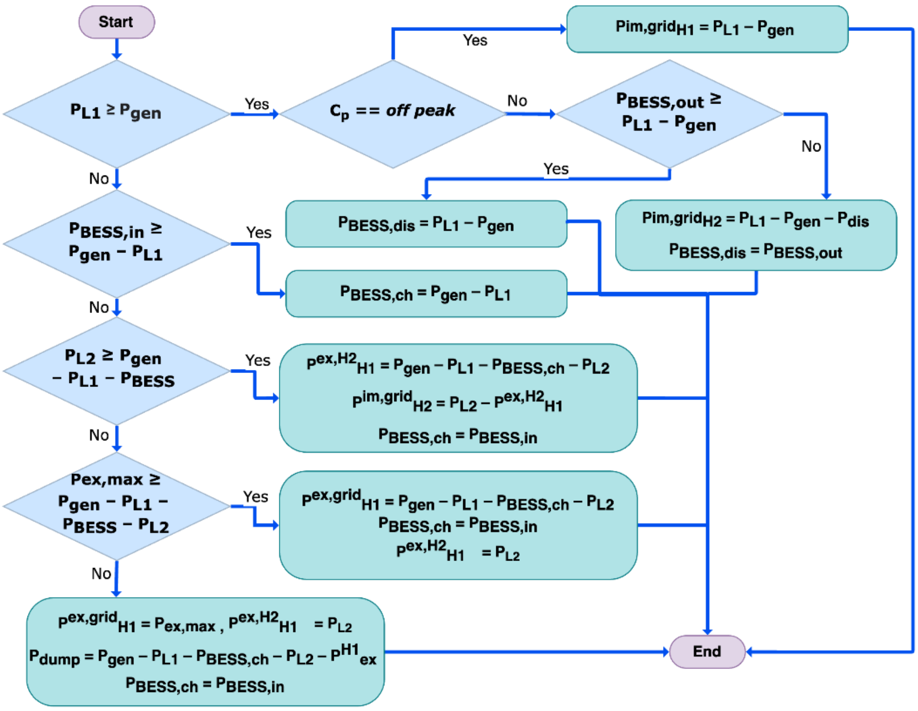



Figure 3.2: Flow chart of the rule-based energy management system.

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).

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

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

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

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:

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

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.

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

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

## 3.3 Methodology

### 3.3.1 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. The model used to calculate the optimal size of components is clarified in this section. 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:

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

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:

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

Components present replacement cost can be calculated as follows:

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

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

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

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

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

$$DOD(t) = 1 - SOC(t) \quad (18)$$

To determine degradation of the battery, DOD and its associated number of cycles should be found out. Rain flow cycle counting algorithm was used for this paper to pull out the battery cycles data from the yearly 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 © the experimental model used to find out the battery degradation was calculated as a function of DOD as follows [25]:

$$BD(c) = \frac{20}{33000. e^{-0.06576.DOD(t)} + 3277} \quad (19)$$

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:

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

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.

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

### 3.3.2 Net Present Cost

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

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

Whereas H2 does not have system component, its NPC would be same as its NPC of electricity as follows:

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

### 3.3.3 Design Constraint

Energy sharing constraint refers to the limitations or restrictions imposed on the energy sharing between prosumers with distributed energy resources (DER). The energy sharing mechanism takes network limitations and fairness among prosumers into account. This indicates that energy sharing is subject to the physical constraints of the network, such as power transfer limits for transmission lines which is considered in this study by paying reasonable amount to the grid.

Battery energy storage (BES) degradation, battery salvage revenue, and EV charging characteristics are all real-world variables that reflect the realities of homes with EVs and renewable energy. Maintaining synchronization and equilibrium in a power system, both under normal and perturbed conditions, is what we mean when we talk about stability.

Time-of-use tariffs rate are used but consumers are not forced to use electricity when rate is lowest, for example during daytime when electricity generation is highest. If constraints are applied in this case, it may have drawbacks including difficulties altering consumption habits to meet tariff periods. If their daily habits or business processes are rigid, customers may struggle to switch to off-peak hours. Time of use rates may require users to buy equipment to monitor and manage their energy use, which can be expensive. Following represents the constraints suitable for this study.

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

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

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

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

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

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

### 3.3.4 Optimization Procedure

This model can be optimized in MATLAB by using the tools available in software, but particle swarm optimization (PSO) is used because it is simple to use and is proven for its reliability in this kind of study. The results obtained with the help of PSO is approved for the optimal sizing of the components in [26-27]. In addition, different research done for power system planning has also used similar method and achieved efficient result [1-6]. PSO depends less on initial points and has very high convergence rate. It also has high computational efficiency [28]. Fig. 3.3 shows the flow chart for the optimal sizing of components using PSO.

Research has shown that PSO exhibits superior performance in terms of both efficiency and cost-effectiveness when compared to alternative methods. Furthermore, it has the potential for parallelization. Furthermore, the optimization process does not make use of the gradient of the problem. In contrast to conventional optimization techniques, PSO does not necessitate the problem to possess differentiability. The present study serves as a benchmark model, as it uniquely combines the areas of EVs, energy sharing, and optimal sizing. It is important to note that there is a lack of existing research that directly compares these three aspects. Hence, the examination of the PSO in relation to other optimization algorithms falls beyond the scope of this study.

To achieve the optimal solution large number of generation and population are selected so that PSO can search in a wide space and finally achieve the global solution. The total number of generation and population used in this study are 200 each which means simulation is run for 200*200 times in PSO to achieve optimal results. All data that includes whether data, irradiance data and load data are needed before simulation. Also, PSO checks the design constraint, objective function, and work accordingly. The whole simulation process is run 10 times for this study to make sure algorithm gave the optimal solution. When the simulation starts, each particle in the particle swarm has its own solution, the minimum one is considered as particles best position. When 10 generation is carried out, each generation has its own particles best position. Best solution out of those 10 best positions is global best solution. Other parameters of PSO algorithm such as cognition, social and inertia weights are considered 2, 2 and 0.5, respectively.

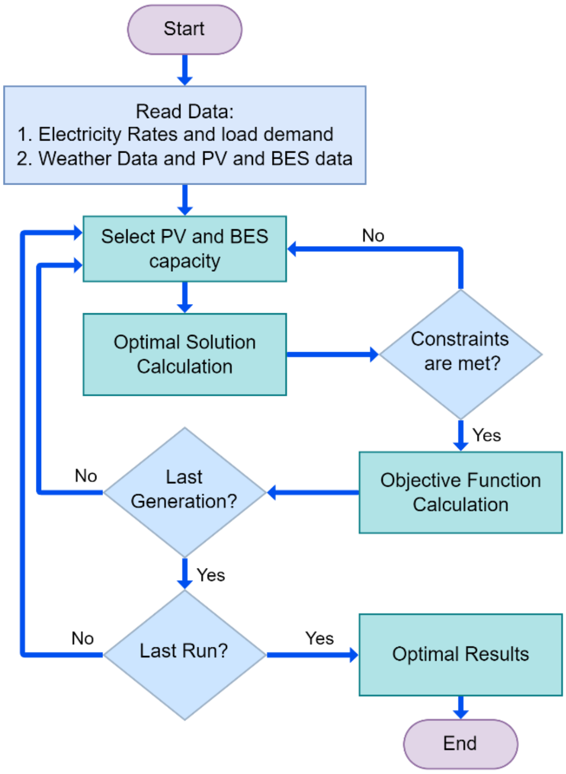



Figure 3.3: Flow chart of the optimization procedure.

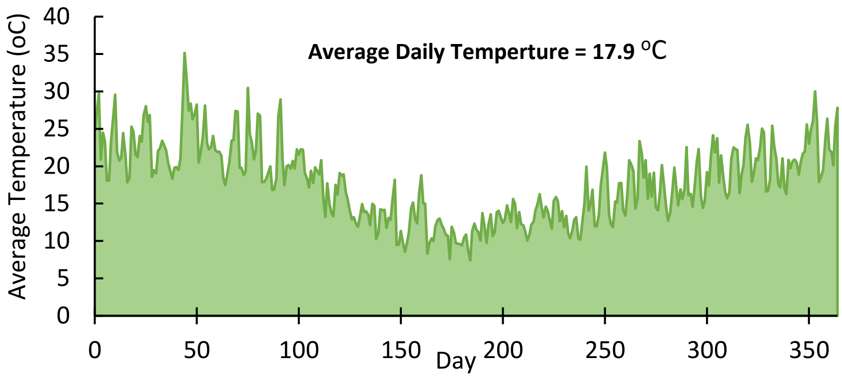
## 3.4 System Model and Case Study

The developed model in general in nature and can be used for any 2 houses if they agree for energy sharing with pre-fixed rate. Two grid connected houses located in South Australia is taken for case study.  The first part of the case study is done for each of the 8 schemes and optimal sizing of components as well as COE for both the house was investigated. And finally best scheme is selected for different analysis.

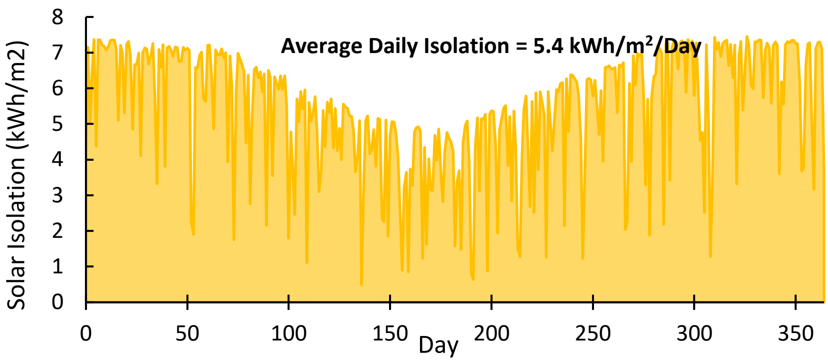
### 3.4.1 Data Collection for Optimal Sizing and COE Calculation

a. Meteorological Data

Solar irradiance data and temperature data was taken from Bureau of Meteorology of Australian government [29]. Fig. 3.4 shows the annual meteorological data. Fig. 3.4a shows the temperature which varies from 2.2°C to 41.9°C. Fig. 3.4b shows the solar irradiance which shows average irradiance of 5.4 kwh/m$^2$.




(a)

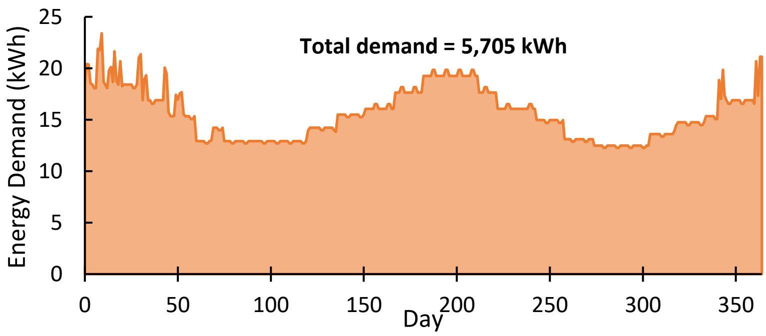



(b)

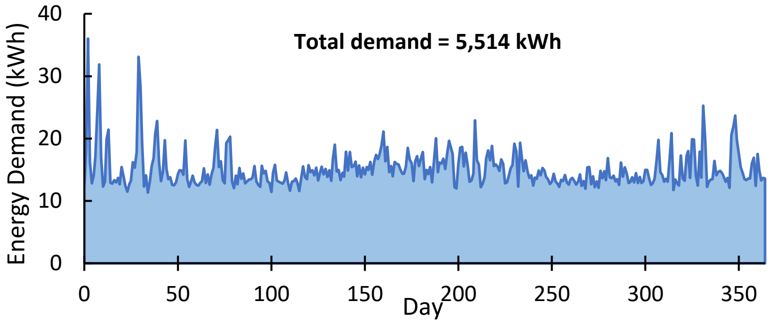
Figure 3.4: Yearly meterological data in SA, (a) Ambient temperature, (b) solar irradiance.

b. Load Data

Load consumption of H1 is taken from [3] and load consumption of H2 is taken from [30] which are shown in figs. 3.5a and 3.5b, respectively. The load demand varies from 0.3kw which is lowest to 1.6kw which is highest for H1 whereas for H2, the lowest load demand is 0.19kw and highest is 3kw. Power loss, while energy sharing, is neglected in this study due to insignificant loss and short distance between two houses.




(a)




(b)

Figure 3.5: Daily energy consumption in a year for: (a) H1, (b) H2.

c. Components Cost and Electricity Price

Table 3.2 shows the rates for electricity and components' data. Interest rate and grid escalation rate is 8% and 2% respectively. Retail price, flat Fit and daily supply of charge (DSOC) is taken from AGL website, one of the Australian energy providers [31]. Peak and off-peak tariff rate and all the mutually agreed rate was reasonably assumed for the investigation of this study.

Table 3.2: 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 OandM 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** | 1,500 $/kw | | |

### 3.4.2 Different Scenario Case Study

The second part of the case study will be done for 4 different scenarios shown in Fig. 3.6. 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. By 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. 1$^{st}$ contract period, 2$^{nd}$ contract period and no contract between houses are assumed for the investigation as shown in Fig. 3.6.

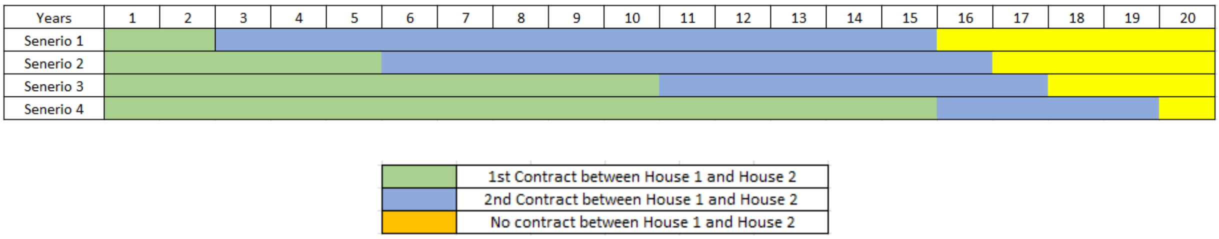



Figure 3.6: Considered scenarios for the duration of P2P sharing contracts between the houses.

## 3.5 Results and Discussion for Flat rates

### 3.5.1 Optimization Results and Discussion

PSO is run 20 times with 100 generation for each run. We selected the best run with minimum objective function. In this case, the optimal solution was achieved similar for all runs. Table 3.3 lists the optimal capacity of PV and Battery Storage system, along with total net present cost and COE of house 1. It also shows dumped annual energy and import and export energy to the grid by house 1. Additionally, it shows the electricity sold to house 2 by house 1. For the below configuration, the optimized PV capacity is found as 10 kw and Battery Capacity as 7 kwh. Due to limitation of 5kw power export to grid in South Australia, extra energy produced and not sold would be dumped.

Table 3.3: Optimized 20 years NPC and COE for house 1 with Import, Export and Dumped energy.

| Summary for H1 | PV (kw) / BES (kwh) | $NPC_{comp}^{H1}$ ($) | $NPC_{tot}^{H1}$ ($) | $COE^{H1}$ (¢/kwh) | Export Energy (kwh) | Import Energy (kwh) | Sold to H2 (kwh) | Dumped Energy (kwh) |
|---|---|---|---|---|---|---|---|---|
| **No PV/BES system** | 0 / 0 | - | 26,560.2 | 40.2 | - | 5,704.9 | - | - |
| **PV/BES system, no contract** | 10 / 7 | 2,0748.7 | 18,610.4 | 33.81 | 7,513.0 | 1,468.0 | - | 18.0 |
| **PV/BES system, 20-year contract** | 10 / 7 | 20,748.7 | 16,908.2 | 31.23 | 7,236.40 | 1,435.90 | 1,552.50 | 37.60 |

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

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

For third configuration COE reduced to 31.23 ¢/kwh. This is 22.3% reduction in COE compared to the first configuration and 7.6% reduction in COE compared to second configuration. Net present component cost is same as optimal solution of component is same. Total net present cost decreased 9% compared to the second configuration as the reduction of COE and net present cost is completely due to energy sold to house 2 as it is found that total annual energy sold is 1552.50 kwh. Export energy to the grid is less compared to second configuration because energy sold was divided between grid and house 2 for this configuration. Import energy came similar as it depends on the time of use.

Table 3.4: Total NPC and COE for house 2

| Summary | Years | H1 and H2 Electricity Rate (¢/kwh) | $NPC_{tot}^{H2}$ (\$) | $COE^{H2}$ (¢/kwh) |
|---|---|---|---|---|
| **H2 without any Contract** | 20 | - | 25,813.1 | 40.42 |
| **H2 with 20 years contract with H1** | 20 | 20.00 | 23,317.7 | 36.51 |

Table 3.4 shows the total NPC and COE of house 2 for two different configurations. One without the contract and another one with 20 years of contract. As seen in Table 3.4, installation of PV system on house 1 has affected the electricity rate for house 2, this rate is decreased by 9.7% from 40.42¢/kwh to 36.51¢/kwh due to cheap electricity bought from house 1. Likewise, the total net present cost also decreased by 9.6%.

### 3.5.2 Calculation Time for Optimal Planning

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

### 3.5.3 Case Study on Real Life Scenario

In this section some real scenarios are studied which is shown in fig. 3.7.

| Years | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Senerio 1 | 25.00 | | 21.94 | | | | | | | | | | | | | | | | | |
| Senerio 4 | 24.17 | | | | | 22.50 | | | | | | | | | | | | | | |
| Senerio 9 | 22.78 | | | | | | | | | | 23.61 | | | | | | | | | |
| Senerio 14 | 21.39 | | | | | | | | | | | | | | | 24.44 | | | | |
| Senerio 19 | 20.00 | | | | | | | | | | | | | | | | | | | |

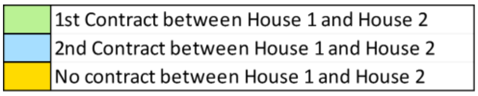



Figure 3.7: Five real life scenarios.

Five scenarios are discussed in the fig.3.7 where there are two different contracts between house 1 and house 2, each for different duration. NPC and COE comparison for houses 1 and 2 are shown in Table 3.5 and 3.6.

Table 3.5: COE and NPC Summary for five scenarios of house 1

| Summary | 1st Contract Duration (year) / 2nd Contract Duration (year) / No Contract Duration (year) | H1 and H2 Electricity Rate (¢/kwh) | $NPC_{elec}^{H1}$ ($) | $NPC_{comp}^{H1}$ ($) | $NPC_{tot}^{H1}$ ($) | COE (¢/kwh) |
|---|---|---|---|---|---|---|
| **H1 (No PV)** | 20 | - | 26560.2 | - | 26560.2 | 40.20 |
| **H1 with PV system without any contract** | 20 | - | -2138.25 | 20749 | 18610.4 | 33.81 |
| **Scenario 1** | 2 | 25 | -751.57 | 20749 | 16789.7 | 31.39 |
| | 13 | 21.94 | -2876.28 | | | |
| | 5 | - | -331.06 | | | |
| **Scenario 4** | 5 | 24.17 | -1675.03 | 20749 | 16607.9 | 31.09 |
| | 11 | 22.5 | -2208.67 | | | |
| | 4 | - | -257.07 | | | |
| **Scenario 9** | 10 | 22.78 | -2773.96 | 20749 | 16560.4 | 30.89 |
| | 7 | 23.61 | -1227.09 | | | |
| | 3 | - | -187.19 | | | |
| **Scenario 14** | 15 | 21.39 | -3457.04 | 20749 | 16642.3 | 30.83 |
| | 4 | 24.44 | -590.48 | | | |
| | 1 | - | -58.87 | | | |
| **Scenario 19** | 20 | 20 | -3840.43 | 20749 | 16908.2 | 31.23 |

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

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

Table 3.6: House 2's COE and NPC summary for five considered scenarios.

| Summary | 1st Contract Duration (year) | H1 and H2 | $NPC_{elec}^{H2}$ | $NPC_{tot}^{H2}$ | COE (¢/kwh) |
|---|---|---|---|---|---|

| | 2nd Contract Duration (year)<br>No Contract Duration (year) | Electricity Rate (¢/kwh) | ($) | ($) | |
|---|---|---|---|---|---|
| **H2 without any Contract** | 20 | - | 25,813.12 | 25,813.1 | 40.42 |
| **Scenario 1** | 2 | 25 | 3,840.32 | 24,086.1 | 37.99 |
| | 13 | 21.94 | 16,249.23 | | |
| | 5 | - | 3,996.55 | | |
| **Scenario 4** | 5 | 24.17 | 8,782.69 | 24,122.7 | 37.98 |
| | 11 | 22.5 | 12,236.66 | | |
| | 4 | - | 3,103.36 | | |
| **Scenario 9** | 10 | 22.78 | 15,222.46 | 24,033.0 | 37.85 |
| | 7 | 23.61 | 6,550.76 | | |
| | 3 | - | 2,259.79 | | |
| **Scenario 14** | 15 | 21.39 | 19,918.73 | 23,699.2 | 37.26 |
| | 4 | 24.44 | 3,069.87 | | |
| | 1 | - | 710.64 | | |
| **Scenario 19** | 20 | 20 | 23,317.72 | 23,317.7 | 36.51 |

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

## 3.6 Results and Discussion for TOU rates

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 3.7 presents the considered schemes.

Table 3.7: 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 |

### 3.6.1 Optimal Solution Results and Discussion

Optimal sizing of components and COE for both houses are calculated based on the real data for all schemes. Fig. 3.8 shows the 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 7kwh but with T-T-F and T-T-T scheme, it is 6kwh and 5kwh respectively. Optimal PV varies between 10kw and 11kw PV system.

Grid NPC is total earnings by PV and battery due to selling of electricity. Although components total NPC is low for four schemes which is $20,749, grid NPC is not that much attractive. Despite the higher NPC of components, T-T-T has most attractive grid NPC that is $11,819. It can be observed that the grid NPC is attractive when PV size is more. It is because more power is generated and sold to grid or H2. The lowest grid NPC is observed in F-F-F. This is because h1is unable to take benefits when it sells electricity to grid or H2 during peak hours as flat rate is low compared to peak hours, therefore it earns less.

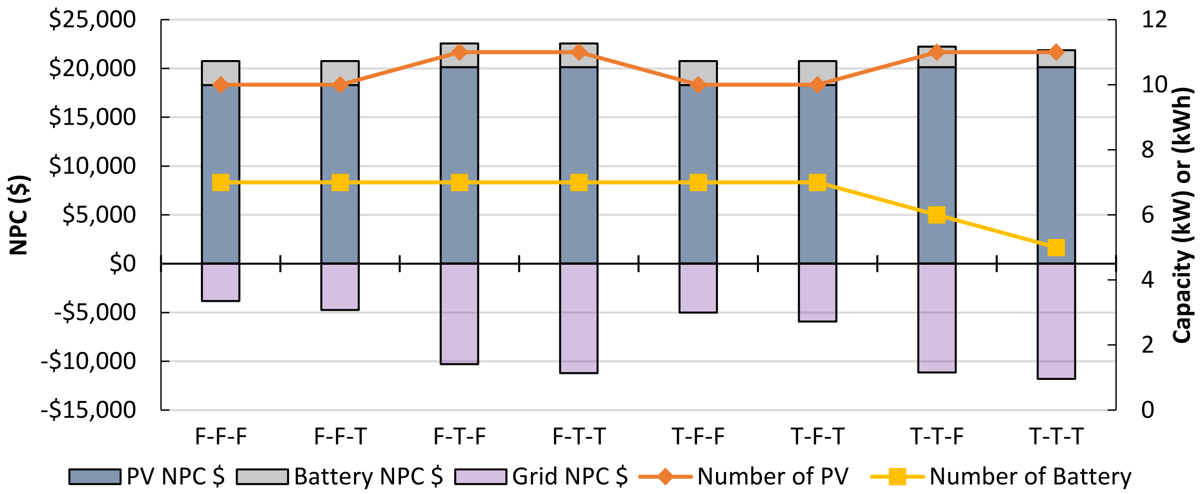



Figure 3.8: Optimal capacity and NPC of components obtained for all schemes.

Fig. 3.9 shows the NPC and COE for both houses with and without PV-BES that is normal. In Normal case, without system components h1and h2has same NPC for 4 schemes which has flat rate of buying and same NPC for 4 schemes which has TOU rate of buying. 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 the schemes in normal case. It is observed that in all the schemes NPC for H1 is lowest with PV-BES. Out of all the 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 lowest NPC of 22,954.50$

COE for normal case do not have significant difference for both the house because it just depends on buying of electricity from the grid which depends on the load of house 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 of same 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 which is 10.9% COE reduction.

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 of same 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.

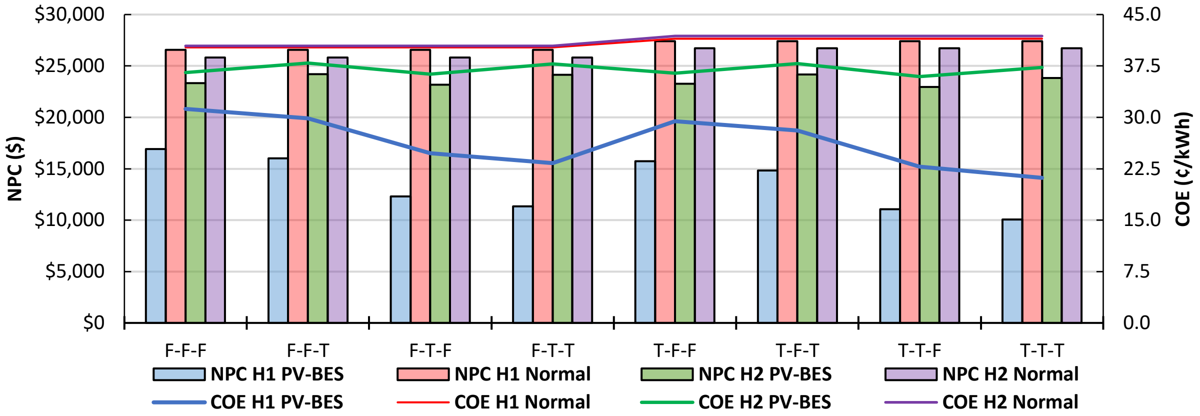


Figure 3.9: NPC and COE of H1 and H2 with and without PV-BES system for all schemes.

### 3.6.2 Different Scenario Results and Discussion

For each of 8 schemes, different scenarios results are observed to be more flexible in contract between the houses. The electricity rates for energy sharing between houses are updated for each year of contract in Flat and TOU tariffs. Table 3.8 provides the summary for the rate that 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. Rate is assumed for the 2 years and 20 years in energy sharing.

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

Where $M_1$ Is rate at 2-year contract, and $M_2$ Is the rate at 20-year contract.

Table 3.8: 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 | 25 | 30.00 | 22.00 |
| | | Second contract: 14 | 21.94 | 26.94 | 18.94 |
| | | No contract: 4 | - | - | - |
| **Scenario 2** | | First contract: 5 | 24.17 | 29.17 | 21.17 |

| | | | | | |
|---|---|---|---|---|---|
| | H1 with PV with 5- and 11-years contract | Second contract: 11 | 22.5 | 27.50 | 19.50 |
| | | No contract: 4 | - | - | - |
| **Scenario 3** | H1 with PV with 10- and 7-years contract | First contract: 10 | 22.78 | 27.78 | 19.78 |
| | | Second contract: 7 | 23.61 | 28.61 | 20.61 |
| | | No contract: 3 | - | - | - |
| **Scenario 4** | H1 with PV with 15- and 4-years contract | First contract: 15 | 21.39 | 26.39 | 18.39 |
| | | Second contract: 4 | 24.44 | 29.44 | 21.44 |
| | | No contract: 1 | - | - | - |
| - | H1 with PV with 20 years contract | First contract: 20 | 20 | 25.00 | 17.00 |
| | | Second contract: 0 | | | |
| | | No contract: 0 | | | |

Fig. 3.10 shows the NPC and COE of H1 and H2 for all schemes in different scenarios. H1 has the highest NPC and lowest NPC in 1st and 3rd scenario respectively. H2 has the highest and lowest NPC in 2nd and 4th scenarios respectively. Both the houses have got the lowest COE for 4th scenario, but highest scenario is fluctuating depend upon the scheme between 1st and 2nd scenario. H1 has the highest COE in 1st scenario because, although the rate H2 needs to pay is more if taken smaller contract which decreases the COE for H1 but there is no contract for the last 5 years in which H1 cannot take advantage of selling electricity to H2. Due to last 5 years, despite the high electricity cost taken from H2, its COE is high. COE for H2 is the highest in 1st scenario because when it takes low period of initial contract, it is paying highest energy sharing rate. Both the houses have lowest COE in 4th scenario. This is because H1 can take advantage of sharing rate with H2 for 19 years out of 20 years whereas for H2, as it took higher period of initial contract and get advantage from H1 in mutual sharing COE.

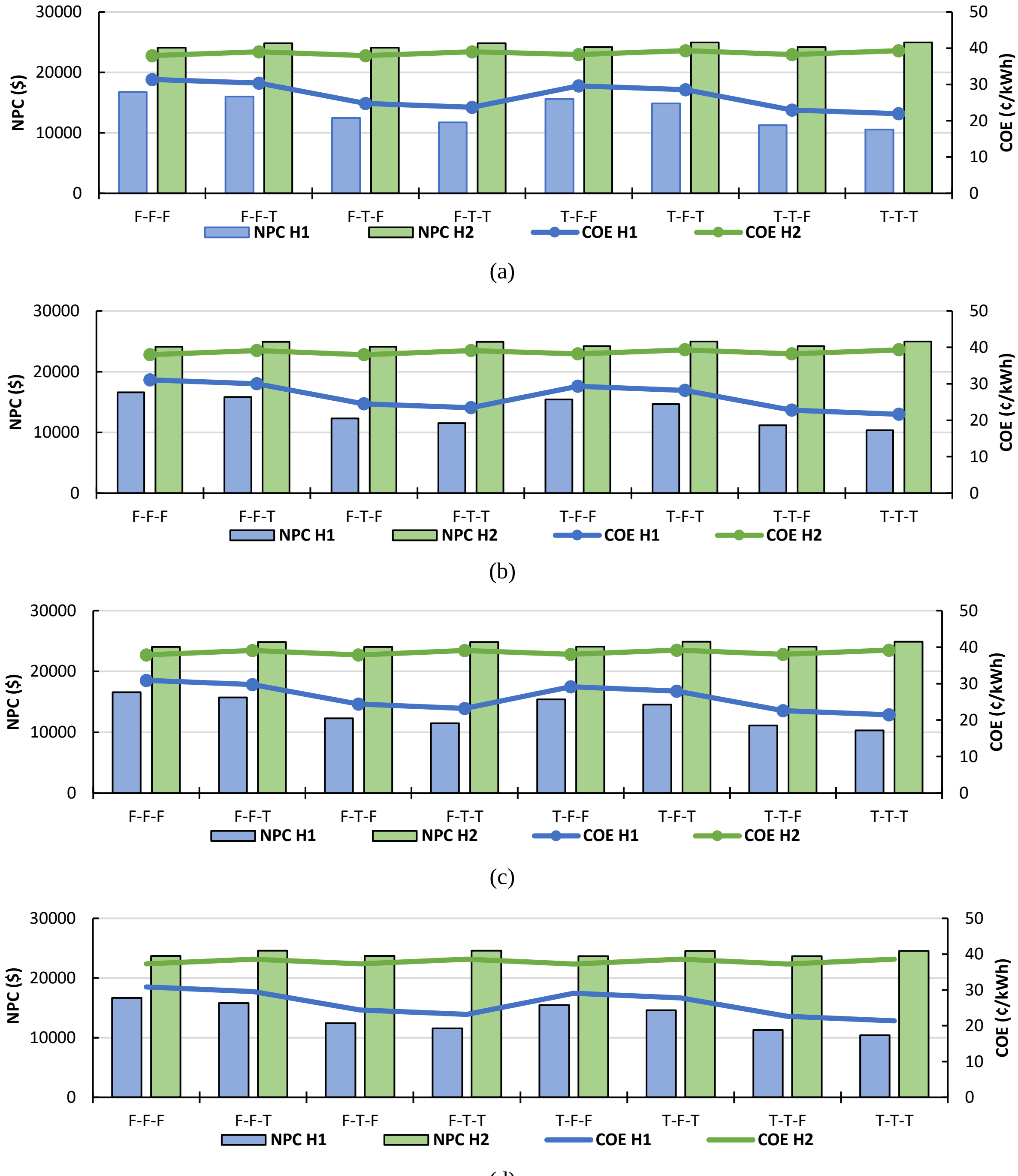



Figure 3.10: NPC and COE of H1 and H2 for all schemes in different scenarios. (a) H1 with PV with 2- and 13-years energy sharing contract, (b) H1 with PV with 5- and 11-years energy sharing contract, (c) H1 with PV with 10- and 7-years energy sharing contract and (d) H1 with PV with 15- and 4-years energy sharing contract.

### 3.6.3 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. 3.11 shows the summary for all the scenario 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 lower COE compared to other scenarios. It can be inferred that prolonging the first contract between the customers achieves lower COE for both houses.

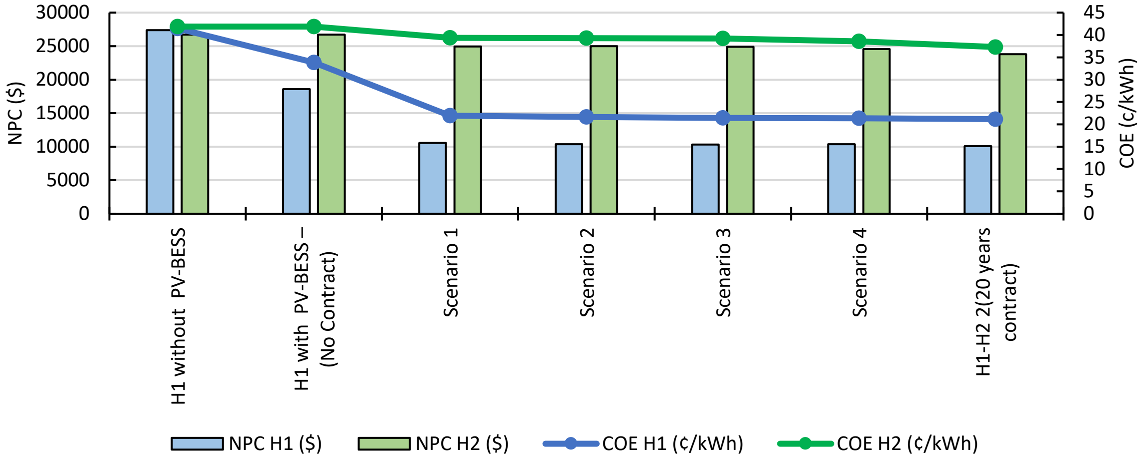



Figure 3.11: COE and NPC summary for best the scheme (T-T-T) for different scenarios.

## 3.7 Analysis

All the analysis is done for the optimal solution of best scheme investigated that was found for TOU-TOU-TOU.

### 3.7.1 Sensitivity Analysis

a. Effect of Export Power Limitation

One of the most important parameters in this study is restriction in South Australia set up by power networks and government which is 5kw. These things are temporary and might vary with the popularity of solar and energy sharing. So, it is important to see its effects on our study. Fig. 3.12 shows the results obtained when grid restriction varies from 0kw to 10kw. With the increase of power that can be exported to the grid, the optimal PV size gradually increases. Optimal battery is pretty much constant with 5kwh and 6kwh. For H1, it can be observed that COE decreases significantly with the increase in export power. This is because when export power limitation is increased, H1 can take full advantage of selling extra electricity produced to the grid instead of dumping electricity. Additionally, H2 electricity also decreases gradually because of increase in PV power generation as more generation, more advantage for h2to buy electricity from H1 rather than buying from grid.

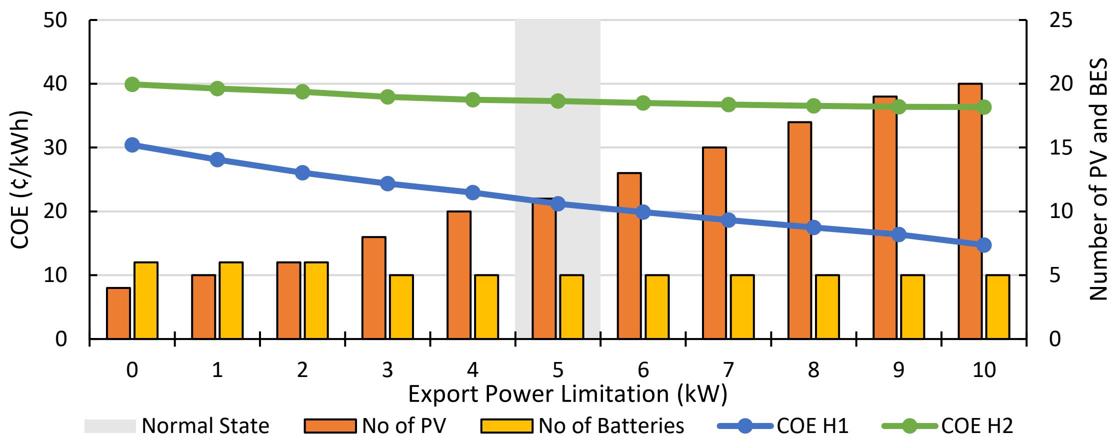


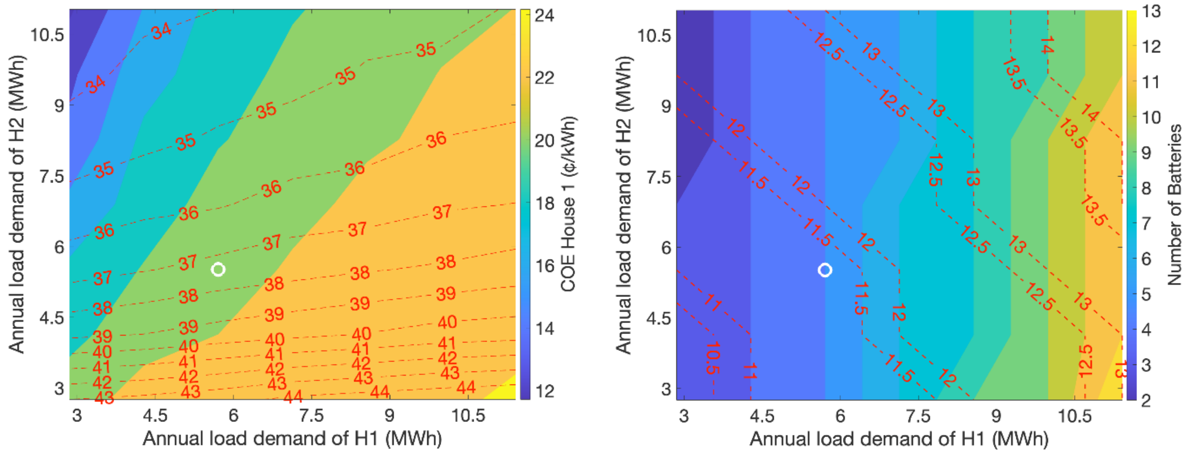

Figure 3.12: Sensitivity analysis on COE when export power limitation is changed from 0kw-10kw for H1.

b. 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 is investigated and shown in the counterplot diagram in Fig. 3.13. It can be observed that the least COE for H1 is when load consumption of H1 is lowest whereas H2 is 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 h2in agreed energy sharing rate in high price compared to selling electricity to grid in low price. But when 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 H1 COE.

For H2 COE, it is observed that the lowest COE is when load consumption of H2 is highest and h1is 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 load of H1 increases and load of H2 decreases, first thing is H2 cannot buy more electricity from H1 in cheaper rate because h1needs to satisfy its own demand first. Additionally, although load consumption of H2 is lowest, DSOC is same as when it is highest. This increases COE for H2.

For optimal sizing of components, it can be observed that when load consumption of H1 and H2 is lowest, number of PV is 10. When load consumption of H1 and H2 increases, optimal PV size increases gradually. We can see BES has no effects on H2, this is because h2does not get any power from battery. The higher the load consumption of H1, higher the optimal battery size.

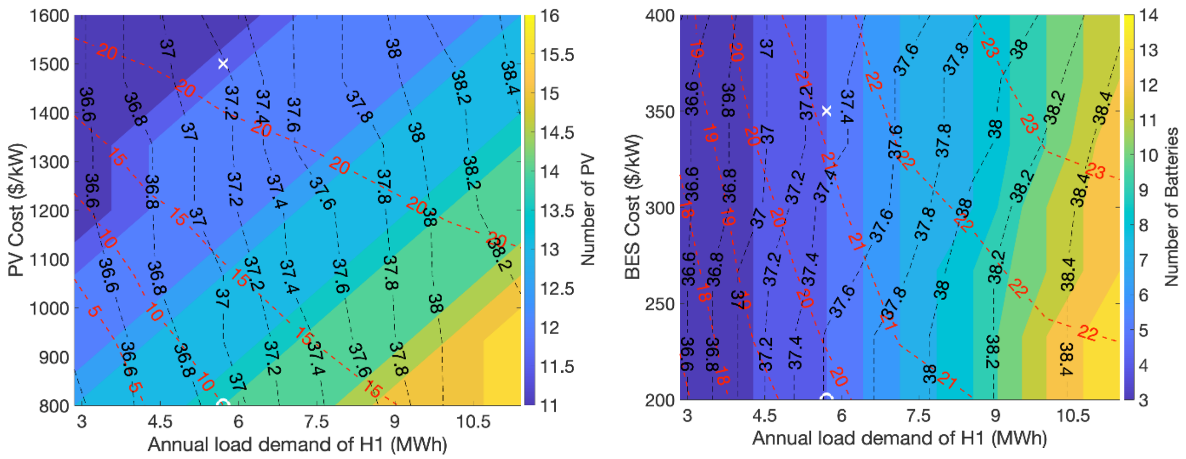



(a) (b)

Figure 3.13: Effect of houses' load demands on optimal sizing, (a) color bar shows the COE for H1 and the red lines show the COE for H2, (b) color bar shows the battery capacity in kwh and the red lines show the PV size in kw.

c. PV and Battery Energy Storage Cost Variations

Fig. 3.14 shows the counterplot diagram 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 sold to H2. The highest COE is observed when PV-BES cost and load demand is highest which was expected because when PV-BES cost increases, NPC of components increases which increase COE and when load demand of H1 increases, it cannot take advantage of selling electricity to grid and H2. COE does not change significantly for H2. PV-BES cost has not significant effects 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.




(a) (b)

Figure 3.14: Effects of load demand of H1 and cost of components on optimal sizing, (a) color bar shows the PV size in kw, red lines show the COE for H1, and black lines show the COE for H2, (b) color bar shows the BES capacity in kwh, red lines show the COE for H1, and black lines show the COE for H2.

d. Effects of Grid Charge

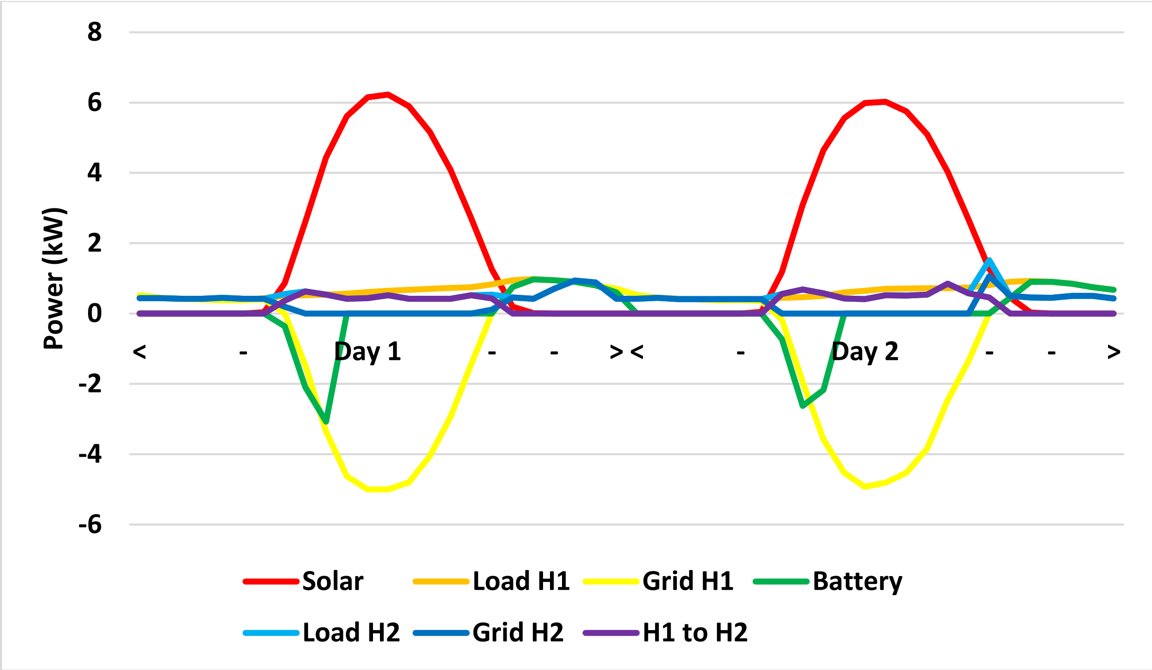
For this analysis we tried to find out our breakeven if grid charges certain amount for houses because houses are using grid for energy transfer. Grid charge will be paid equally by H1 and H2. Our breakeven point would be when grid charges 0.20 $/kwh for the energy transfer between the houses. Beyond this point, it would not make sense for H1 to share the energy as cost would be so high that it makes sense for H1 just to sell to grid instead of selling to H2 and paying grid charge. Table 3.9 shows the effects on cost reduction in % and COE for both the houses due to different charge of grid.

Table 3.9: Grid charge effects on cost reduction and COE for both the houses.

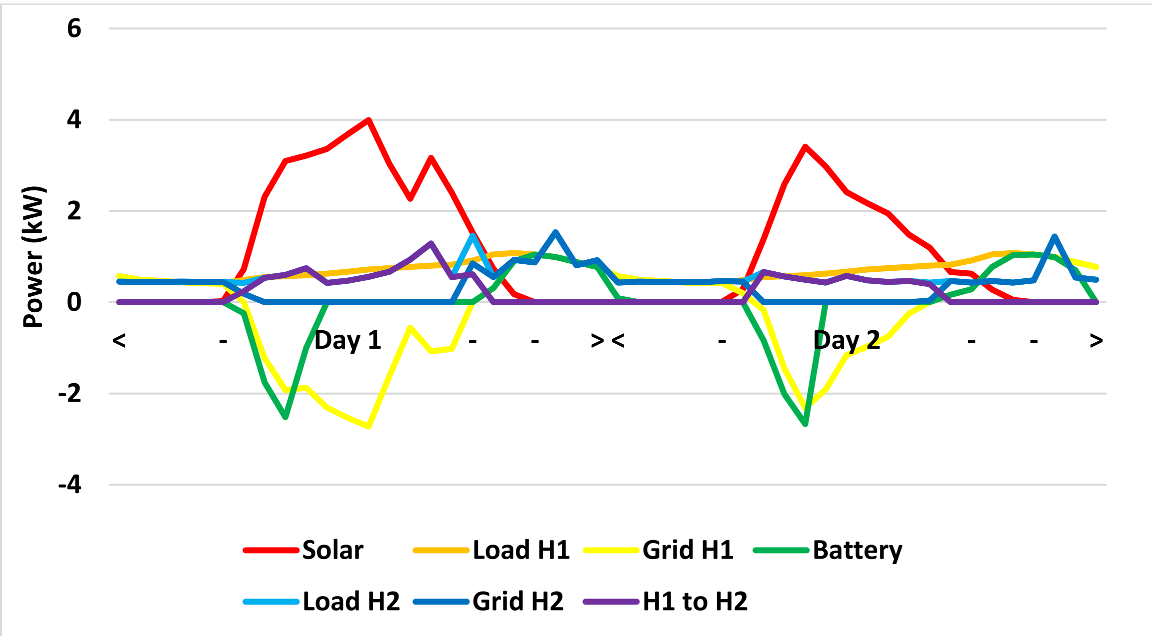
| Grid charge ($/kwh) | Energy sold to H2 by H1 (kwh) | Cost reduction for H1 (%) | Cost reduction for H2 (%) | COE of H1 (¢/kwh) | COE of H2 (¢/kwh) |
|---|---|---|---|---|---|
| **0** | 1552.50 | 12.9 | 10.9 | 21.17 | 37.31 |
| **0.05** | 1552.50 | 9.8 | 9.0 | 21.94 | 38.10 |
| **0.10** | 1552.50 | 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 |

### 3.7.2 Operational Analysis

Fig. 3.15 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. Due to high energy production during daytime, PV can satisfy the load demand of both the houses whereas in the evening time and night-time, battery comes to play. 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. The grid restriction of 5kw is shown in the fig. 3.15 and it is observed that export power is taken into consideration and export power does not cross 5kw.




(a)




(b)

Figure 3.15: Operational analysis for 2 days of: (a) Summer (b) Winter.

### 3.7.3 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 from year 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 results are shown in fig. 3.16. Results show that uncertainties in solar irradiance and temperature do not change the optimal size of components. This means the capacities of PV and BES are remained as 10 kw and 5 kwh for all scenarios or years. The 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. The COE of H2 slightly varies between 37.12 ¢/kwh and 37.34 ¢/kwh which is neglectable.

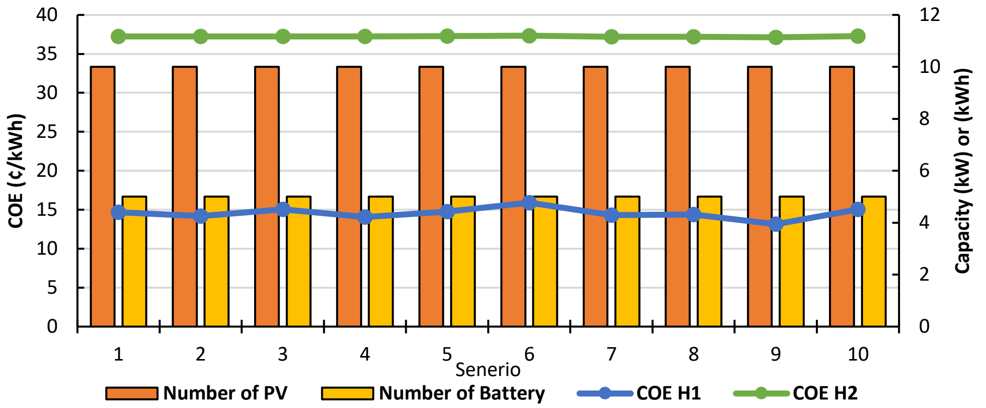



Figure 3.16: Uncertainty analysis on COE and optimal sizing of components due to change in solar irradiance and ambient temperature for ten scenarios of variations.

## 3.8 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. A novel rule-based energy management system was developed under TOU tariff and energy sharing between two houses. 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 7kwh 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. It is because of the TOU selling rate to grid and TOU selling rate to H2. COE for house2 is more attractive in T-T-F but we consider T-T-T as our best options to do the analysis because of our objective function which is maximizing COE reduction for h1and decreasing COE for H2. Out of all the 4 scenarios, it was observed, $1^{st}$ 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 h2it took a smaller number of years as an initial contract and energy sharing cost was high compared to other scenarios. Both the houses have least COE in 4$^{th}$ 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.

Different analysis was done and found out that COE will decrease significantly if export power limitation is increased. Additionally, analysis was done when load consumptions of both houses vary investigating its effects on COE. The effect of PV and BES costs on COE, and optimal capacity of components was investigated. Furthermore, operational analysis for power flow is done for 2 consecutive days of summer and winter and finally uncertainty analysis due to uncertain parameters like solar irradiance and temperature.

Future work can be done by adding electric vehicles 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 investigate the effect of demand response programs on the optimal sizing problem by considering the energy sharing program.

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# Chapter 4. Optimal Capacity of Solar PV and Battery Energy Storage for Grid-tied House with EV Based on Energy Sharing

**Abstract:** This study investigates the optimal solution of solar photovoltaic (PV) and battery energy storage (BES) systems for grid-tied homes with electric vehicle (EV) when electricity is shared between the homes. The home which has PV-BES and EV is referred as home-1 (H1) in this paper which shares the electricity with home-2 (H2). Power loss during the time of energy sharing is ignored in this study due to insignificant loss because of short distance between the homes. The optimization is done to achieve the minimum cost of electricity (COE) for H1and to reduce the COE for home-2while taking consideration of the design constraints over the project life of 20 years. Time of use (TOU) electricity pricing is chosen over the flat rate tariff. A rule-based energy management system is developed for different sets of configurations to compare the simulation results. Particle swarm optimization (PSO) technique is used to obtain optimal results by incorporating realistic annual data of the solar irradiance, ambient temperature, load consumption of each home and EV. Uncertainties in EV are considered for departure time, arrival time and initial state of charge (SOC) for the time of arrival. The developed optimization technique is general in nature and can be used for any grid tied homes who are willing to share the electricity. Sensitivity, uncertainty, and operational analysis is done for the configuration when energy is shared between the homes and H1 has solar PV, BES, and EV.

***Keywords:*** Energy sharing, battery energy storage, cost of electricity, optimal components sizing, solar photovoltaic.

## 4.1 Introduction

### 4.1.1 Background and Motivation

Around 30% of global energy demand is consumed by residential households [1]. To decrease this demand, installing solar PV 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 solar PV due to lower FIT compared to retail price. BES, which can be used to store energy and can be discharged 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 solar PV, 31% prefer BES 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 has drastically altered the way energy is generated, distributed, and consumed in the energy pipeline, including microgrids. 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 and Saskatchewan in Canada are starting to phase out these net metering programs. If more areas follow suit, the incentive to install solar PV 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 [10-12].

At the end of 2020, Australia had the highest uptake of rooftop solar power systems globally, with 21% of homes, or 2.66 million installations, having solar PV [13]. Installation of solar PV 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 [14]. Additionally, it is estimated that 8% of solar PV systems also include BES in 2019 [15]. 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

PV-BES systems under TOU pricing, as EV sales in Australia grew by 90% between 2018 and 2019 [16]. 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 [16]. With a high percentage of homes in South Australia which is 35% having rooftop solar power systems and a trend towards more installations of solar PV and PV-BES, it is important to consider how to optimize these systems with respect to TOU pricing mechanisms. The cost of rooftop solar power systems has reached an all-time low due to a steady decrease over the last 20 years, decreasing from around $4,550 per kilowatt in 2000 to $650 per kilowatt in 2020. Similarly, the price of BES has decreased significantly, dropping from $1,430 per kilowatt-hour in 2010 to $203 per kilowatt-hour in 2020 [17]. Developing guidelines for households that already own an EV and are looking to install a PV-BES system would allow them to make informed decisions about system capacity. It is crucial to determine the optimal size of solar PV 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.

### 4.1.2 Literature Review

Paper [18] discusses the energy trading between locally based energy consumers and small-scale distributed energy resources like offices and factories. Game theory was used in the development and simulation of the energy trading platform. The local balance of energy generation and consumption was improved because of the energy trade between homes. The game theoretic strategies for P2P energy trading are also used in papers [19–21] as a practical and efficient way to manage energy and drastically lower energy costs. Although the trading platform was established, the home's component sizes were not optimized. A unique game-theoretic model is put forth in Paper [22] for P2P energy trading among prosumers in a community. According to the study's findings, consumers can modify their energy consumption habits based on the cost and availability of energy from suppliers. The analysis demonstrates that the community will reap considerable financial and technological benefits. This work does not include EV, and it is not explained in this paper how the results obtained will change if EV is present.

A power management device that provides the power conversions required to power loads employing power generating sources and storage elements has enabled Paper [23] to build a market for the consumer and prosumer for affordable electricity rates. Flexibility of contract for in and out of the network is not discussed in the paper. Power management unit is extendible or not is not discussed in the paper whereas this paper has flexibility in contract and energy management system is extendible. Low-cost digital electricity meters have been suggested in Paper [24] for use in residential P2P networks to improve grid efficiency and value-added services. This paper does not give a clear explanation about the prosumer generation and storage system of electricity. Although there is an increase in grid stability, the appropriate component sizes to accomplish this result are not provided, and it is not explained how EV load can affect grid efficiency.

A successful bidding approach for P2P energy trading has been developed in paper [25] to address the issue of unfair trade restrictions and a lack of flexibility in recent studies. In this mechanism, fair competition in the market, participant economic gains, and microgrid self-sufficiency are all attained in equilibrium, however contract flexibility and ideal components size for best economic gains are not investigated. To achieve the greatest COE savings, paper [26] discusses the optimization of solar PV and BES with customer demand profiles, real-world constraints, energy retail prices, and FIT rates. The findings of this study demonstrate that using solar PV and BES together offers higher economic advantages than using BES alone. This paper does not discuss about the impact of EV in optimization as well as do not discuss about the grid restriction constraint in Australia to export power. In paper [27], the double-sided auction model is discussed to secure customer benefits and privacy while facilitating near real-time energy trade amongst users. To maximize system stability, a decentralized strategy is used. Although EV, solar PV, and BES are taken into consideration in this analysis, the components are not optimally sized to maximize economic benefits while minimizing initial capex costs to the home.

Paper [28] has created a trading platform with an activity-based model to forecast daily EV travels and has demonstrated financial advantages for Belgian citizens. The load of homes, how they share energy, and how this affects the power system during peak and off-peak hours are not covered in this study. P2P energy sharing has advantages and limitations, and paper [29] has active energy management strategies in a community instead of only focusing on prosumers, which has helped to better understand both aspects and has given advice for its implementation. Even though this research offers a trading mechanism, the best solar PV size for each home has not been suggested to optimize economic benefits.

Table 4.1: Summary of current papers for energy sharing between houses.

| Paper | Electricity rates | Mutually agreed price | PV/ BES | EV | Optimal components sizing | Grid constraint | Contract flexibility |
|---|---|---|---|---|---|---|---|
| **18** | Flat | × | PV | × | × | L.V | × |
| **19** | Flat | × | PV | √ | × | × | × |
| **20** | Flat | × | PV + BES | × | × | × | × |
| **21** | Flat | × | PV + BES | × | × | × | × |
| **22** | Flat | × | PV + BES | × | × | × | × |
| **23** | TOU | × | PV + BES | × | × | L.V | × |
| **24** | TOU | × | N.M | × | × | × | √ |
| **25** | Flat | × | PV + BES | × | × | × | × |
| **26** | TOU | × | PV + BES | × | √ | × | × |
| **27** | TOU | × | PV + BES | √ | × | × | × |
| **28** | TOU | × | BES | √ | × | × | × |
| **29** | TOU | × | PV | × | × | × | × |
| **This Paper** | TOU | √ | PV + BES | √ | √ | √ | √ |

### 4.1.3 Contribution

Table 4.1 shows a summary of 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. L.V in the table under grid constraint represent low voltage. The major contributions of this study as compared to other existing studies are as follows:

- Development of separate energy management system for grid tied home with EV sharing electricity with other home under TOU tariffs.
- Integration of TOU electricity tariffs on a mutually agreed energy sharing price between the grid tied homes.
- Optimal components sizing for grid connected household with EV and energy sharing with another home.

This work also include minor contributions as follows:

- Optimization model includes all the practical parameters such as daily supply charge of charge (DSOC) 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.
- Developing and investigating different scenarios to make contracts between the homes flexible if any home wishes to extend or cancel the energy sharing contract.

### 4.1.4 Article organization

The paper is structured as follows: Section 4.2 describes the operational strategies of home energy management system when EV is at home and when it is not. The role of energy management system and flow chart is included in this section. Section 4.3 describes methodology that includes objective function, optimization flow chart and constraints of the study. Section 4.4 contains the case study and data collection to obtain the results. Section 4.5 includes results and discussion. All the analysis that includes sensitivity, uncertainty and operational analysis is presented in section 4.6. Finally, section 4.7 discusses the conclusion and future work.

## 4.2 Operational Strategies

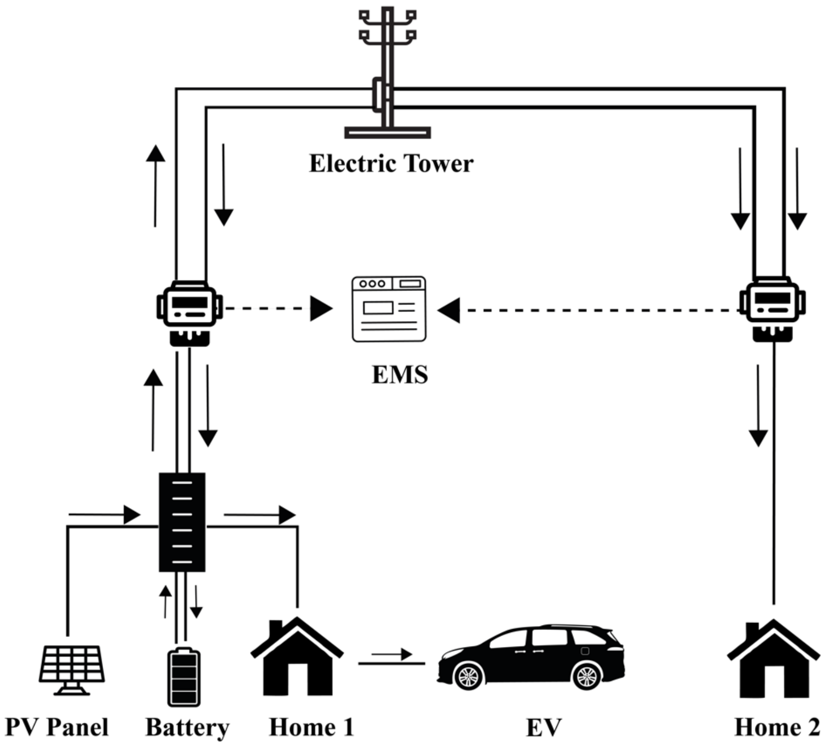
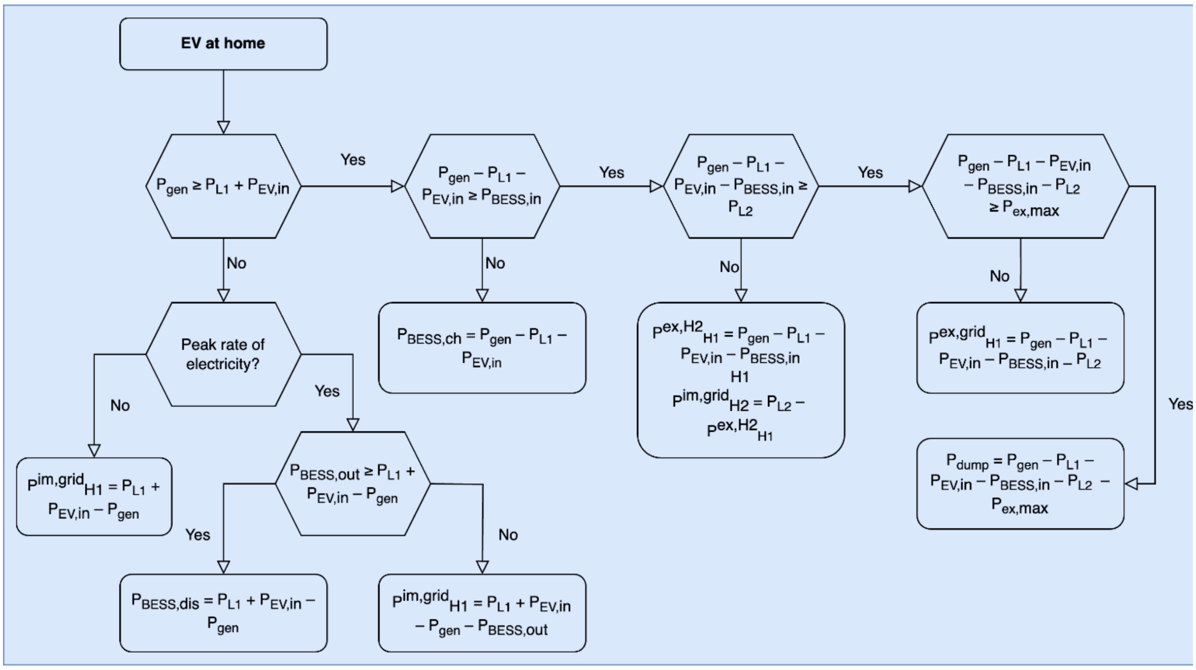
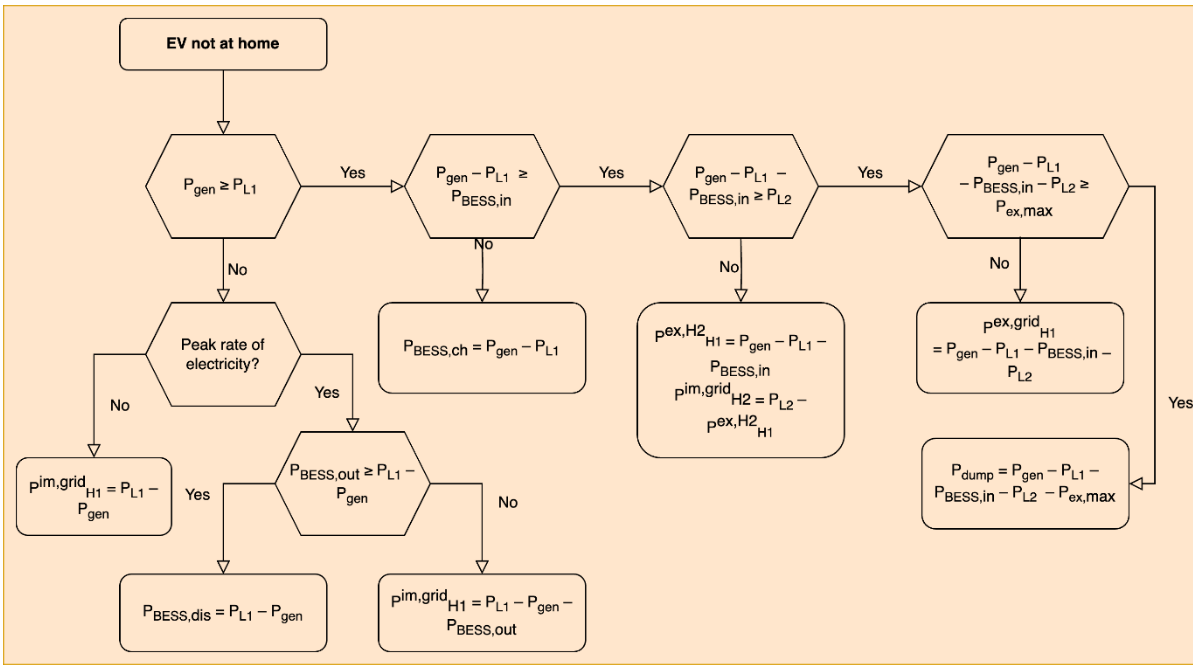



Figure 4.1: Network configuration showing energy sharing between H1 and H2

The network configuration of energy sharing between the homes is shown in Fig. 4.1. Both homes (i.e., Load 1 and Load 2) are tied with the grid. H1 has solar PV, BES, and EV whereas H2 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 H1 will purchase the solar PV and BES 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, H1 will be n number of homes with solar PV and BES components and H2 will be *m* number of homes without PV/BES 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.




(a)




(b)

Figure 4.2: Flow chart for rule-based home energy management system: (a) When EV is at home; (b) When EV is not at home.

The flowchart for the energy management system is shown in Fig. 4.2. The role of energy management system is to direct the energy flow from PV to home and battery, H1 to H2, H1 to and from grid, H2 from grid, BES to H1. The first flowchart is used when EV is at H1 whereas the second flowchart is used when EV is not at H1. Several past papers have discussed the equation without EV [30], [31], [33-35]. This section discusses the equation when EV is at home. When solar PV produces the power more than the combined power needed for H1 and EV but smaller than combined power needed for H1, EV, and battery, it will initially satisfy the H1 demand, it then charges the EV, and the remaining power is used to charge the battery. As such, no power is left to be sold to H2, the export power to grid and dump power is then zero. So, all the load demand for H2 will be fulfilled by grid.

In our research, we delve into the SOC dynamics of EV batteries within the context of grid-connected houses. To begin, we assume an initial SOC of 85% when the EV is parked at home. As the EV embarks on its daily journeys, the battery gradually discharges while it is in operation. The amount of energy left in the battery upon its return to the house depends on the distance it traveled during the day. To replenish the battery, the EV begins to charge during off-peak hours, specifically during the nighttime from 10 pm to 4 am. By the end of this charging window, the EV's state of charge is restored to its full capacity.

It's important to note that we account for uncertainties in the SOC when the EV returns home and its arrival and departure times to and from the residence. To capture these uncertainties, we employ a truncated Gaussian distribution, which helps us model the stochastic, or random, behaviors observed in our analysis as demonstrated in Table 4.2 of our research.

Furthermore, it's essential to recognize that different EVs may come equipped with varying battery capacities and characteristics. These differences can significantly influence SOC dynamics. Factors such as charging and discharging rates, as well as efficiency losses, play pivotal roles in shaping how the SOC evolves over time.

When solar PV power generation is greater than combined power needed for H1, EV, and battery, it will initially satisfy demand of H1, EV and battery, remaining power will be sold to H2 as follows.

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

where $P_{EV,in}$ is available input power of EV.

If the generation is high enough, the power is exported to the grid by H1 which can be written as

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

If anything remains will be dumped via control system and can be calculated as

$$P_{dump}(t) = P_{gen}(t) - P_{L1}(t) - P_{EV,in}(t) - P_{BESS,in}(t) - P_{L2}(t) - P_{ex,max}(t) \quad (3)$$

Home-2 has an option to buy power from grid if the exported power from H1cannot satisfy its full demand (4).

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

When solar PV power generation is less than the combined load demand of H1 and EV, battery satisfies the partial or total demand. If battery is unable to fulfill its total demand, H1 imports the required power from grid (5). For this case, H2 buys all the electricity from the grid and power exported to H2 or grid by H1 will be zero.

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

SOC of EV for each time interval can be calculated as [32]

$$SOC_{BEV}(t + \Delta t) = \frac{(P_{BEV,in}(t)\eta_{BEV,ch})\Delta t + SOC_{BEV}(t)}{\mathbf{E_{bc}^{EV}}} \quad (6)$$

where $SOC_{BEV}$ is EV's battery state of charge. $P_{BEV,ch}$ and $\eta_{BEV,ch}$ represents power delivered to EV during charging and charging efficiency of EV respectively. $E_{bc}^{EV}$ is the total battery capacity of EV.

Available input power of the EV is found as follows.

$$P_{BEV,in}(t) = \frac{E_{bc}^{EV}}{\Delta t}(SOC_{BEV,max} - SOC_{BEV}(t)) \quad (7)$$

where $SOC_{BEV,max}$ represents maximum state of charge of EV's battery.

## 4.3 Methodology

### 4.3.1 Objective function

The aim is to find the minimum COE for H1. This is done by finding optimal components

$$0 \leq P_{gen}(t) \leq P_{gen,max} \tag{12}$$

$$0 \leq P_{BESS,im}(t), P_{BESS,ex}(t) \leq P_{BESS,max} \tag{13}$$

$$0 \leq P_{EV,in}(t) \leq P_{EV,max} \tag{14}$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{15}$$

$$SOC_{BEV,min} \leq SOC(t) \leq SOC_{BEV,max} \tag{16}$$

$$P_{gen}(t) + P_{BESS,in}(t) + P_{H1}^{im,grid}(t) + P_{H2}^{im,grid}(t) - P_{H1}^{ex,grid}(t) \geq P_{L1}(t) + P_{L2}(t) \tag{17}$$

$$0 \leq P_{ex,grid}(t) \leq P_{ex,grid_{max}} \tag{18}$$

$$R_{el}(Peak) > R_{el}(flat) > R_{el}(off-peak) \tag{19}$$

$$R_{H1\_H2}(Peak) > R_{H1\_H2}(flat) > R_{H1\_H2}(off-peak) \tag{20}$$

$$R_{ta}(Peak) > R_{ta}(flat) > R_{ta}(off-peak) \tag{21}$$

sizing. In this paper, all buying/selling electricity rates are based on the TOU tariffs. This section discussed the methodology to obtain the optimal sizing of components and minimum COE. COE of any given home can be found out by the ratio of total electricity cost and electricity consumed in a year. The formula to calculate COE for each home is as follows [33]:

$$COE_{H1} = \frac{NPC_{H1}^{co}\, CRF_{co} + NPC_{H1}^{el}\, CRF_{el}}{L_{H1}^{an}} \tag{8}$$

$$COE_{H2} = \frac{NPC_{H2}^{el}\, CRF_{el}}{L_{H2}^{an}} \tag{9}$$

### 4.3.2 Net present cost

Therefore, the total NPC for H1includes its component cost and electricity cost whereas total NPC of H2 includes its electricity cost which can be written as follows.

$$NPC_{H1}^{tot} = NPC_{H1}^{co} + NPC_{H1}^{el} \tag{10}$$

$$NPC_{H2}^{tot} = NPC_{H2}^{el} \tag{11}$$

### 4.3.3 Design constraints

Equation (12)-(14) represents the power constraint for PV, BES, and EV respectively. Equation (15), (16) represents the SOC constraints for battery and EV respectively. Equation (17) represents the power balance constraint between PV, BES, EV, house, and grid for any given interval of time. Equation (18) represents export power limitation constraint set by Australian government. Equation (19)- (21) represent that flat rate is always in the middle compared with peak and off-peak rate for buying, sharing, and selling of electricity respectively.

### 4.3.4 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. PSO has been successfully used for optimal components sizing in several past research papers for the power systems [2], [31-34]. 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 [33]. Fig. 4.3 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 the random number of each component until an optimal solution is achieved. It also checks the design constraints to achieve the valid optimal solution.

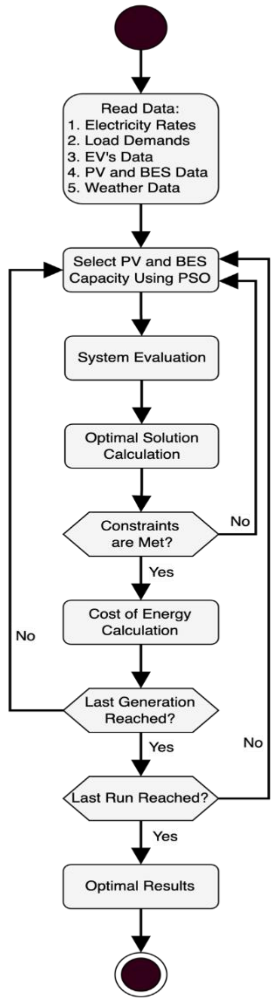



Figure 4.3: PSO optimization Flow chart

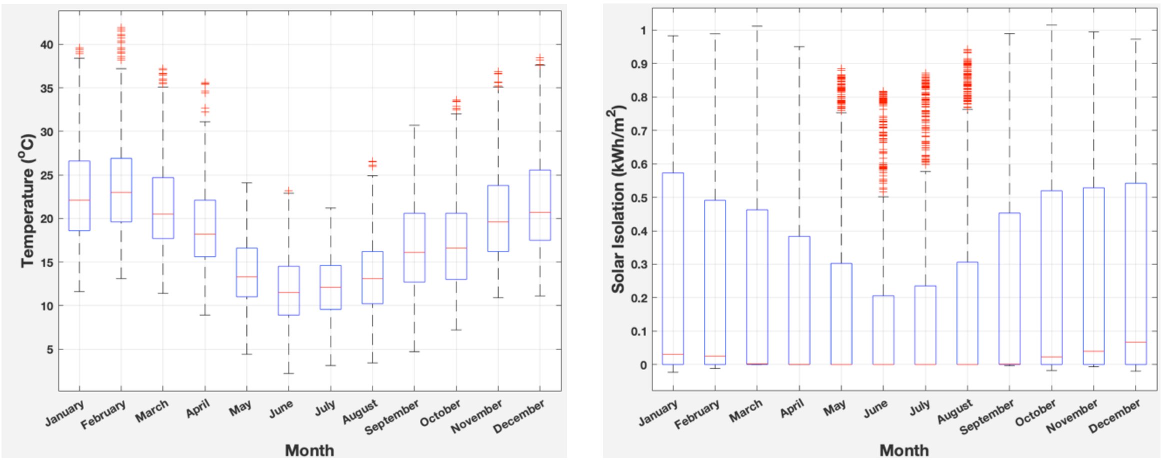
Optimal solution is ensured to be achieved when higher number of runs, population and generation is chosen [35]. Therefore, 200 population and 200 generations are chosen for this study. Furthermore, 10 runs are repeated to ensure the optimality to obtain global optimal results. Several other parameters in PSO algorithm such as social, inertia and cognition weight are assumed as 2,0.5 and 2 respectively.

## 4.4 Case study

### 4.4.1 Data collection for optimal sizing and COE calculation

a. Meteorological data

Fig. 4.4 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 [36]. 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/ $m^2$.



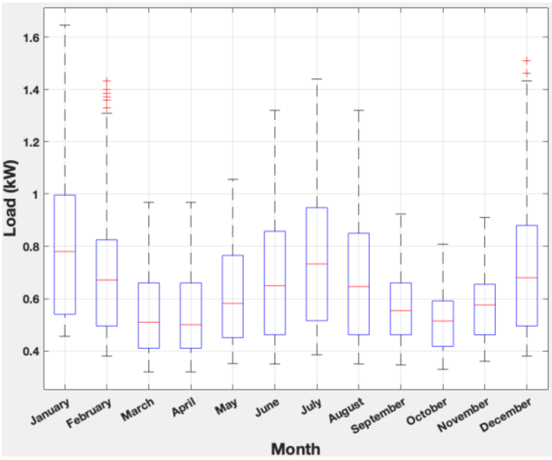

(a) (b)

Figure 4.4: The annual meteorology data of South Australia: (a) Ambient temperature; (b) Solar irradiance

b. Load data

Fig. 4.5 shows the load data for H1, H2 and EV. The load data were taken from [33] and [37] for H1 and H2, respectively. The minimum and maximum load for H1 is 0.32kW and 1.65kW respectively with an average load of 0.65kW. The minimum and maximum load for H2 is 0.19kW and 2.97kW with an average load demand of 0.63kW. Minimum and maximum load for EV is 0.32kW and 6.85 kW respectively with an average load of 1.47kW.

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 54kWh is taken for this study [38] 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 4.2.

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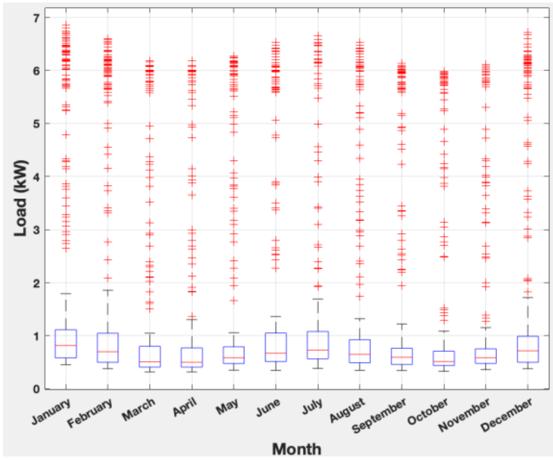


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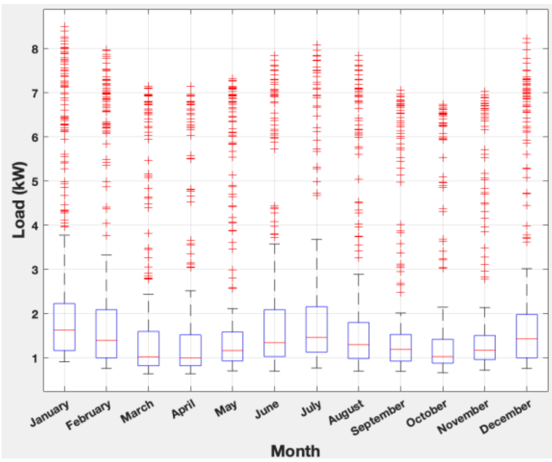
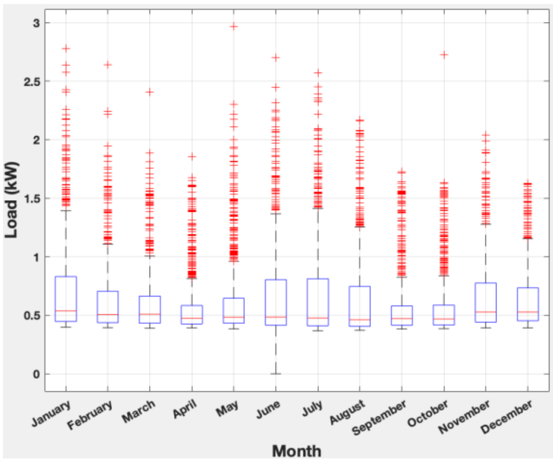



(c)




(d)

Figure 4.5: Daily load consumption for a year: (a) Load of H1, (b) Load of EV, (c) Load of H1 with EV, (d) Load of H2

Table 4.2: Probability parameters for the uncertainties of EV

| | Mean | S.D | Min |
|---|---|---|---|
| **Initial SOC at arrival (%)** | 50 | 30 | 20 |
| **Arrival time (h)** | 18 | 3 | 15 |
| **Departure time (h)** | 8 | 3 | 5 |

### 4.4.2 Different Scenarios case study

The next part of the study is done to investigate the flexibility of contracts and how it effects COE with different scenarios shown in Fig. 4.6. 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 are happy with the benefits, contract will be extended 70% of the project life. COE will be calculated for each of the scenarios.

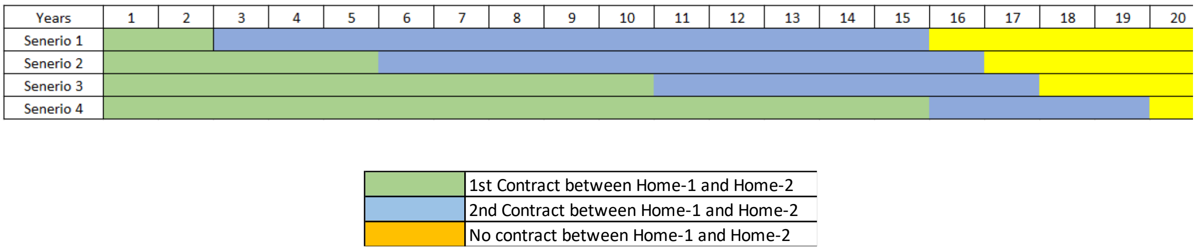



Figure 4.6: Different scenarios of contract between the homes for 20 years

## 4.5 Results and Discussion

### 4.5.1 Optimal sizing and COE calculation

Optimal component and NPC results have been calculated for three different configurations and shown in table 4.3. The highest number optimal components are seen when energy is shared between the homes with EV, solar PV, and BES. This is because of more energy demand overall which includes H1, EV and H2. COE for each configuration is shown in Fig. 4.7(a). The lowest COE is obtained for the 3rd configuration for the homes. This is because H1 can take full benefit of generated power by selling to H2. Similarly, H2 can benefit because of the lower energy prices compared to buying in retail rate. For the other 2 configurations, there is no energy sharing because of which the homes cannot take full benefit for themselves.

Fig. 4.7(b), (c), (d) shows the pie chart which contains the energy shared between homes, energy bought and sold to grid by H1, energy bought from grid by H2 and dumped energy. For the 1st configuration where there is no solar PV and BES, 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 H2 is satisfied by H1. Exported energy to the grid is high for H1 compared to 2nd configuration which resulted in buying more energy from grid for H1.

Table 4.3: H1 Optimal component sizing for 3 different configurations with and without H2 load.

| Configuration | PV (kW) | BES (kWh) | NPC_H1 ($) | NPC_H2 ($) |
|---|---|---|---|---|
| **Load 1 + EV** | 0 | 0 | 55164.1 | 26318.8 |

| | | | | |
|---|---|---|---|---|
| **Load 1 + EV + PV BES** | 11 | 18 | 39070.1 | 26318.8 |
| **Load 1 + EV + PV BES + Load 2** | 12 | 16 | 37030.3 | 24033.9 |

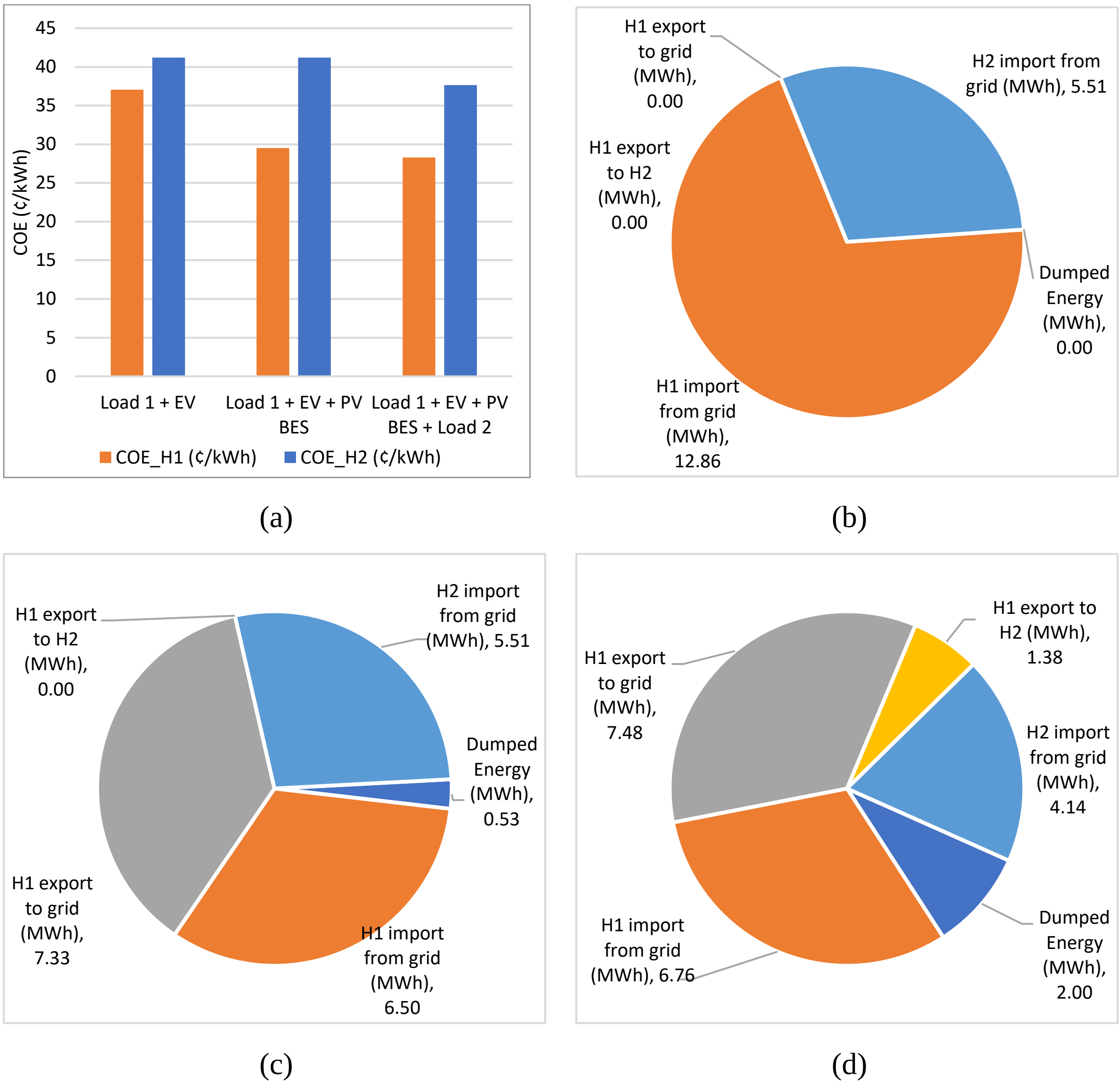


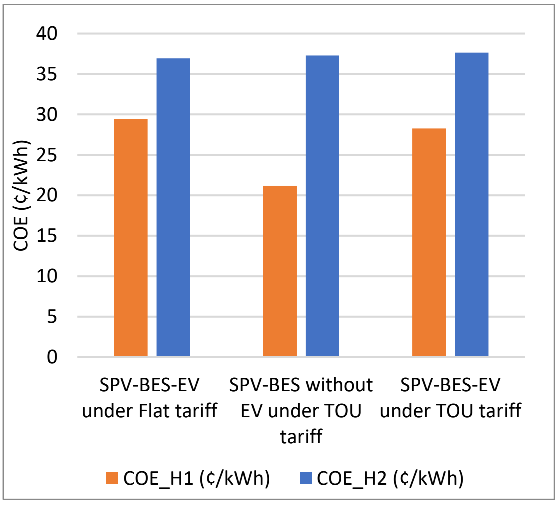

Figure 4.7: COE and energy import, export of each house for different configuration: (a) COE of H1 and H2; (b) Energy import, export for 1st configuration; (c) Energy import, export for 2nd configuration; (d) Energy import, export for 3rd configuration.

Results are presented by making 3 configurations for flat and TOU tariff which is shown in table 4.4. 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. 4.8(a). The lowest COE for H1 is when it does not have EV. Comparing H1 having EV with flat and TOU tariff, H1 has lower COE under TOU tariff. This is because H1 can take advantage of selling power to H2 in TOU rate and sell power to grid in TOU rate which is higher than flat rate. H2 has minimal effect on COE for all the configurations. COE for the 3rd configuration is higher for H2 which is due to buying some electricity from H1 in peak hours in TOU rate which is higher compared to flat rate.

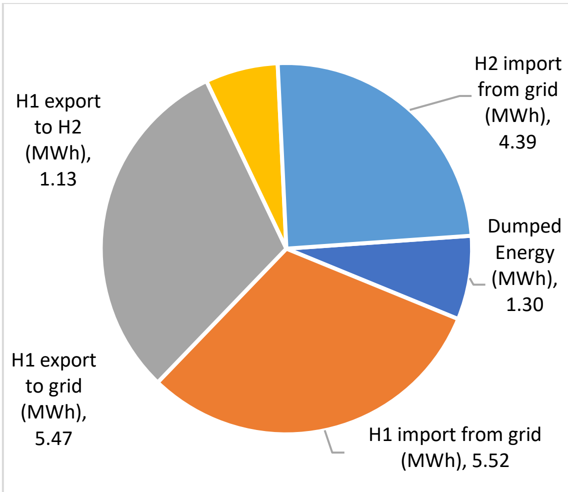
Pie chart in fig. 4.8(b), (c) and (d) represents the energy shared, energy bought from the grid by both the houses, energy sold to grid by H1, and energy dumped by H1. The maximum energy sold to H2 is in 2nd configuration because there is no EV. When there is no EV unlike other 2 configuration, H1 can sell extra energy to H2 or grid. When EV is present, more energy is shared between houses in TOU tariff compared to flat tariff as well as more electricity is sold to grid in TOU tariff.

Table 4.4: H1 Optimal component sizing for 3 different configurations with Flat and TOU electricity rates.

| Configuration | PV (kW) | BES (kWh) | NPC_H1 ($) | NPC_H2 ($) |
|---|---|---|---|---|
| **PV-BES-EV under Flat tariff** | 11 | 20 | 39462.6 | 23584.5 |
| **PV-BES without EV under TOU tariff** | 11 | 5 | 10059.5 | 23822.1 |
| **PV-BES-EV under TOU tariff** | 12 | 16 | 37030.3 | 24033.9 |




(a)

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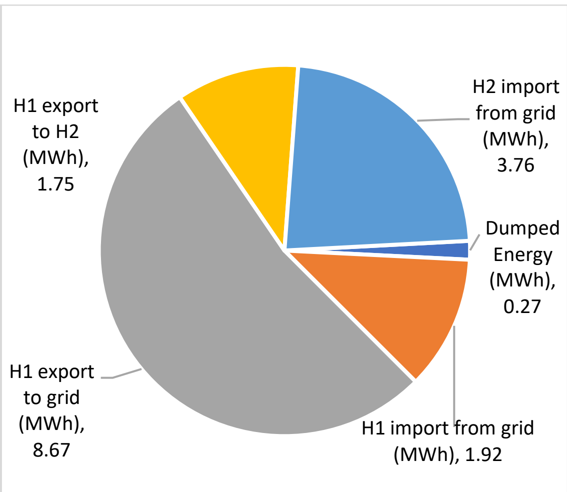
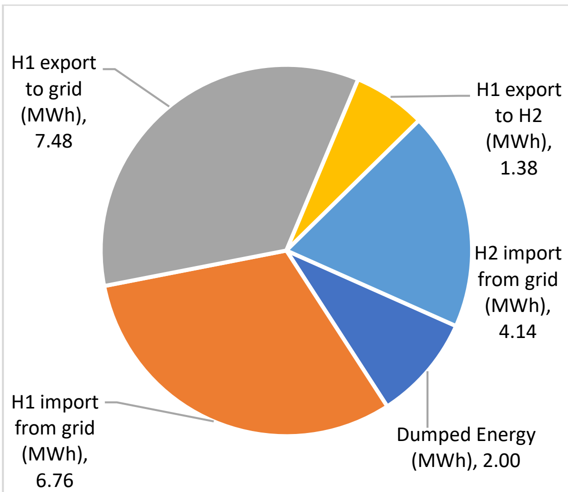


(c) (d)

Figure 4.8: COE and energy import, export of each house for different configuration: (a) COE of H1 and H2; (b) Energy import, export for 1st configuration; (c) Energy import, export for 2nd configuration; (d) Energy import, export for 3rd configuration.

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. 4.9 are investigated for comparison purpose. Data were taken from [32]. As such, the optimal components are shown in Fig. 4.10 along with COE for the homes. The lowest COE for H1 is achieved for Hyundai IONIQ because of its lowest battery capacity. For H2 BMW i3 and Hyundai IONIQ has the lowest COE if H1 uses those EV.

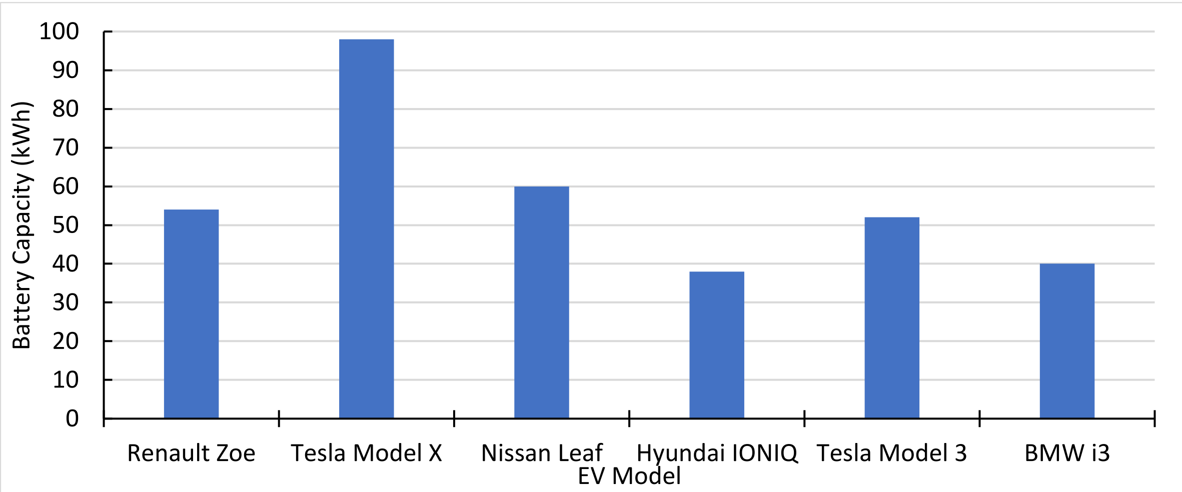



Figure 4.9: EV with different battery capacity

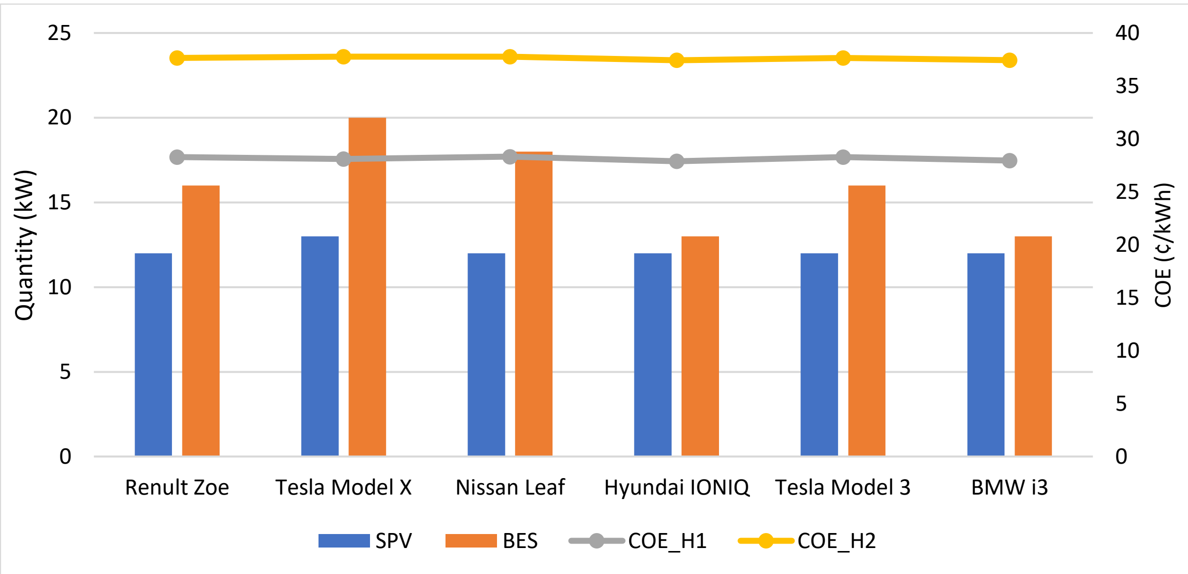


Figure 4.10: Optimal components and COE for H1 and H2 with different EV

### 4.5.2 Different scenarios results 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 H1 shown in Fig. 4.11. COE is the lowest in the 1st scenario which is due to the last 5 years with no contract. In the last 5 years, H1 cannot take advantage of the energy sharing rates between the homes. For H2 the lowest COE is when the contract between homes is 20 years as shown in Fig. 4.12. This is because H2 can take full advantage of 20 years of lower energy sharing rate from H1 compared to buying electricity from grid in retail rate.

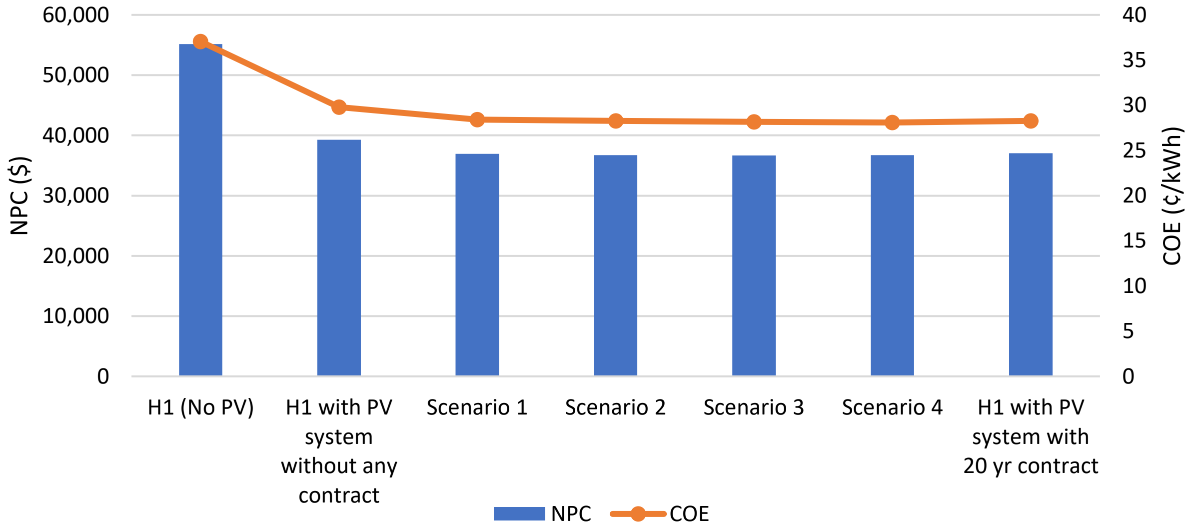



Figure 4.11: NPC and COE of H1 with different scenarios contract of energy sharing.

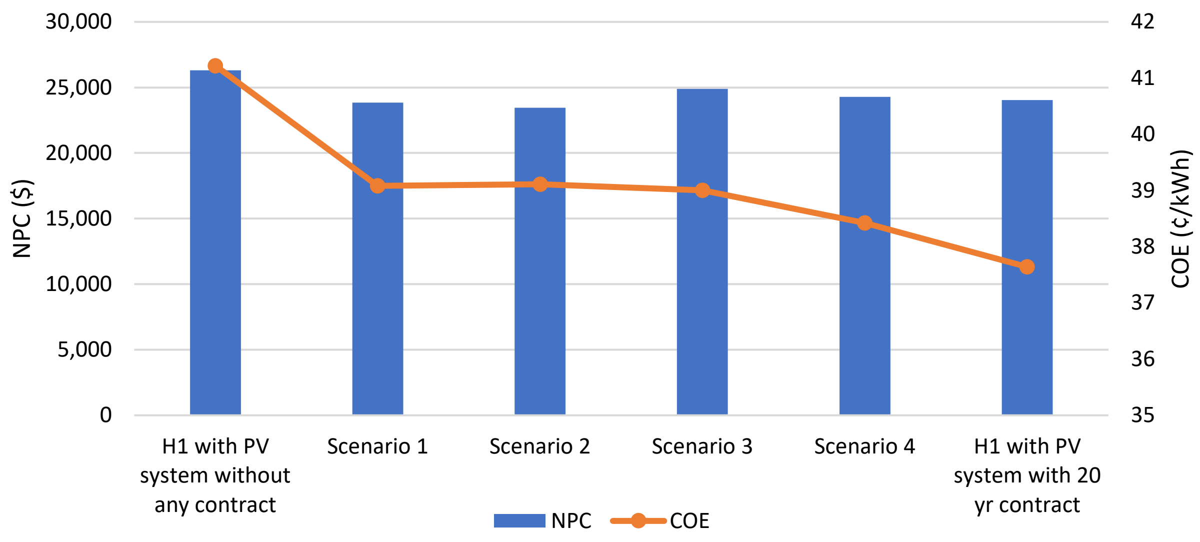



Figure 4.12: NPC and COE of H2 with different scenarios contract of energy sharing.

## 4.6 Analysis

### 4.6.1 Sensitivity Analysis

a. When export power limitation is changed

5kW 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 soon due to the gaining popularity of renewable energy sources, there is a good possibility that this restriction might vary. It is important to investigate its effect in our study which is presented in Fig. 4.13. The lowest COE is observed when the export power limitation is 10kW. This is because H1 can take full advantage of selling electricity to the grid instead of dumping electricity. Likewise, with the increase in number of solar PV, the power generation increases, and H2 can take advantage of buying electricity from H1 at a lower price as compared to the retail rate.

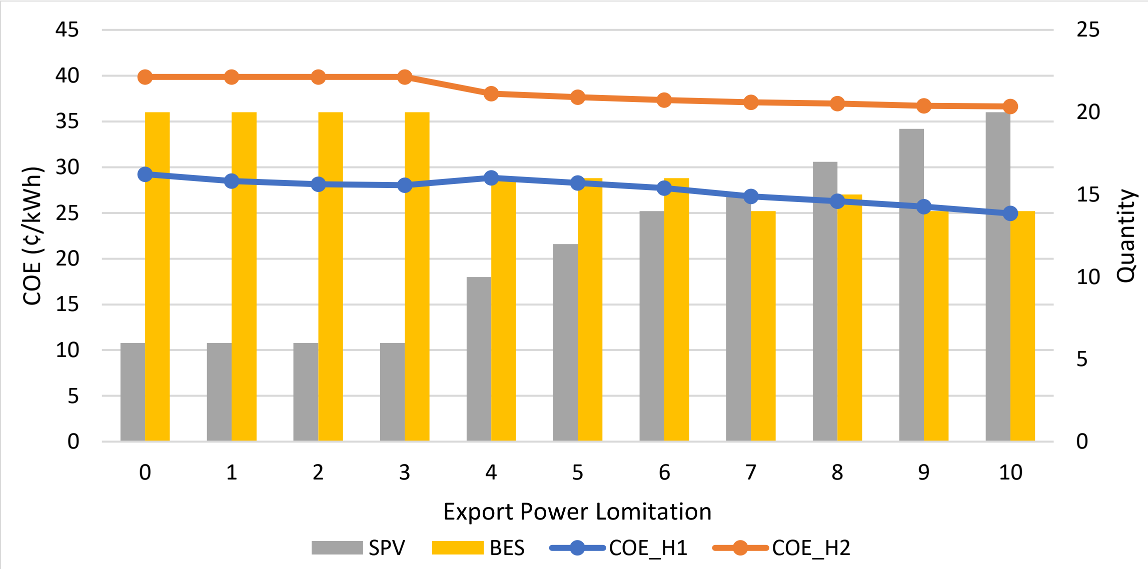



Figure 4.13: Sensitivity analysis in optimal components and COE when export power limitation varies for H1.

b. Changing export power limitation (with fixed PV and batteries)

The analysis is also done when export power limitation is changed but numbers of solar PV and BES are kept the same as optimal solution which is shown in Fig. 4.14. H1 shares electricity with H2, sells to the grid and dumps the extra electricity. The highest COE can be observed when export power limitation is lowest. This is because H1 cannot sell the electricity to grid for its benefit. When export power limitation is increased, COE for H1 gradually decreases till the point when optimal components are fully functional, and no power will be left to be exported which is 5kW as seen in Fig. 4.14. After this point COE for H1 remains the same. Export power limitation does not have impacts for H2.

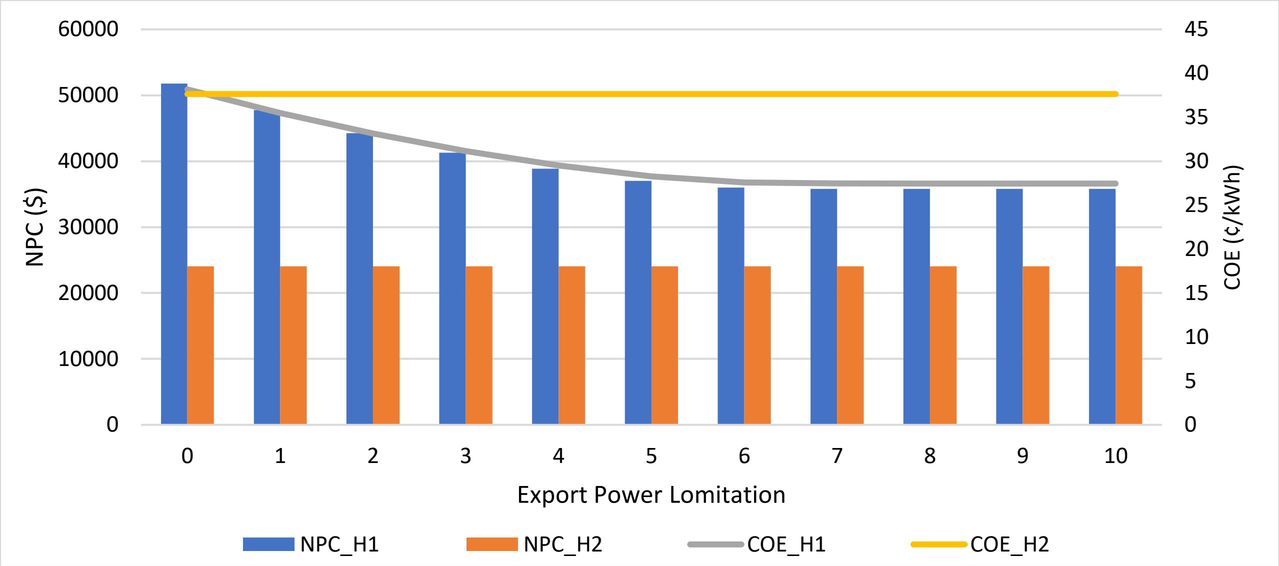
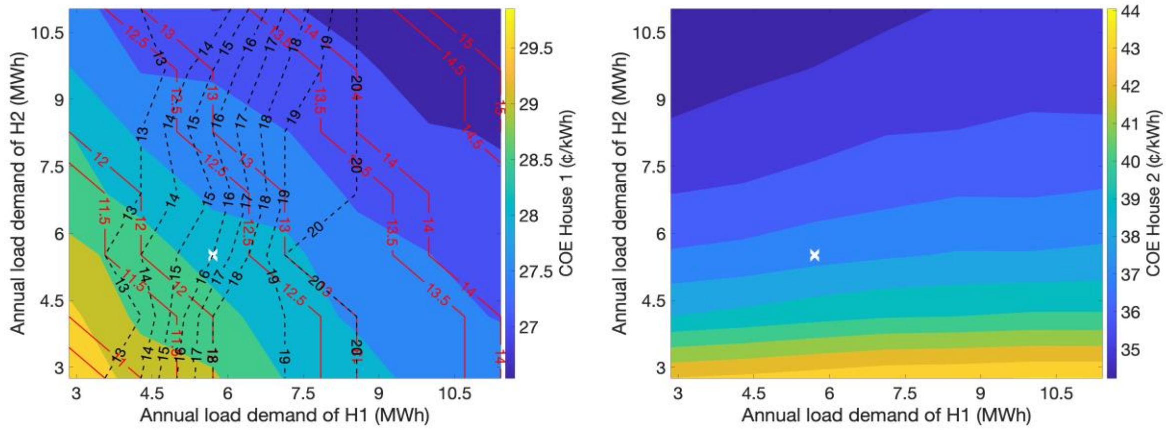



Figure 4.14: Sensitivity analysis when components is fixed as optimal solution and export power limitation is changed.

c. Variation of load demand of both the houses

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. 4.15 shows the contour plot diagram of this analysis. When the loads of H1 and H2 increase, the number of solar PV increases to satisfy the increased demand of the homes. The number of batteries increases when load of H1 increases which supports the load demand in peak hours whereas the number of BES does not have impact with the change in load of H2. It is because H2 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 H1 shown in Fig. 4.15(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 H1 by selling the electricity at a higher cost to H2. The lowest COE for H2 is when load demand of H1 is lowest and H2 is highest shown in Fig. 4.15(b). This is because when load demand of H1 is less, H2 can take extra advantage by buying more electricity at a cheaper rate. The reason behind H2 being able to buy more electricity is because the H1 demand is less, and generation is high. The cross sign (x) shows the COE for the homes of this study.



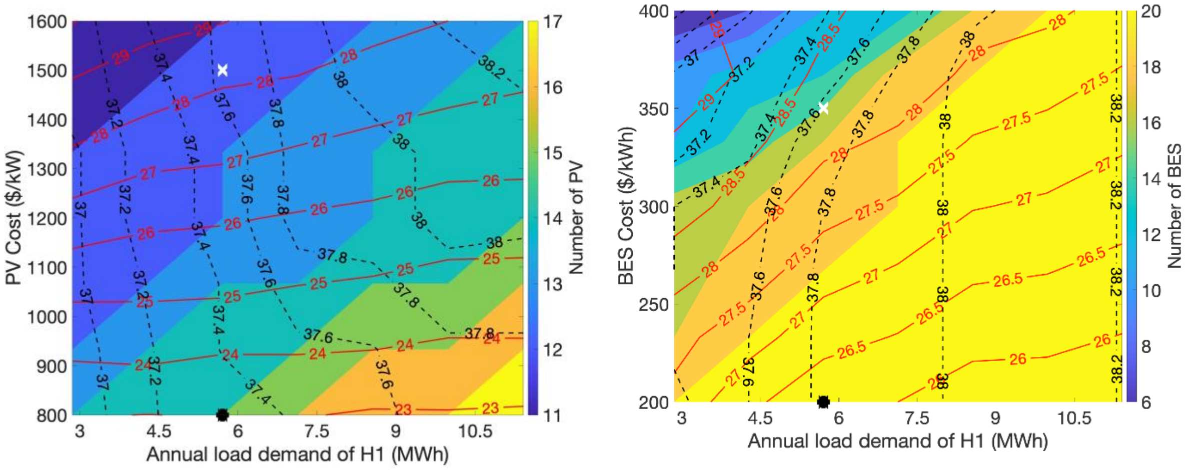

(a) (b)

Figure 4.15: Sensitivity analysis: COE represented by colour (a) Annual load demand of H1 vs Annual load demand of H2 (Red line represent number of PV and black dashed line represents number of battery), (b) Annual load demand of H1 vs Annual load demand of H2.

d. Cost variations of PV-BES

solar PV and BES 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. 4.16 represents the contour plot diagram when solar PV and BES costs vary and its effect on COE of homes. The red lines represent COE for H1 and dashed black lines represent COE for H2. Cross mark (x) in Fig. 4.16(a) shows the solar PV cost we used in this paper that is $1500/kW and dot mark (**.**) in the same figure shows the COE for H1 when solar PV cost is decreased to $800/kW. When solar PV cost decreases, COE of H1 also decreases. There is no effect on COE for H2 when solar PV cost decreases.

Cross mark (x) in Fig. 4.16(b) shows the battery cost used in this paper that is $350/kWh and dot mark (.) in the same figure shows the COE for H1 when battery cost is decreased to $200/kWh. When battery cost decreases, COE of H1 decreases but there is no effect on COE of H2 which suggests there is no effect on COE of H2 with component price.




(a) (b)

Figure 4.16: Sensitivity analysis: Red line represents COE of H1, and black dashed line represents COE of H2 (a) Annual load consumption of H1 vs PV cost (Colour region represent number of PV), (b) Annual load consumption of H1 vs BES cost (Colour region represent number of BES).

e. 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 4.5 shows the grid charge and its effect on COE and cost reduction for both homes. Breakeven point was achieved in 0.11 $/kWh in which H1 neither makes profit nor suffer loss with energy sharing. It is important to note that if grid charges 0.12$/kWh or more, there is no benefit for H1 to sell the electricity for H2. Beyond the breakeven point, H1 benefits more by just selling to the grid instead of sharing and paying the grid cost.

Table 4.5: Effects of grid charge on COE and cost reduction of both the houses.

| Grid charge as a rent/($/kWh) | Energy sold to H2 by H1/(kWh) | Cost reduction H1(%) | Cost reduction H2(%) | COE H1/(¢/kWh) | COE H2/(¢/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 |

### 4.6.2 Uncertainty Analysis

a. When the sharing rate and FIT changed.

Energy sharing rate between H1 and H2 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. 4.17. The (o) mark represents the rate that we used for this study. When energy sharing rate between the homes and FIT is high, COE of H1 is the lowest and vice versa as shown in Fig. 4.17(a). This is because H1 can take advantage of the high electricity sharing rate from H2 as well as it can take advantage of high FIT rate which lowers its COE. For H2 shown in Fig. 4.17(b), it is observed that the lower the energy sharing rate between homes, the lower the COE of H2 as it is benefitted when it can buy electricity from H1 at the lowest possible cost. There is not significant difference in COE for H2 with the change in FIT as COE of H2 does not depend on FIT of H1.

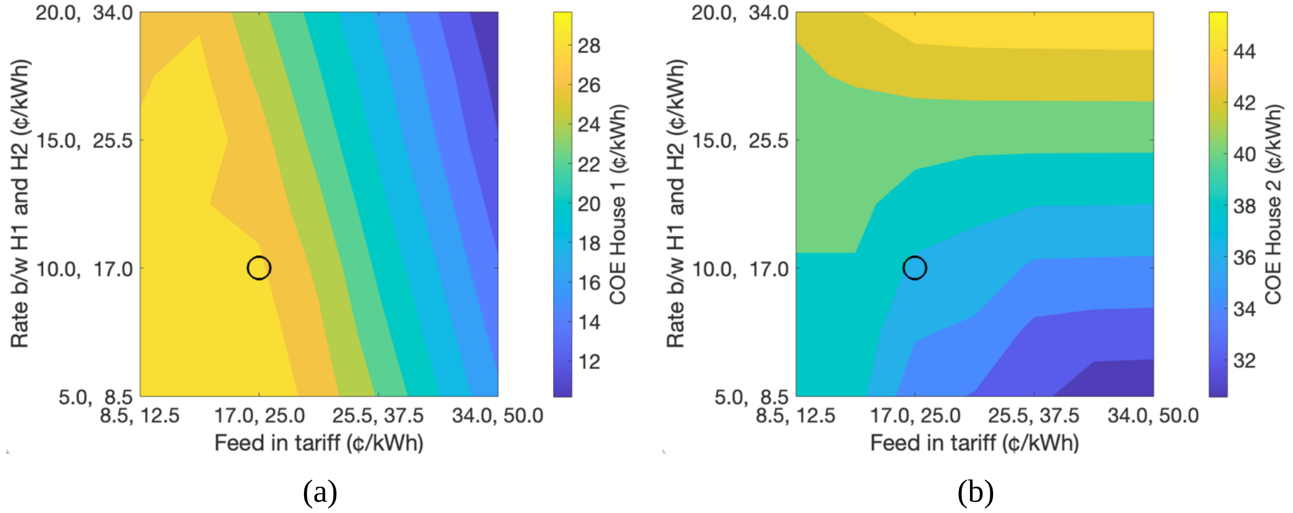



Figure 4.17: Uncertainty analysis: Rate between H1 and H2 vs FIT (a) Colour region represents COE of H1, (b) Colour region represents COE of H2.When solar isolation and ambient temperature changed.

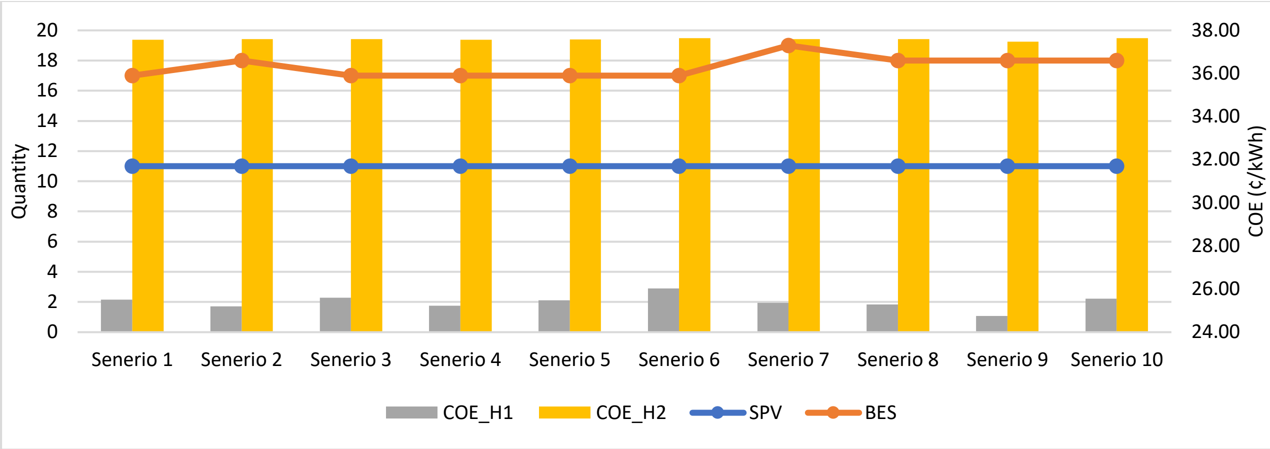
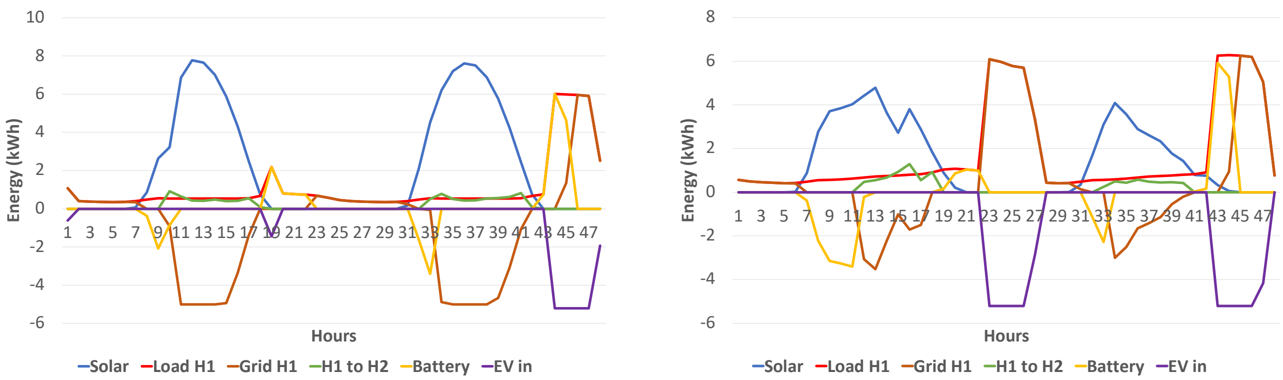



Figure 4.18: Uncertainty analysis on optimal sizing and COE due to the change in ambient temperature and solar irradiance from 2011-2021

Fig. 4.18 shows the scenarios from the year 2011 to the 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 H1 is in the range of 24.75¢/kWh to 26.03¢/kWh whereas for H2, COE is in the range of 37.47¢/kWh to 37.64¢/kWh.

### 4.6.3 Operational Analysis




(a) (b)

Figure 4.19: Operational analysis of 2 days: (a) Summer (b) Winter

Power flow diagram for H1 in summer and winter for 2 consecutive days is shown in Fig. 4.19. 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, H1 load has been satisfied by solar PV and extra power is sold to the grid. In the evening when solar PV 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.

## 4.7 Technical challenges and Discussion

Battery degradation can result in a decrease in its capacity, efficiency, and even pose safety risks. The term "cycle life" refers to the maximum number of times a battery can be discharged and recharged before it needs to be replaced. PEVs can be recharged using standard plug sockets, although it is important to note that these sockets charge PEVs at a slower rate. Additionally, it is not always convenient for vehicles to access these sockets due to their limited availability. PEVs face technical challenges in terms of convenience and efficiency due to the slow charging speed and limited accessibility of standard plug sockets. The integration of electric vehicles (EVs) into the grid necessitates the use of sophisticated control and communication systems. These systems are essential for effectively managing the charging and discharging of EVs, as well as enabling vehicle-to-grid (V2G) capabilities. Determining the optimal sizing of charging infrastructure is a challenging task due to the variability in EV charging patterns and the need to balance charging demand with the available power supply. Advanced modeling and simulation techniques, such as Particle Swarm Optimization (PSO), in conjunction with data-driven approaches, can be utilized to optimize the sizing of electric vehicle (EV) charging infrastructure. These techniques consider multiple factors and scenarios, enabling more efficient and effective decision-making.

## 4.8 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 solar PV and 16 kWh of BES 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 H1 with components and EV without energy sharing is 29.5 ¢/kWh whereas for H2, it is 41.2 ¢/kWh. After energy sharing, the COE for H1is reduced to 28.3 ¢/kWh and for H2, it is reduced to 37.6 ¢/kWh. The reduction of COE for H1 is 4.23% and for H2 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. Negligible change in uncertainty analysis proves the robustness of the results obtained despite the variation in solar insolation and ambient temperature.

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# Chapter 5. Conclusion

This study presented the optimal sizing of components for grid-tied houses. The objective function was achieved to minimize COE for house 1 while reducing the COE for house 2. It was observed that energy sharing has reduced the COE for both houses reasonably. The study conducted for energy buying from the grid, selling to grid, and sharing between houses using flat rates shows COE reduction on house 1 was 7.6%. This was due to energy sharing on high rate instead of selling electricity to grid in a lower rate. COE was reduced 9.7% for house 2 in the same study. Flexibility in number of contract years and its effects on COE was analysed so that houses would be flexible in the contract they make for energy sharing by making 4 different scenarios. No matter the scenarios, if electricity was shared between the houses with mutually agreed rate, both the houses got benefit as COE of house 1 was found less than 33.81¢/kwh and COE of house 2 was found less than 40.42¢/kwh in all the scenarios. The optimal component size achieved for the flat rate of buying, selling, and sharing electricity was 10kW of PV and 7kWh of BES.

Likewise, the study that uses TOU rates shows more reduction in COE. Out of eight different studied schemes, T-T-T scheme is obtained as the best option which has significant reduction in COE. The reduction for house 1 was 37.4% and for house 2, it was 7.7% compared with just selling electricity to the grid in flat rate and without energy sharing. The massive benefit for house 1 is because of electricity sold back to grid as well as house 2 in higher TOU rates. Additionally, for house 2 instead of buying in peak rate from grid, it has more benefit to buy on peak rate of shared energy price. The optimal component size achieved for this scheme was 11kW for PV and 5kWh for BES. Sensitivity analysis was done by changing the parameters such as export power limitation, load consumption of both the houses and PV-BES cost and its effects on components sizing and COE is discussed. On top of sensitivity and operational analysis, this study has also investigated the results for uncertainty analysis and effects on optimal sizing and COE was observed and discussed.

Finally, the study looked at the ideal component sizing for grid-connected homes that have EVs and share energy. When considering TOU rates, 12kW of PV and 16kWh of BES were discovered to be the best components. Finding the lowest and best COE for H1 and lowering the COE of H2 through energy sharing was one of the most significant aims. COE has been reduced from 29.5¢/kwh to 28.3¢/kwh which is 4.23% for H1 and 41.2¢/kwh to 37.6¢/kwh which is 8.69% for H2 when compared with COE for each of these houses without energy sharing. Investigations were done with different EVs having different batteries capacities and how COE and optimal sizing is affected for the houses. The robustness of the obtained results was tested and verified with the negligible change in uncertainty analysis despite the variation of ambient temperature and solar insolation.

This was the research conducted with the load data of 2 different fixed houses, solar insolation, and ambient temperature of fixed region. But this research is general in nature and the methods can be used for any houses throughout the world to take the benefits. To implement the method, following data are needed: load consumption data of 2 houses who are willing to share the energy, solar insolation, ambient temperature of region where houses are located, components cost, electricity rates of the energy provider used by those houses in that region and mutual agreement rate between the households. The developed methodology helps consumers to buy the optimal size components in the beginning of the project which helps them to pay optimal cost for maximum benefits before installation of components. The consumer can get an estimation of the savings that they can make before the project. Additionally, the developed method also helps in reducing COE for the houses who already owned PV-BES. The installed PV-BES may not be of optimal size, but it does not stop households from taking some benefits via energy sharing. The simulation can be run using the proposed methodology along with the integration of all relevant data which will provide an estimated value of cost reduction for both the houses.

However, it is important to observe that households present, and future electricity consumption may vary. The guidelines presented would be according to their present pattern of electricity consumption.

# Chapter 6. Future Work

Future research can explore the optimization problem and effects on COE for multiple homes by expanding the number of prosumers and consumers involved. A separate home energy management system could be developed to find the optimal components sizing for each of the houses in the network. On top of reducing electricity cost, this will help in reducing total upfront capex cost when buying components for the houses in a network. Additionally, demand-size management could be introduced to enhance the efficiency of the network. With the help of demand-size management, prosumers and consumers are encouraged to use the electricity during off-peak periods so that the network would function smoothly during peak hours. Also, adding incentives for those using electricity during off-peak periods could be introduced.

This research and methodology can be taken as a base study and separate automated methods can be developed to provide proper guidelines to the customers who intend to use this methodology instead of manual simulation for each prosumer and consumers. The guidelines may include the percentage of COE reduction comparison before and after this method is used, COE reduction comparison in different scenarios, estimation of initial Capex and maintenance costs of systems.

## Publications

Most of the work in this research is either published or pending for publication.

**Published Paper:**

[Pub. 1] S. Khanal, R. Khezri, A. Mahmoudi, S. Kahourzadeh, “Optimal capacity ofsolar photovoltaic and battery storage for grid-tiedhouses based on energy sharing,” IET Gener. Transm.Distrib. 17, 1707–1722 (2023). https://doi.org/10.1049/gtd2.12824

**Pending Journal Paper:**

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

- Submitted to Applied energy journal.
- Under review.

**Pending Conference Paper:**

Optimal capacity of solar PV and Battery energy storage for grid-tied house with EV based on energy sharing.

- IEEE international conference on energy technologies for future grid (ETFG)
- Under review