# Energy Storage and Solar PV comparison for Grid-Connected Australian Households (Gas-Electricity against Electricity Consumption)

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Amandeep Kaur Kalsi

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## ABSTRACT

Increasing electricity prices and energy consumption, results in more and more attention towards photovoltaic (PV) system for electricity generation. This study investigates the impact of PV and battery sizes on price reduction for South Australian residential houses by comparing two cases, gas and electricity energy consumption and only electricity energy consumption. The optimal PV and battery capacities are determined for both cases. The aim of this study is to reduce the overall costs of the system and proposing most beneficial option for South Australian (SA) houses with reduced $CO_2$ emissions. The load demand input data of a real Adelaide household is used in this study. The simulations are carried out in HOMER Pro in which different models are created namely grid tied PV, grid tied PV-battery for houses with gas and electricity energy consumption as well as only electricity consumption. In simulation, all the parameters are calculated including net present cost, replacement costs, capital costs, renewable fractions, operating costs, operation and maintenance costs, electricity purchased from grid and sold to the grid, $CO_2$ emissions and energy produced by different PV sizes. The assumed feed-in tariff of $0.11 is taken in this study. The results pointed out that the house with electricity and gas is more economical option than only electricity in case of residential consumers. Moreover, grid and PV option has more economic benefits while with battery the purchase power from grid is least but has higher capital costs of the system with battery. The results of this research also outline the sensitivity analysis which shows the effect of volatility of gas and electricity prices over a period of 20 years by changing the prices and analysing the outcomes in HOMER Pro.

Keywords: Battery energy storage, Renewable fractions, $CO_2$ emissions, grid-connected household, HOMER Pro, gas and electricity consumption, photovoltaic system, feed-in tariff.

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# CHAPTER 1

## INTRODUCTION

Nowadays, people are investing in battery storage option in PV tied dwellings due to the fluctuation in electricity demand and decrease in feed-in tariffs [1]. These systems have benefits based on economic and environmental aspects. In Australia, about 89% of the electricity is produced by non-renewable sources which produces excessive amounts of greenhouse gases and only 15% of electricity is produced by renewable energy sources according to Australian department of environment and energy [2]. Recent trends of renewable energy system lead to the reduction of $CO_2$ emissions in the atmosphere. This

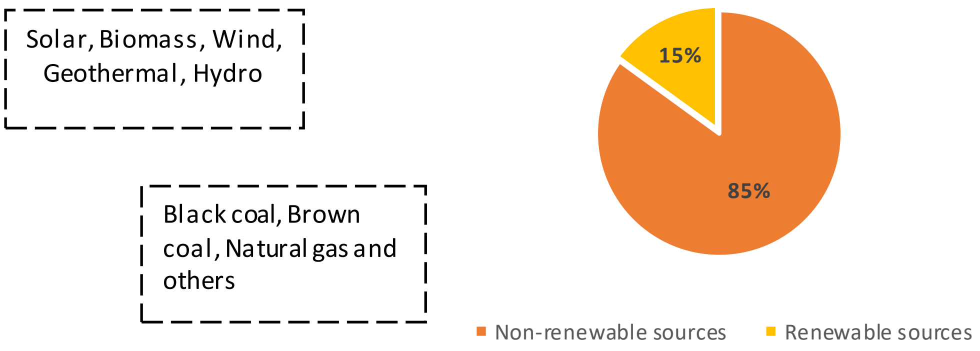


Figure 1 Electricity generation across Australia [2]

research is based on South Australian dwellings to provide households, an optimal system with least net present costs and least harm to environment. Based on earlier studies that has been examined under Photovoltaics- Battery energy storage (PV- BES) system economics, this research includes a simulation model that is created with optimal battery size for grid connected PV systems for residential area in Adelaide, South Australia. The generated electricity from the PV, fulfil load demands during peak hours when sun shines and excess energy is stored in the battery. But many factors are considered in this case like discharging of power from battery that effect the overall system performance. The structure of the research involves the evaluation of optimal battery size for different PV panel sizes. It also compares the dwellings with electricity and with electricity and gas and determines which case is less expensive for different number of occupants. Optimal sizing of PV and battery with electricity has been done in past studies while this research analysing a new aspect of the same scenario with gas and electricity both and finding a cost-effective option. The houses which purchase electricity from grid and has only PV installed are compared with the houses which has PV and battery both. The main objective of this research is to reduce the overall costs of the system over a period of 20 years including installation, operation and maintenance costs and capital costs while at the same time costs associated with purchasing power from grid meeting load patterns.

## 1.1 Background

In the beginning, fossil fuels were mainly used for electricity production that leads to greenhouse gas emissions. But today various renewable energy sources are being used, for instance solar, thermal, wind, hydro etc. About 32% of houses in South Australia has installed rooftop PV according to AEMO (Australian Energy Market Operator) [1]. Figure 2 shows the estimated actuals and forecasts of annual roof top PV generation for South Australia which shows a linear increase in the generation in coming years. The renewable energy generation has increased in all the states of Australia including South Australia with 50.5% and Victoria with 13.5% [3].

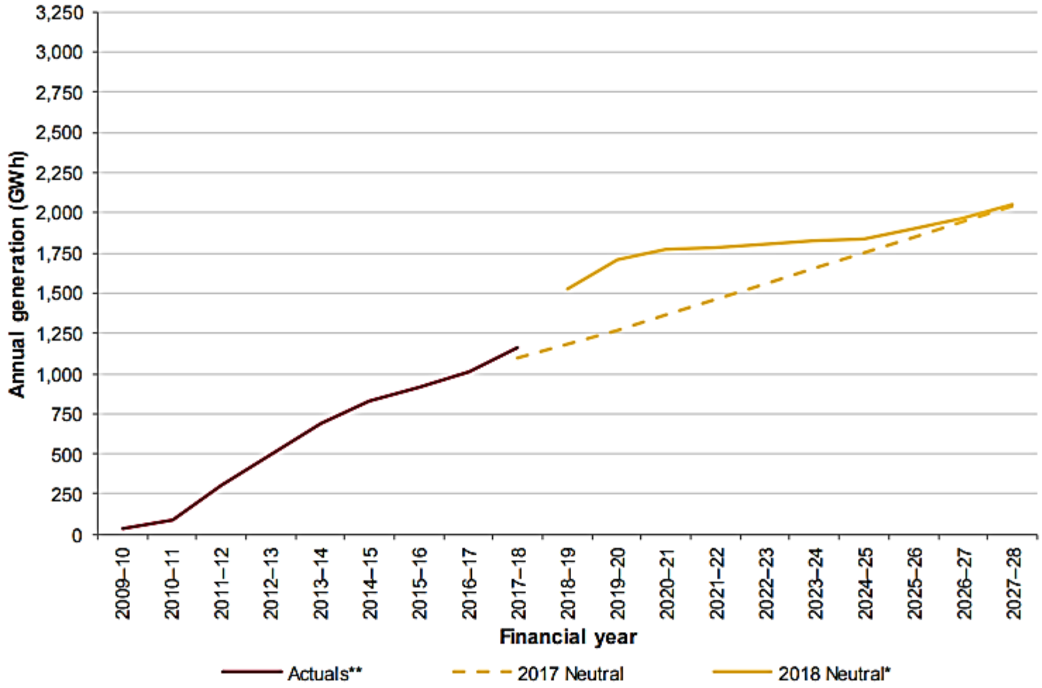


Figure 2 South Australian roof top PV generation forecast [1]

The residential electricity demand in South Australia is less dependent on grid from last few years due to the increasing use of solar panels. There are few factors that affect the overall consumption from grid i.e. storage options for PV installed houses, number of electric appliances installed, type of electric space heaters etc. During the day light hours when consumption is low, storage devices stores the excess electricity produced by rooftop PV panels and then that energy is utilized in the evening when demand is high which leads to purchasing least amount of electricity from grid. Many storage devices are used for residential dwellings such as batteries, fuel cells, capacitors and flywheels. According to AEMO South Australian electricity report, 15MW of embedded battery is estimated in South Australia [1]. For residential applications, the most effective approach is battery storage. In South Australia, about 40,000 South Australia households has access to about $100 million in loans for home battery system installation from 2018 October [4]. The subsidy for battery in South Australia is calculated on the basis of kilowatt hour capacity of battery being installed i.e. $500/kWh for all households [4]. The energy types in Australia are electricity and gas. Some dwelling has both gas and electricity connected while others has only electricity connected. This study covers the research based on the comparison of these two approaches and choosing the most cost-effective option for South Australian Dwellings.

## 1.2 Problem statement

Increasing price of electricity and a gap between electricity supply and demand is one of the major issues in South Australia. Moreover, PV system is less efficient due to high mean temperatures of certain months and times. Nationwide adoption of optimised Roof top PV system with storage can provide following benefits:

- Reduction in electricity bills and less dependency on Grid for load consumption
- Blackout protection due to the battery storage option
- Reduced $CO_2$ emissions
- Reduced overall cost of the system

## 1.3 Objectives

This study implements an important role in the field of energy optimisation economically and safeguarding the environmental. Economically, the main objective is to reduce the overall operating costs of the system. From nature preservation viewpoint, environment issues are analysed by comparing different systems based on their $CO_2$ emissions. Therefore, the results of these two issues will help decision-makers to choose optimal model according to different system design including PV against PV-BES system and electricity and gas against only electricity energy consumption.

## 1.4 Method

The focus of this project is the comparison of different PV sizes and battery sizes and finding an optimal and cost-effective option. The electricity and gas data is analysed in excel and all the load patterns are created which gives an idea about the consumption hourly, daily and seasonally. Solar irradiation data of Adelaide as well as load data is imported in HOMER Pro software in the form of .txt files and different models are created for grid tied PV and grid tied PV and battery storage systems. Models are modified as the inbuilt battery component doesn't meet with the project requirement.

HOMER Pro is a US based software. Initial setup includes currency change, otherwise HOMER Pro will show the results in US dollars, therefore it is changed to Australian dollars under economics tab. It has inbuilt load data files of USA for different locations which is not applicable for Australia. The models are tested for different electricity prices and PV and battery sizes in the end which is explained in sensitivity analysis.

## 1.4 Thesis outline

Chapter 1: Introduction

This chapter gives the brief description of Grid connected roof top PV with and without battery dwellings in South Australia. It also covers the idea of research, background, problem statement and objectives.

Chapter 2: Literature review

The literature review provides an overview of previous research on PV and battery systems for residential areas and methodologies which has been implemented so far for optimisation.

Chapter 3: System configuration and methodology

This chapter covers the project requirements and system layouts which shows PV and battery connections to dwellings and it also covers the description of each component in detail. This chapter also covers the mathematical equations taken from HOMER Pro software which are used for evaluating different parameters for optimal Battery sizing and overall costs calculation.

Chapter 4: Load data

In this chapter, input data of electricity and gas is analysed according to hourly, monthly, seasonally profiles. It has also covered solar irradiation data and financial data. Financial data covers the assumed prices of electricity, components, feed-in tariff in this thesis.

Chapter 5: Results and discussions

In the chapter 5, all the designed models are given and simulated and also passed through sensitivity analysis which includes different PV sizes and their NPC values. For a better understanding and clarity of each and every factor many figures are added in the research for each and every case.

Chapter 6: Conclusion and future works

This chapter provides conclusions drawn from the research followed by recommendations and future works.

# CHAPTER 2

## Literature Review

The investigation has been done on past studies related to PV and battery size optimization and economic parameters of PV equipped residential areas. Many factors affect the optimal sizing of grid tied PV system performance including PV inclination, orientation, shading, climate, temperature, load data, installation area and component capital costs. Many factors are covered by various studies. The PV inclination factor was covered by Australian study in Queensland in which Queensland climate was analysed to evaluate PV system economic, technical and environmental performance using HOMER Pro tool [5]. The study found that the most optimised PV size is 6kW PV system which saves more than 90% of electricity and system reduces 95% of carbon dioxide emission. The study shows that the slope of PV panels put a great impact on cost of energy and for number of cities in Queensland 20-25 degrees slope of panels results in least cost of energy (COE).

Mondol. et al. (2009) investigated that inverter sizing also effects the PV size optimisation as the oversized inverter increases the PV energy cost and found that at higher isolation locations PV savings are least effected with oversized inverter for European countries. The study also covers the impact of feed-in tariff rate changes which concludes that at higher feed-in tariff the PV savings rate at higher PV size is higher as compared to lower feed-in tariff rate. Therefore, the profits can be increased by minimising the PV generated electricity fed to grid when the buying power price is more than the sell back price [6].

Battery type and its lifetime embody an important role in optimization. Lifetime is measured with the help of standard charging and discharging. Yang et al. [7] and Sharma et al. [8] interpret that li-ion is the most suitable battery storage option because of its long lifetime, power density, roundtrip efficiency and energy density. Whereas, Mohcene et al. [9] suggested that lead acid battery is most suitable option as it is of low cost which will in turn reduce the overall costs. When generated power exceeds demand then that power is stored in the battery and excess power beyond storage capacity is fed to the grid whereas if the generated power is less than demand then power is supplied by grid. These two cases are studied in detail by Sharma et al. whose objective is to reduce the overall LCC costs. In this study, replacement and salvage costs of PV are not considered, and O&M and salvage costs of battery are not considered for LCC calculations. Sharma et. al. in [8] concluded that if the retail price of electricity increases then LCC costs of PV tied dwelling without battery also increases in contrast to PV tied dwelling with battery. This is opposite in case of lower retail prices. In this study, consumption of 17kwh/day with retail price, 0.30 cents/kwh is considered and feed in tariff $0.05/kwh is assumed. However, Ru et al. [10] also pointed out that the battery size would be more than $Cref^c$ in order to reduce LCC costs. Here, $Cref^c$ is a unique critical value for battery size. This study analysed battery size for power arbitrage and peak shaving in case of grid tied PV system and its configuration is shown in the figure 3. An algorithm is used in order to evaluate $Cref^c$ with the help of upper and lower bounds of battery size. Similarly, Yann et al. [11] study is also based on peak shaving at a low cost and dynamic programming is used to resolve optimization issue.

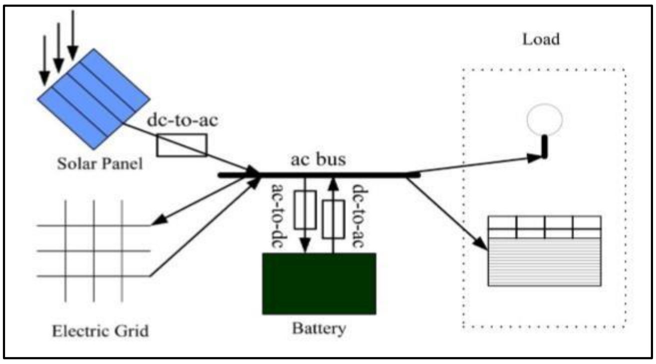


Figure 3 Grid tied PV and battery storage system [10]

In terms of cost-effective approach, Carmen et al. created a MILP (mixed-integer linear programming) model for Adelaide based small residential neighbourhood demands such as electricity, space heating and cooling with the combination of distributed generation (DG) units with thermal or storage units [12]. DG units includes PV units, small scale wind turbines and CHP (combined heating and power) units and Microgrids (MG) involves DG units, storage units and sinks at distribution level. CHP units provide a link between electrical and thermal supply and waste heat can be used for heating and cooling through absorption chillers. Therefore, the power produced by DG units can be fed to grid for feed-in tariffs. Many scenarios with different number of houses are analysed on the basis of sensitivity and variability analysis. Under multi-micro grid approach two MG pools consisting five houses are created with two CHP units in both pools and a pipeline is also Installed within the same pool [12]. The results show that the scenario with combined heat and electricity as well as thermal units is the most cost-effective design [12].

Hongbo et al. in [13] analysed hybrid system model consisting PV panels, fuel cells, residential load and battery storage with main objective is to reduce system costs as well as CO2 emissions. In this case, 82% of produced power is used by residential loads with left over power used for battery charging and no power is fed to the grid for economic benefits. The study also includes that during winter hours from 17-7, the power is supplied by fuel cell and extra power if required is taken from grid whereas during summers between 21-6 hours grid and fuel cell fulfil the whole electricity loads. The study concludes that larger battery size results, reduction in environmental issues but it also effects the economic performance. Moreover, battery is mainly charged by PV or fuel cell but the 74% electric load is fulfilled by grid and fuel cell. Residential load is fulfilled by grid at the time of high buy-back price but at low buy-back price, PV power is used for self-use [13].

However, one more Hybrid based study in Sweden is opted for battery optimization which involves two strategies namely, conventional and peak shaving and two models i.e. shepherd model and single diode model are simulated under three operational strategies namely conventional operational, dynamic price load shifting and hybrid operation strategy [7]. Yang et al. in this study pointed that life cycle of battery decreases with depth of discharge. In case of excess power production, after storing power in battery, the excess power is fed into the grid and battery discharges when PV don't meet the load. Battery increases the system revenue and self-consumed electricity. But this is not appropriate for dark and cold months. The study concluded that in case of conventional strategy, at a fixed PV size, with rise in battery size results in decrease in NPV and self-sufficiency ratio (SSR) increases which shows that employing a battery is not economical option but it increases the renewable penetration level. Here, SSR represents the environmental goal which means that higher the SSR, "greener" the system is. Dynamic load shifting is also not a beneficial approach due to battery costs. However, Hybrid strategy is found as optimal solution as it shows that when battery size is less than 72kWh then Net present value increases with the battery capacity [7]. However, another study in [14] covers optimal storage strategy which covers a battery optimisation analysis that shows that optimal system size increases at lower battery price and for current battery cost, 5kWh has shortest payback and it is assumed that in 2020- and 2030-year battery costs, the optimal system will be 6kWh and 7kWh.

Iromi et al. [15] analysed two different cases for battery connected PV systems i.e. DC as well as AC coupled. For DC, battery is through bi-directional converter to the dc link while in case of AC, battery is connected through bi-directional converter and inverter to ac link. During the solar noon, due to the excessive power production from PV leads to reverse power and it results in over voltage. controlled the cycling of storage to resolve the issue of over voltage in PV system equipped with battery. It involves three cases i.e. when there is less production from PV system without sell-back price for the energy from storage for one day, when there is high production from PV system without sell-back price for the energy from storage for single day and with separate sell-back price from storage for energy. For the first case the battery remains idle as the battery degradation cost can't be recovered in this case and for second case it is charged to maximum even if the battery degradation cost is higher or not. In the third case, sell back price is zero and battery is charged to minimum point at the end of peak period and the excess energy is fed to the grid.

Mulder et. al. [16] studied measured data from seven different houses in Belgium in order to calculate dwelling consumption with the help of ac power out of inverter, power drawn and out from the grid. In [16] two design criteria are analysed i.e. power required (includes charging and discharging) and storage capacity. The power production through PV is five times more in summer than winter. The author in this study concluded that due to less flow of energy towards battery in summer leads to low plateau value in January and high in June which leads to bigger battery size in summer than in winter. Based on ideal storage, calculations are made towards real storage system and its results show that based on specific dwellings PV panels cover 33% to 73% of electrical energy consumption [16].

V. Raviparsad et al [17] did research on optimal PV sizing for standalone systems using sizing ratio. Sizing ratio is a measure that enhance the overall PV system performance by making a balance between PV capacity and inverter capacity [17]. The research used bottom up approach to find the optimal PV size. The author analysed that over sizing of PV array results in power loss as the inverter input is less than available power and in case of under sizing of PV array, sizing ratio of 0.8 is taken for avoiding temperature breakdowns. The research concluded that, PV to inverter sizing ratio and performance of PV systems depends upon the starting current and if the solar radiation is above STC then power limit controller of inverter will not affect the generated excess power [17].

G. Gursoy et al [18] also did research on optimal sizing of a hybrid system including PV, wind and battery systems in which solar and wind data is converted to useful energy. The author analysed that if the demand is more than generation then demand response technique is applied to avoid excessive battery capacity usage. In demand response technique, consumers manage the consumption and the results in this research show that 65% battery size and 28% capital costs got reduced with this technique [18]. Similarly, T. Nedim et al [19] analysed wind-PV-battery optimisation for residential houses, which has covered six combination models including, solar alone, wind alone and hybrid and the objective of the study was to minimise the total cost of the system. The author concluded that the most cost-effective system was hybrid system with 3kW wind turbine and PV panels of 0.25kW for the given load pattern of residential house [19].

This research covers the optimal battery size of PV and battery for an Adelaide based household in HOMER Pro. The electricity data is taken from South Australian low energy houses of Lochiel park in which about 60 houses are analysed to test their electricity consumption based on different time frames during a day [20]. This study will also compare dwellings with electricity and gas connected system with only electricity connected system by analysing the overall costs of both systems at different PV and battery sizes. At the end, the most favourable and cost-effective approach will be determined.

# CHAPTER 3

## System configuration and methodology

### 3.1 Project requirements

In this research, all the models are designed, analysed and optimised in HOMER Pro. HOMER is hybrid optimisation of multiple electric renewables and 3.12.5 version is used in this analysis. It requires following data for proposing optimised solution.

- Solar irradiation [kW /m$^2$] of Adelaide based household
- Gas [MJ] and electricity [kWh] demand hourly for grid connected house with electricity and gas consumption
- Electricity demand for only electricity connected houses
- Different components and their technical specifications including PV, battery, converter
- Retail price of electricity and gas and feed in tariff rates
- Component prices including purchase cost, operation and maintenance costs and replacement costs at different PV and battery sizes for cost analysis
- Inflation rate Australia
- Discount rates

Determine,

- Net Present Cost (NPC) of the system at different PV and battery sizes and evaluation of optimal size at least NPC
- Optimal design among Electricity connected house and electricity and gas connected house. For the analysis, a flow chart is created in the figure 2. The chart shows a basic layout of research including input, processing and results. For research, input data is required including load data, component specifications and prices, discount rates, electricity retail prices, feed-in tariff prices and inflation rates. In the process, different models are created at different PV and battery sizes and at the end all cases are compared, and most suitable and cost-effective system will be selected.

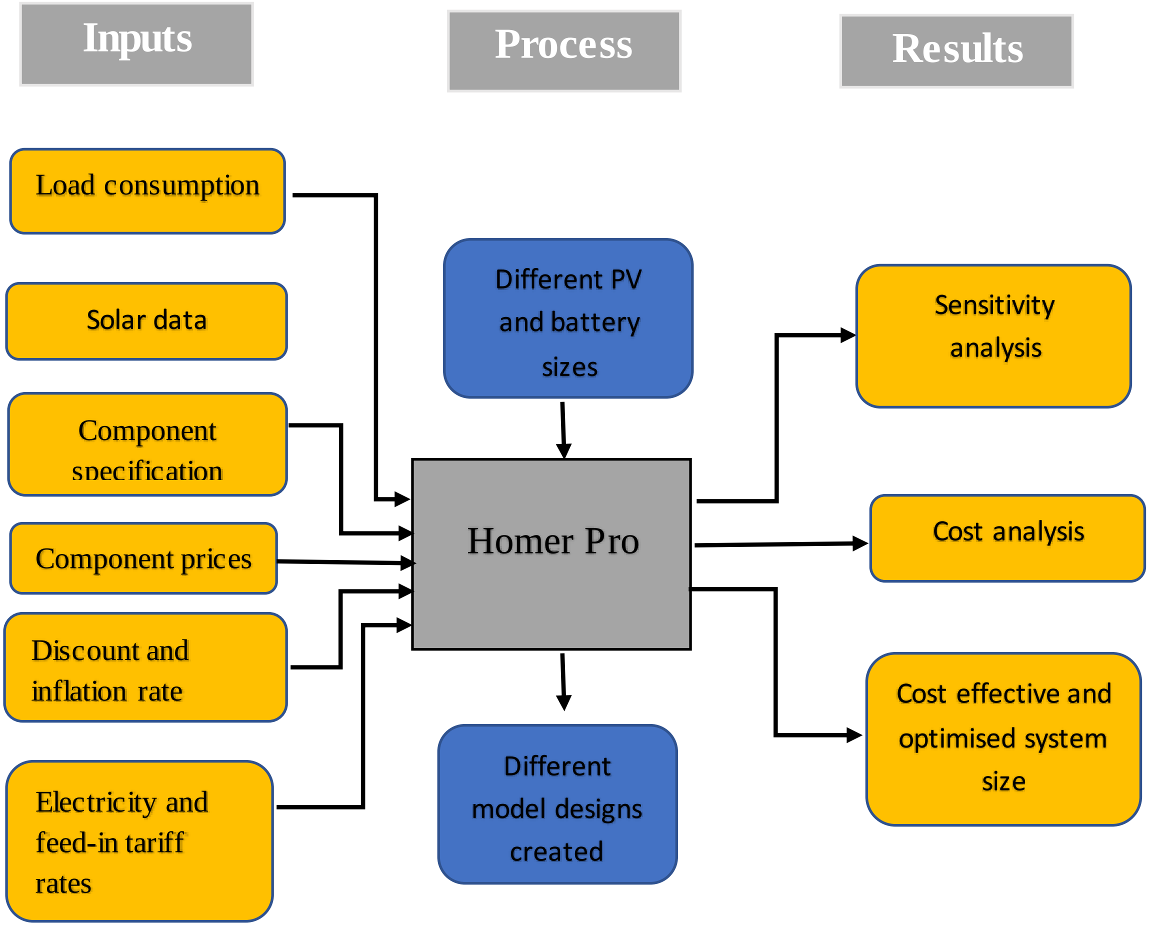


Figure 4 Proposed framework

## 3.2 System layout

In this study, an Adelaide based grid connected house is considered under two scenarios. First scenario i.e. House with electricity and gas consumption is compared with electricity only consumption which is scenario 2. Electricity and gas both can be used for heating and cooking purpose. Gas water heaters are more expensive but more effective than electric heaters. Therefore, the house in both scenarios has same applications but different sources. House with gas and electricity connections are equipped with gas water heaters, gas heaters for room heating and gas cooktops and electricity is mainly used for Televisions, computers, phone charging, fridge, air-conditioning, washing machines and clothes ironing. However, the house with only electricity connection use electric storage water heaters, air-conditioners, electric cooktops and electric heaters for winters as well as for TV, computers, laptops, phone charging etc. Both scenarios 1 and 2 are compared under different designs. The analysis includes four different models as follows:

- Grid and PV connected house with only electricity energy consumption
- Grid and PV connected house with electricity and gas consumption
- Grid, PV and battery connected house with only electricity energy consumption
- Grid, PV and battery connected house with electricity and gas consumption

Figure 5 and 6 shows the basic layout of grid connected PV system with and without battery storage. The system involves, PV panels, meter, converter, breaker box, charge controller, battery and grid supply. When sun shines on PV panels, it converts the solar energy into electricity in the form of direct current (dc) which is converted to alternating current (ac) with the help of inverter. Meter basically keeps the record of incoming power from the grid and outgoing power to the grid. The power beyond consumption is fed to the Grid and based on selling price, grid provides credit which is known as feed in tariff. Ac supply from the inverter goes to home appliances.

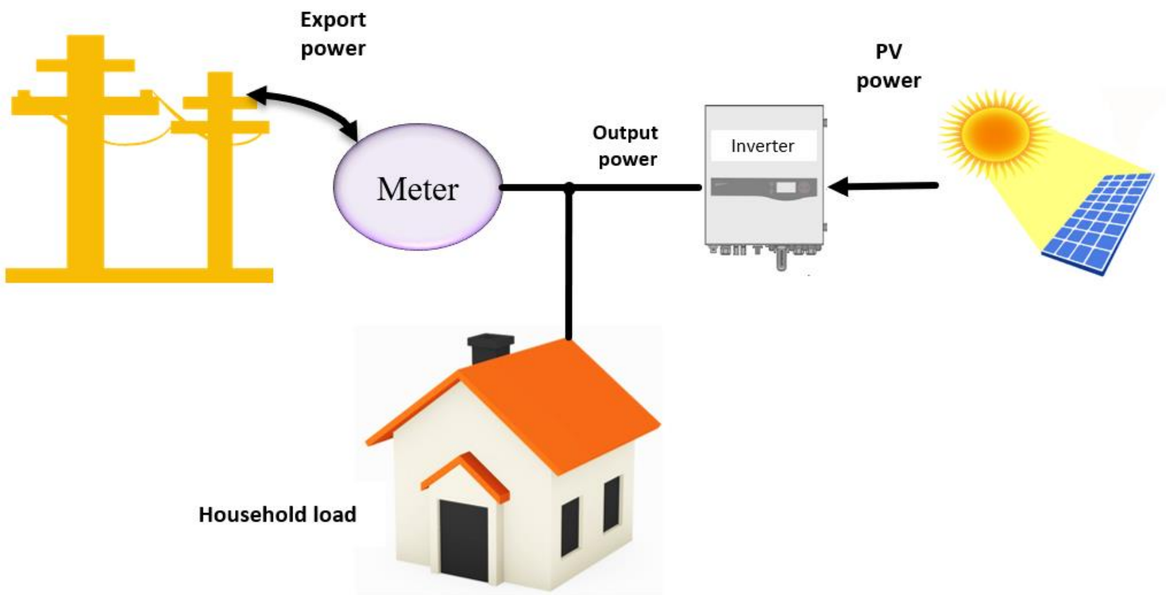


Figure 5 Typical configuration of Grid connected roof top solar PV

In case of storage systems, the excess power charges the battery and it can be discharged for household load rather than buying electricity from the grid. Battery can be used for blackout protection. Electricity prices vary according to different periods. During off-peak periods, grid electricity prices are a lot cheaper than peak demand periods. During off-peak period, the power from the grid which in the form of ac after passing through inverter, also charges the battery. The charged battery can be used during peak demand. An addition component i.e. charge controller is also required in case of grid connected rooftop PV with battery storage as charge controller prevents the battery from over charging.

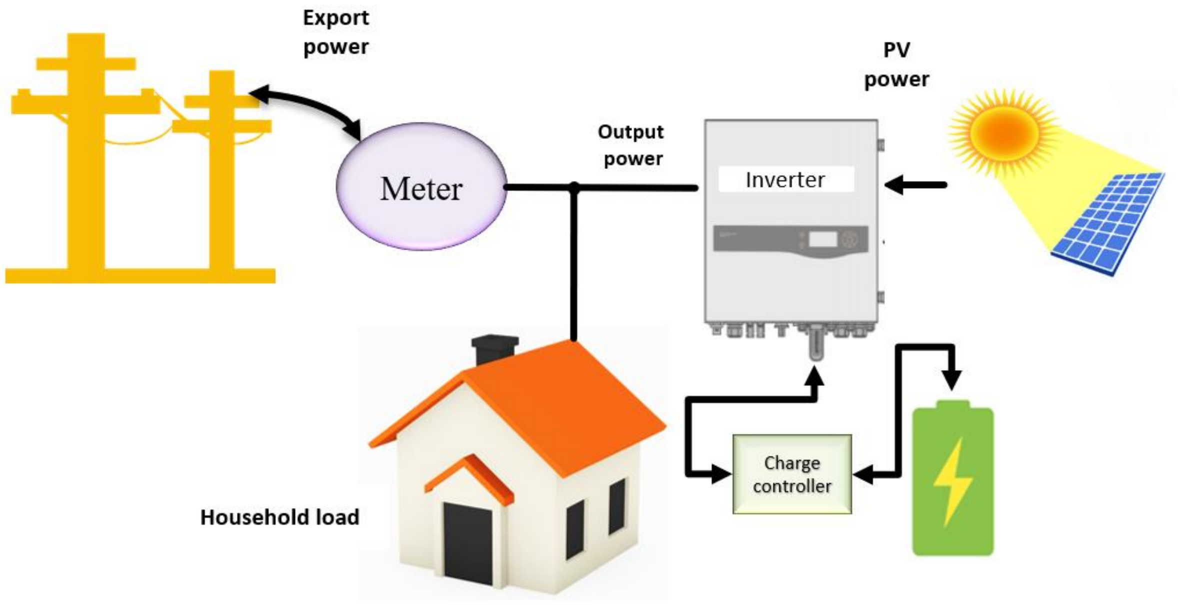


Figure 6 Typical configuration of Grid connected roof top solar PV with battery storage

## 3.3 Components Used

### 3.3.1 PV (Photovoltaics) Panels

In this analysis, generic rooftop PV panels are assumed. PV panels of capacities 3kW, 5kW and 7kW are taken f or the analysis in this research. All three PV panel sizes are compared based on Net present cost which results the most cost-effective option for all four design models which will result in sensitivity analysis that gives the optimised sizes on increasing and decreasing the capacity. There are many factors which effect the power output from PV array for example shading, wiring loss, panel soiling, aging etc. which are defined by a scaling factor called derating factor. Derating factor basically accounts for real-world operating conditions in comparison with the conditions under which PV panel rated conditions. In Australia, all the panels are mounted on roof facing North to get the full solar isolation [21]. All panels are mounted at a tilt to take the full advantage of solar energy and the tilt angle depends upon the roof type and load profiles. If the roof is flat roof then the tilt angle of panels is 0° and panels are tilted at an angle of latitude if the load profiles of winter and summer are same [22].

### 3.3.2 Grid

Grid electricity prices are increasing day by day in Australia as the demand is also increasing. Grid prices are different for different times in a day for instance, high grid prices during peak hours and less prices during off-peak. But in this research, one single price is assumed i.e. $0.43 per kWh as the retail price and $0.11 as selling price for feed in tariff.

### 3.3.3 Battery

Electricity is generated only during the day light hours and for evenings rather than depending upon grid for load consumption, residential consumers are investing in suitable storage options. Battery storage is considered in the system for storing dc power produced by PV panels which is an optimal approach in case of higher Grid electricity prices and blackout protection. There are many types of batteries used for storing power for residential rooftop PV system like Li-ion, lead acid, gelled, flooded and Absorbent Glass Mat (AGM). Battery features like lifetime, power dissipation rate, efficiency and energy density play an important role before buying a battery. In case of lifetime, AGM has very less lifetime while Gel batteries are not suitable for residential rooftop systems. Lead acid batteries are also used for residential PV systems and these batteries are cheaper than lithium ion batteries but have short life span and lower Depth of discharge [23]. Therefore, Li-ion is the most efficient among all types because of the following characteristics [23].

- Light weight
- High depth of discharge
- Increased life cycle
- Low maintenance
- High energy density

About 80% of electricity is fulfilled by PV-Battery system [24]. Li-ion battery is used as a storage for Grid connected rooftop PV system for both electricity and electricity and gas connected houses in this study. In the sensitivity analysis, different battery capacities of 5kW, 10kW and 15kW are considered for different PV sizes.

### 3.3.4 Inverter

DC/AC Inverter are used for both solar systems including grid connected PV and grid connected PV and battery systems. Houses use ac and PV produce electricity in the form dc which is converted to ac with the help of PV inverter. 1 kW PV inverter is used in the design structures.

## 3.4 Mathematical formulation of problem

Before simulation in HOMER pro all model components are analysed based on their mathematical model equations. The proposed system contains, PV, grid, PV inverter, solar power and battery storage and all the mathematical parameters related to these components are mentioned in the nomenclature in Introduction section. All the equations are taken and modified from Homer Pro help guide [25].

### 3.4.1 Mathematical model of Photovoltaics (PV)

PV panel generated power depends upon incident solar radiation, derating factor, panel capacity and temperature effect if considered. In this analysis, temperature effects are not considered.

$$P_{out} = c\ (pv).\, d(pv) \left(\frac{Gt}{G_{t,stc}}\right) [1 + \ \alpha_p (T_c - T_{c,stc})] \tag{1}$$

The generated power without temperature effects is as follows,

$$P_{out} = c\ (pv).\, d(pv) \left(\frac{Gt}{G_{t,stc}}\right) \tag{2}$$

### 3.4.2 Mathematical model of Grid

Many parameters related to Grid play an important role in rooftop PV modelling including energy purchase from Grid, energy sold to the Grid, peak demand and energy charge. Energy charge basically evaluated as the difference between electricity purchase from Grid at retail price and the electricity sold to Grid at selling price for a given month.

$$\text{EC}= \sum_{i}^{rates} E_{gridp}.\, cp, i - \sum_{i}^{rates} E_{grids}.\, cps, i \tag{3}$$

#### 3.4.3 Mathematical model of Battery

Battery charge is calculated as,

$$P_{bat,cmax} = \frac{min(Pbat,cmax,Pbat,dmax)}{\eta bat,c} \tag{4}$$

State of Charge in battery means the current remaining capacity in the battery against total capacity.

$$SOCmin = \ (1 - DOD) \tag{5}$$

Here DOD is the depth of discharge which basically depends upon the charging and discharging cycles of battery.

### 3.4.4 Operating costs ($/year)

These costs are evaluated by deducting total annualised capital costs from total annualised costs

$$C_{op} = C_{an,tot} - C_{an,cap} \tag{6}$$

Here $C_{an,cap}$ is the annual capital cost which is defined by the product of initial capital cost and CRF.

### 3.4.5 Annualised cost

Annualised cost is defined as the total NPC annually.

$$C_{an,tot} = CRF\ (i, l).\, C_{npc,tot} \tag{7}$$

Here CRF is the capacity recovery factor used to evaluate present values of yearly equal cash flows,

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{8}$$

### 3.4.6 Net present value

Net present cost basically defined as the difference between present value of cash inflows (revenue it earns over its lifetime) and the present value of cash outflows [25].

$$NPV = \sum_{t=0}^{T} \frac{\mathrm{C_t}}{(1+r)^t} - \mathrm{C_o} \tag{9}$$

Life cycle cost (LCC) of the system basically defined as the sum of all cots including capital cost, operation and maintenance costs, replacement costs minus revenues or salvage value [25].

### 3.4.7 Levelized cost of energy

LCOE is the useful electricity produced by the system and is evaluated as,

$$COE = \frac{C_{an,tot}}{E_{served}} = \frac{\sum_{t=1}^{n} \frac{Co+M+F}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E}{(1+i)^t}} \tag{10}$$

### 3.4.8 Operation and maintenance cost

Operation and maintenance costs means costs which are incurred to operate and maintain a component to check whether the component is working reliable as expected [25]. For grid, operation and maintenance is calculated as, M = annual cost of buying power from grid – revenues it earns after selling power to the grid (11)

# CHAPTER 4

## Model inputs

## 4.1 Solar data

Solar data for this research hourly solar data is fetched from "NASA Prediction of Worldwide Energy Resources" [26]. By entering the location of Adelaide based household with latitude and longitude in POWER data access viewer hourly solar data is fetched which is imported into HOMER Pro for simulation. The monthly variation of GHI (Global Horizontal Radiation) data FROM Homer pro is shown in the following figure. The scaled annual average is 4.64 kWh/$m^2$/day which is identified in Homer Pro. The sky clearness index is also shown in the graph which ranges between zero and one which defines the striking of sunlight on the top level of atmosphere. Its value is more in case of sunny days and less in cloudy days. More the clearness index, more would be the striking of sunlight on Earth surface.

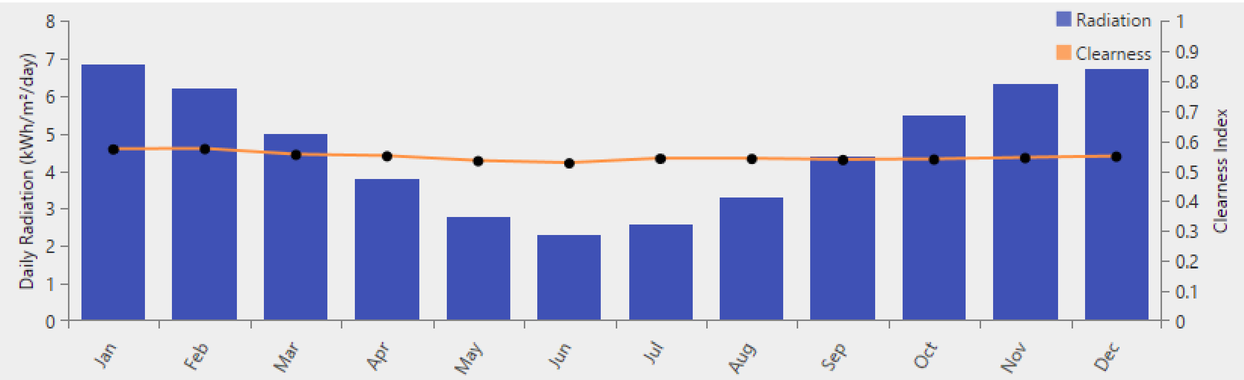


Figure 7 Solar isolation profile for Adelaide at latitude -34.5° and longitude 138.59° [26]

## 4.2 Load data

Load profiles for residential areas depends upon various factors including number of occupants, age of occupants, family composition, dwelling type, weather and lifestyle. These profiles are different for different seasons, weekdays or weekends and also based on hours. Based on occupants the consumption pattern changes. If the number of occupants is two or more the consumption would be more as compared to a house with only one occupant. Load consumption also depend upon the employment status of occupants (retirees or work from home) as the occupants will use more electricity whole day that will increase the overall consumption pattern. Heating and cooling demand of average Australian household is approximately 40% of overall energy bill where hot water heating make up 23% of that and 7% for lighting. Other appliances such as laundry and entertainment makeup 14%, fridge and freezers amount to 8% and for cooking its energy consumption is 5% [27].

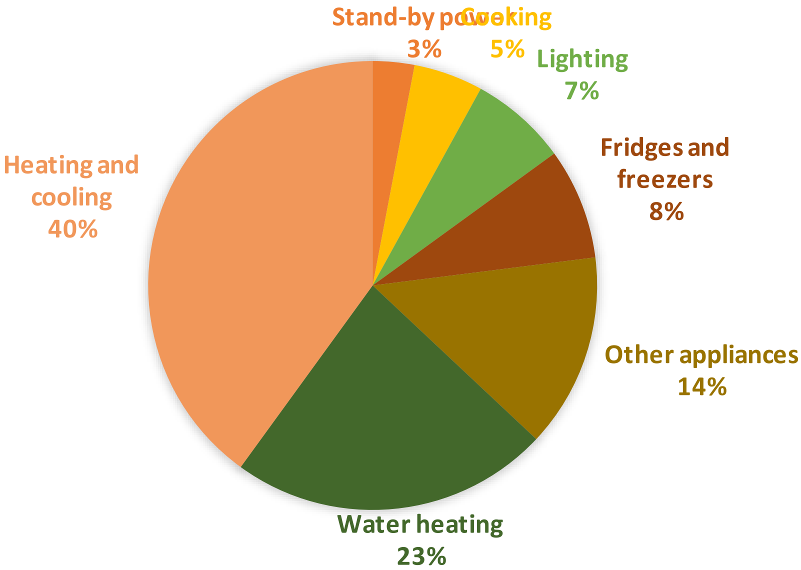


Figure 8 Energy use in Australian residential sector [29]

Suppose a house with only electricity connected, has two people and they use electricity mainly for hot water, cooking, cooling, dishwasher, TV, computer and fridge. Their electricity consumption for day is approximately from 23kWh to 26kWh per day which is the average consumption rate in Australia [28]. If the same house has four number of people then the electricity consumption increased to approximately 41kWh a day [30]. In case of house with electricity and gas connections, the electricity usage is less as gas is being used for all heating purpose and cooking. Suppose a house with electricity and gas connected has two people then their electricity consumption would be between 13.7 kWh to 16kWh a day and gas with approximately 72.9MJ a day [29]. If the same house has 4 to 5 number of people then the electricity consumption is approximately above 17kWh electricity and for gas about 79.1 MJ [29].

Scenario 1 taken for the study:

- Adelaide based dwelling
- Dwelling has two to three number of people
- Electricity and gas connected house
- Average daily electricity consumption is 15.63kWh and 5704.92 kWh per yearly
- Average daily gas consumption is 31MJ and 5704.92MJ yearly
- Gas is used for cooking, heating water and heating rooms

For the second scenario when house is only connected with electricity, the same gas data which is shown in scenario 1 is converted into electricity by converting MJ into kWh by multiplying with 0.277778 and then added to the electricity of scenario 1 which give the only electricity data which will fulfil all the load of the house. For second scenario, the average electricity consumption is 25.14 kWh/day.

### 4.2.1 Gas and electricity consumption patterns

This section covers the consumption patterns of house connected with electricity and gas. All the graphs are created and analysed in Microsoft excel and all the graphs are based on Australian weather months i.e. summers from December to February, autumn from march to May, winter from June to August and spring from September to November. Dwellings mainly use gas for heating and cooking. Two types of gas heaters are available for household applications i.e. ducted heaters and space heaters [30]. Space heaters basically located inside the room while ducted heaters are located outside. Ducted heaters heat the water and air which circulates the whole house while space heaters are limited to room heating only [30]. The consumption varies hourly. During weekdays consumption is slightly less in comparison with weekends as people normally stay out for work during weekdays. Figure 9, 10 ,11 and 12 shows the weekdays and weekend comparison which shows that during winter, energy consumption is more as shown in the figure 11 and 12 due to the various heating appliances for water heating and space heating.

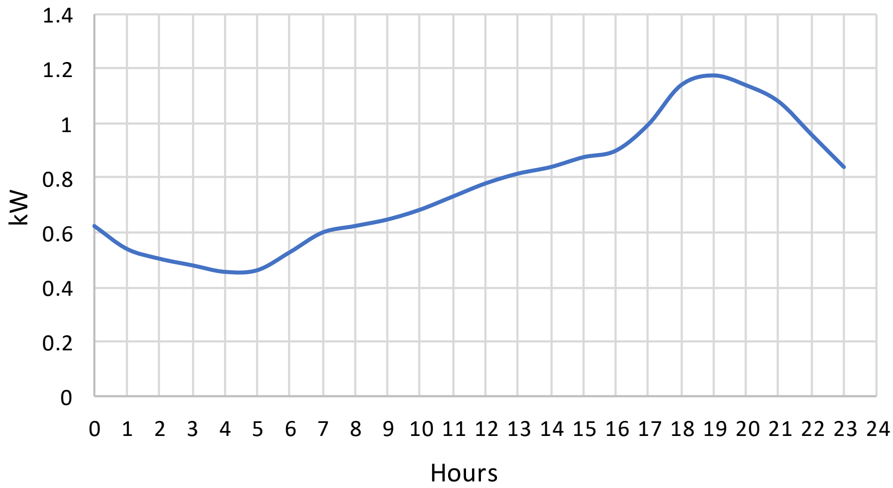


Figure 9 Daily average profile of electricity consumption during weekdays in summer

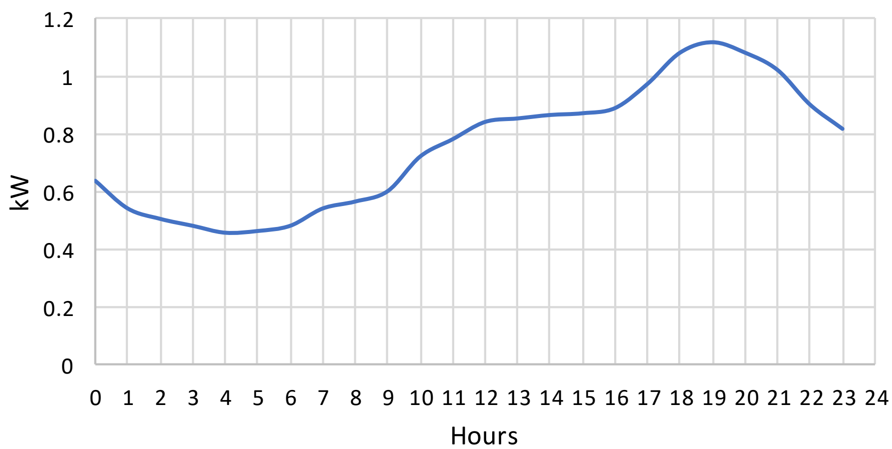

Figure 10 Daily average profile of electricity during weekends in summer

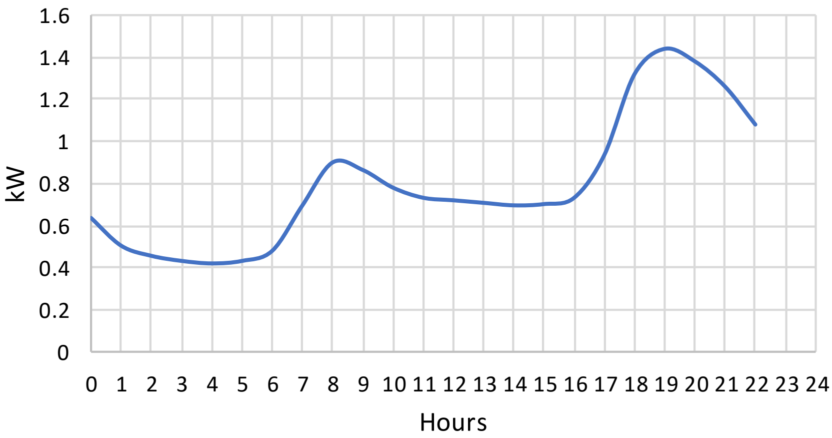


Figure 11 Daily average profile of electricity during weekdays in winter

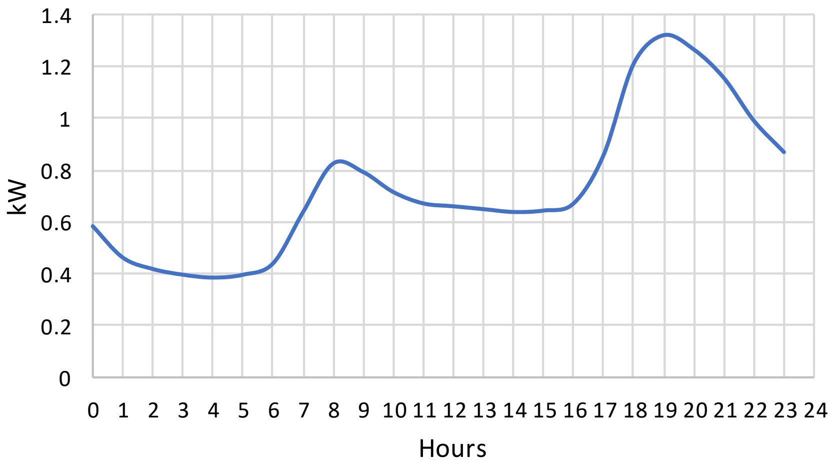


Figure 12 Daily average electricity profile of weekends during winter

The hourly profile for a single day for all seasons in the figure 13 shows that the maximum electricity consumption is in winters followed by summer, autumn and spring. The electricity demand is at high peak from 5 pm to 10 pm and less during noon during all four seasons. Mid-day consumption is less as many people work outside from 9 am to 5pm.

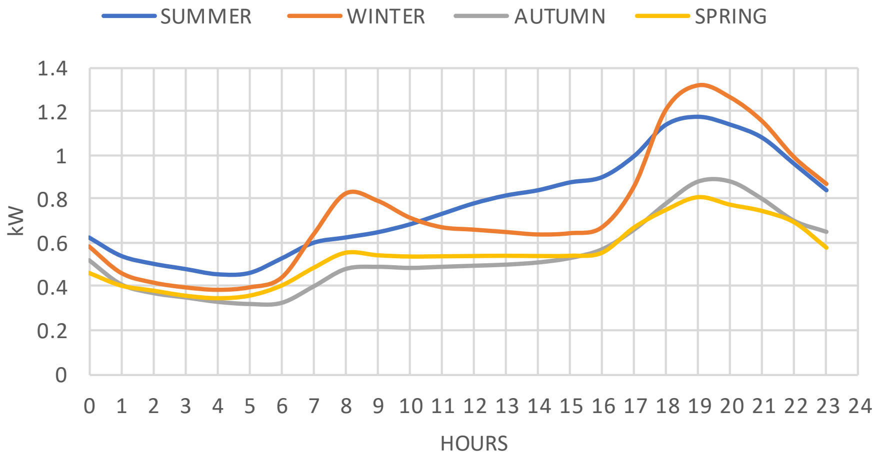


Figure 13 Daily profile of electricity consumption for all four seasons

In case of Gas consumption, dwelling use more gas on weekends as compared to weekdays. During summer, gas is mainly used for cooking while in winters, gas is used for heating purposes which in turn increases the overall gas consumption during winter. The average gas consumption for summer weekday is 31.31MJ and for weekend is 40.46 MJ. In winters, the consumption is more as people use gas heaters for space heating and hot water. In winters, the average gas consumption for weekend is 60.34 MJ while for weekdays the consumption is less i.e. 50.39MJ. During weekends people stay at home which increases the overall consumption.

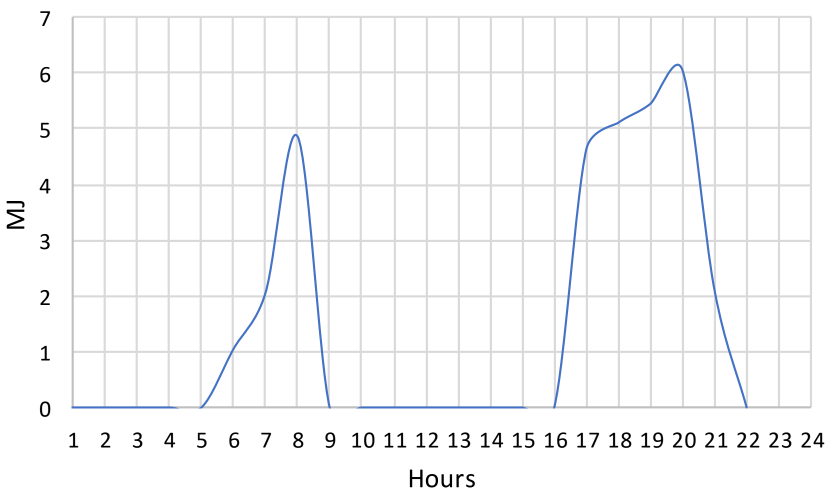


Figure 14 Daily average consumption profile of Gas for weekdays during Summer

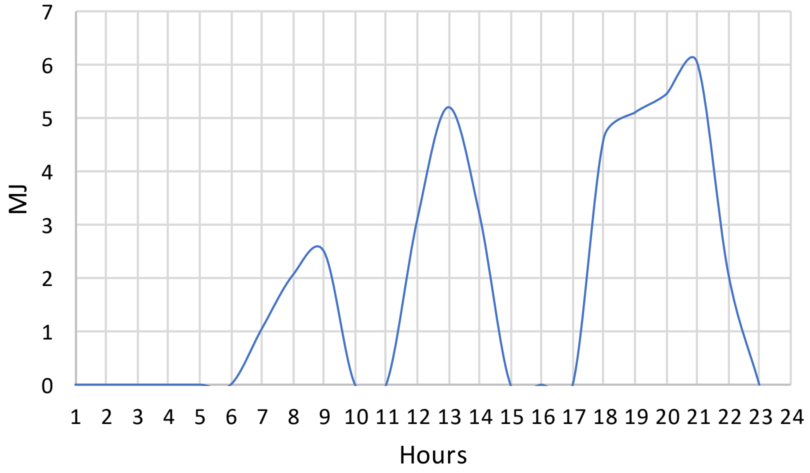


Figure 15 Daily average consumption profile of Gas for weekends in summer

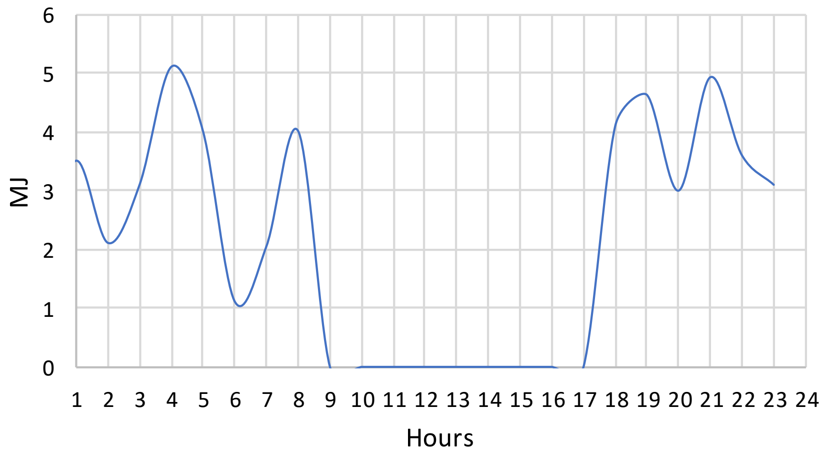


Figure 16 Daily average consumption profile of Gas for weekdays in winter

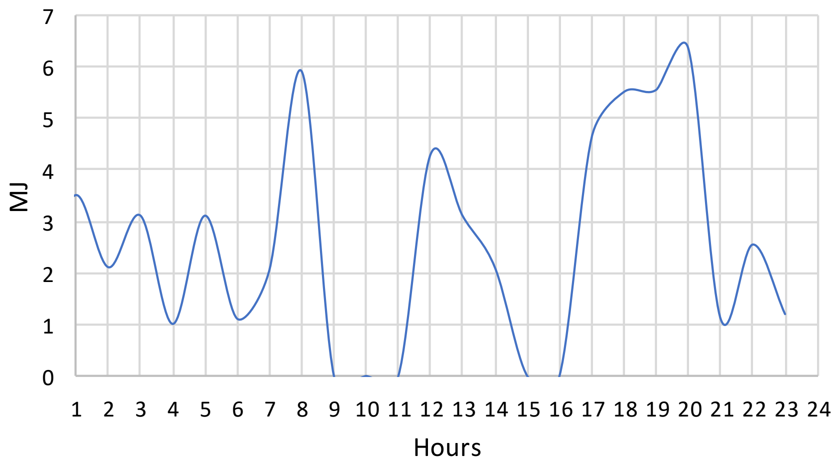


Figure 17 Daily average consumption profile of Gas for weekends in winter

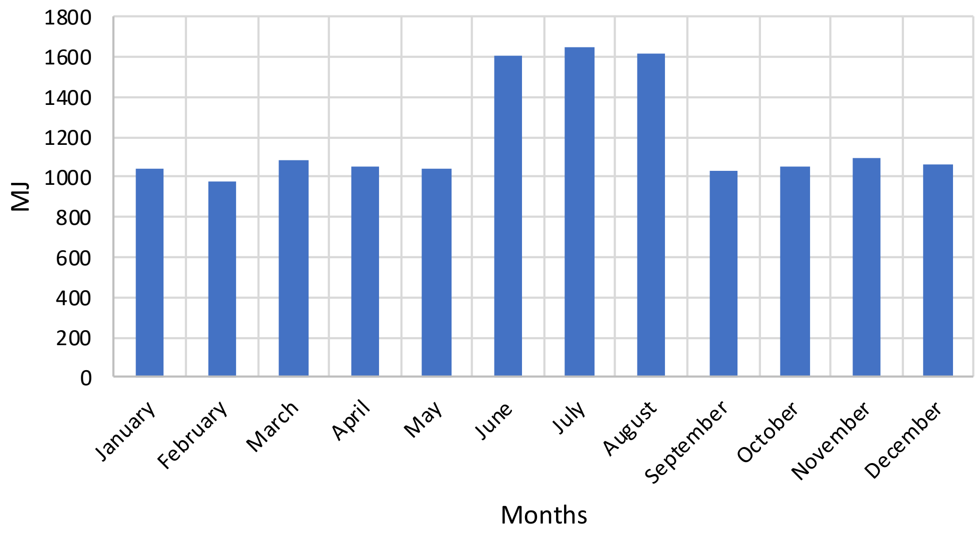


Figure 18 Monthly consumption profile of gas in MJ

The monthly gas consumption pattern in the figure 18 shows the maximum consumption in winter months and least consumption in summer months e.g. February. Hourly consumption pattern also shows a huge difference in summer and winter during peak hours.

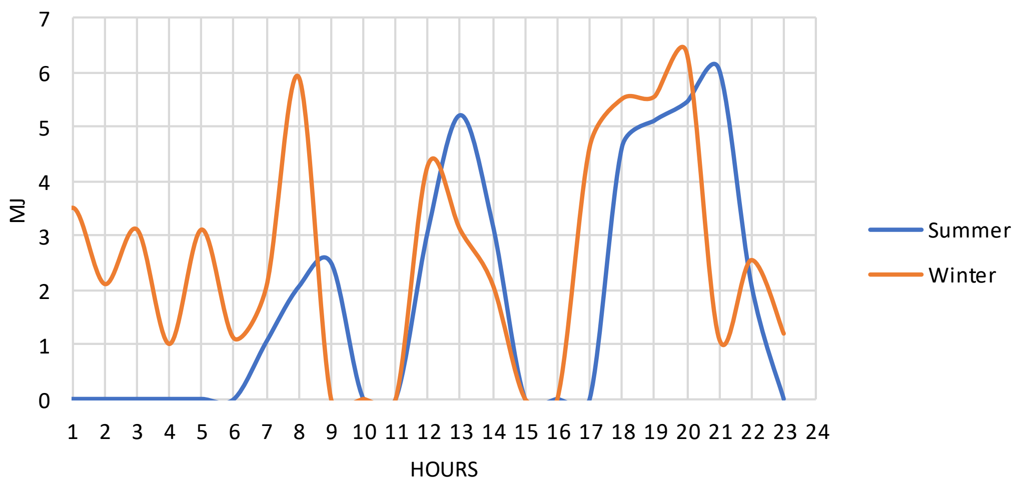


Figure 19 Gas consumption comparison between summer and winter for a single day (weekends of both seasons)

### 4.2.2 Only Electricity energy consumption patterns

This section shows the consumption patterns of house with only electricity connected. In this case electricity is mainly used for house heating and cooking. Many types of electric heaters are available for instance fan heaters, convection heaters and off-peak electric heaters [30].

In case of less heating requirement, fan heaters and radiators are used while off-peak heaters heat up the heat bank material overnight with the help of electricity. It releases heat during day and heat the whole house. Reverse cycle air conditioners are responsible for both heating and cooling which are more efficient than ordinary heaters [30]. Other appliances that use electricity includes, refrigerator, laptop, television, lights, computers, washing machine, clothes dryer and phone chargers. Electricity consumption of weekends is more than weekdays (see figure 21 and 23). Average electric load for weekday in summer is 27.12 kWh while at weekend it rose up to 29.2989 kWh.

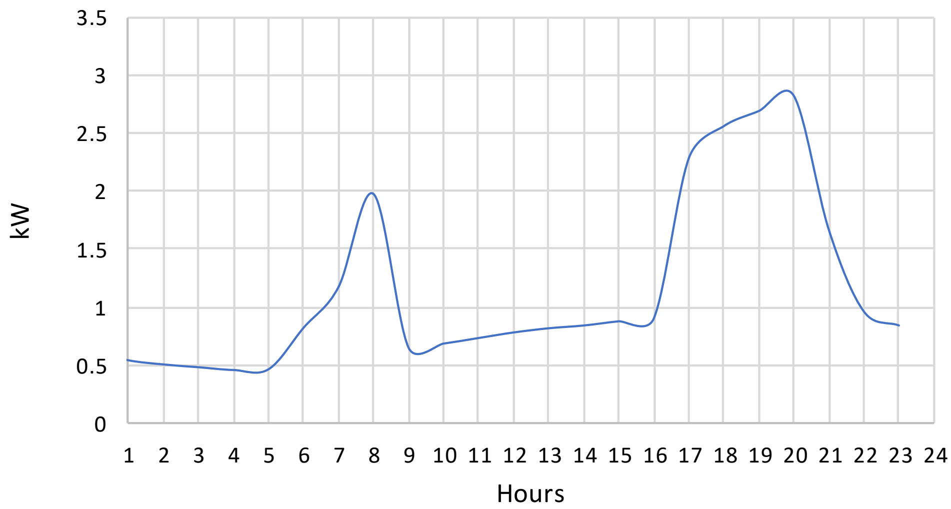


Figure 20 Daily average consumption profile of electricity during weekdays in summer

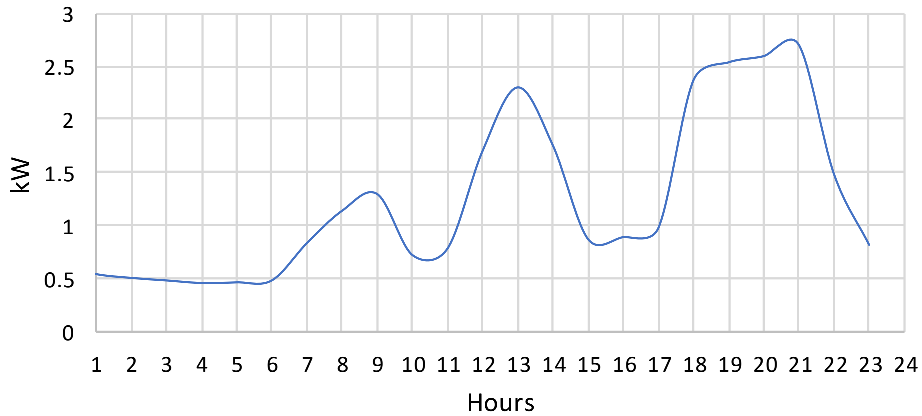


Figure 21 Daily average consumption profile of electricity during weekends in summer

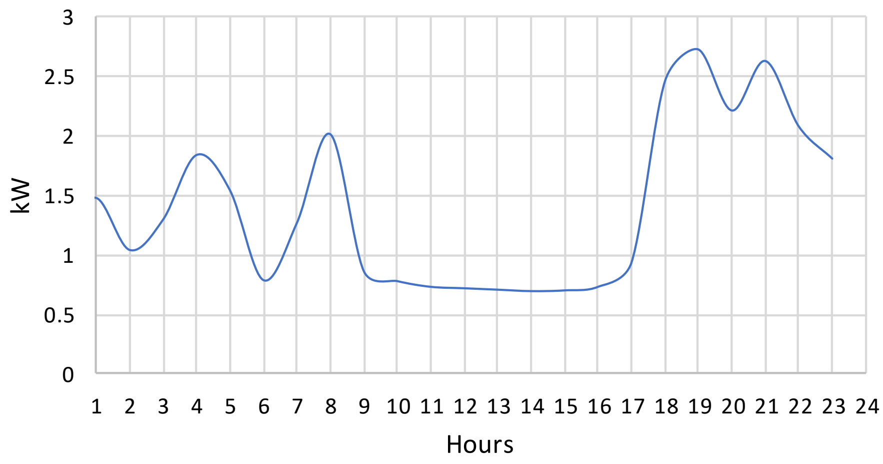


Figure 22 Daily average consumption profile of electricity during weekdays in winter

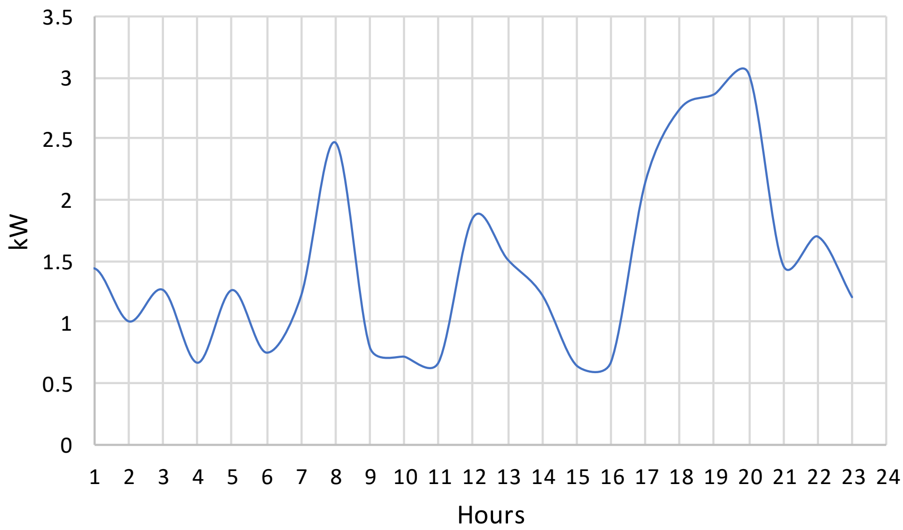


Figure 23 Daily average consumption profile of electricity during weekends in winter

For winters, the average electricity consumption for weekdays is 33.25kWh and for weekends is 34.41kWh which shows a slight difference because the gas consumption was having huge difference between the consumption of weekdays and weekends but after conversion its value became less in kWh (Gas data from first scenario is converted into electricity and then added to the electricity of scenario 1 from which the electricity of only electricity connected house is generated as discussed above in section 4.2). Heater is turned on during highly cold temperature due to which the consumption shows a peak during nights between 5pm to 12 pm. Winter has maximum electricity consumption followed by summer, autumn and spring for a house with only electricity connected.

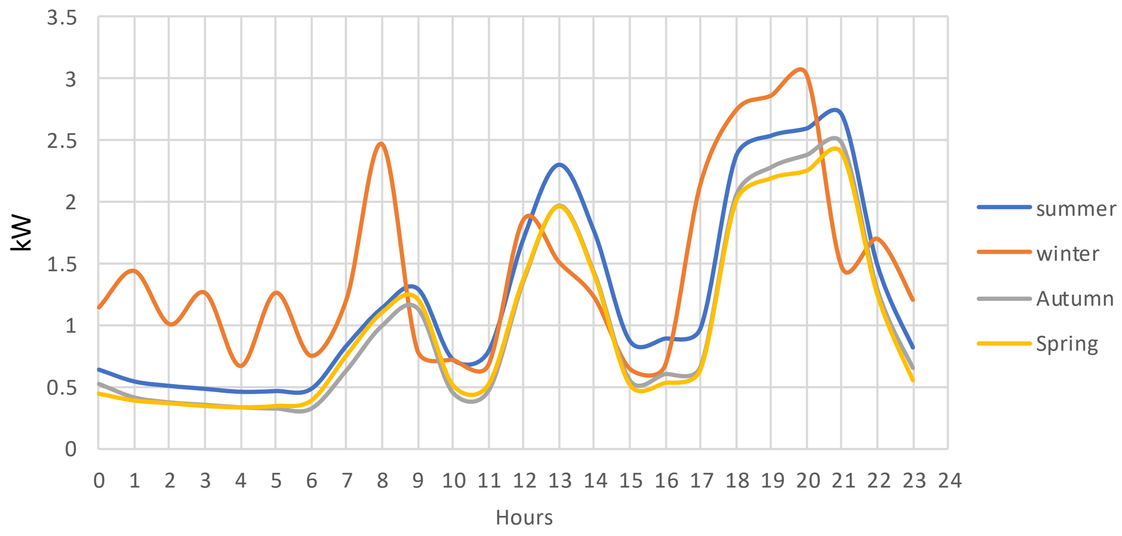


Figure 24 Seasonal profile of electricity consumption of a single day (weekend)

## 4.3 Technical data and study assumptions of PV and batteries

After importing all the data in the HOMER Pro, components are added. Each component has capital cost, replacement cost and operation and maintenance cost. No salvage cost is considered in this study. All the prices are taken from solar panel retailer [31].

Table 1 Component parameters based on prices, technology and capacities

| Technology | Model | Lifetime (years) | Capacity PV (kW) Battery (kWh) | Capital cost ($) | Operation and maintenance costs ($/year) | Replacement costs ($/year) |
|---|---|---|---|---|---|---|
| PV (Photovoltaics) | Generic flat plate PV | 10 | 3kW | $4500 | $30 | $1500 |
| | | | 5kW | $7500 | $33.33 | $2500 |
| | | | 7kW | $10500 | $46.66 | $3500 |
| Battery | Lithium Ion (Flat plate) | 10 | 5kWh | $3500 | $0 | $1500 |
| | | | 10kWh | $7000 | $0 | $3000 |
| | | | 15kWh | $10500 | $0 | $3500 |
| Converter | Generic | 10 | 5kW | $1500 | $0 | $300 |

Then all the components are added to the models according to their inputs (see Table2). Some important parameters are set according to table 2. Inflation rate is taken from reference [32] and grid power prices are taken from reference [28].

Table 2 Some important parameters for simulation [29] [26]

| S.no. | Parameters | Values |
|---|---|---|
| 1. | Project lifetime | 20 |
| 2. | Inflation Rate | 1.26% |
| 3. | Discount Rate (%) | 8% |
| 4. | Electricity purchase price ($/kWh) | $0.43 |
| 5. | Electricity sell back price ($/kWh) | $0.11 |
| 6. | Gas ($/MJ) | $0.0468 |

# CHAPTER 5

## RESULTS AND DISCUSSIONS

### 5.1 Optimization results

HOMER Pro 3.12.5 version is used for modelling and analysis. Grid connected PV house with and without battery is modelled in Homer pro for electricity as well as electricity and gas energy consumption. In the end, all models are compared at different electricity prices to find cost-effective option.

#### 5.1.1 Grid tied house without PV and battery for electricity and gas energy consumption

In this case, no PV or battery is connected to the house. Electricity data is imported in the HOMER Pro and home load is fulfilled by Grid only. The overall energy consumption for this house equipped with two to three people is 15.63kWh electricity and 39.19MJ gas. Net present costs of electricity and gas are calculated separately and added together in table 3 so that NPC of all systems can be compared. Electricity yearly cost is calculated at 43 cents per kWh and gas is calculated at $0.0468 price. Gas is much cheaper than electricity which results in less yearly costs. Highlighted NPC and yearly costs will be compared with other scenarios in the following sections.

Table 3 Costs and energy consumption comparison for Grid only system

| | Daily consumption | Yearly consumption | Total cost yearly | NPC |
|---|---|---|---|---|
| **Electricity** | 15.63kWh daily | 5704.92kWh | $2453.11 | $26,698 |
| **Gas** | 39.19 MJ daily | 14307.63MJ | $669.59 | $ 7,203 |
| **Total** | | | $3115.15 | $33,900 |

#### 5.1.2 Grid connected house without PV and battery for only electricity consumption

Without PV and Battery, the overall electricity consumption for one year is 9679.27 kWh. All appliances including heating and cooling demands, laundry appliances, lighting, refrigerators, cooktops, television etc. use electricity for this case. Daily summer consumption is 27.12 kWh whereas winter load is 33.25kWh due to more heating and cooling demand. The grid price for electricity is taken as $0.43/kWh. The net present cost of this system is $45,297 (referred to table 4) which is more than the NPC of electricity and gas. On the comparison of houses with electricity and electricity and gas, a conclusion is drawn on the basis of NPC which shows that without PV and battery system, house with electricity and gas is much cost effective.

Table 4 Costs and energy consumption comparison for Grid connected electricity only system

| | Daily consumption | Yearly consumption | Yearly cost | NPC |
|---|---|---|---|---|
| **Electricity** | 26.52kWh daily | 9679.27kWh | $4162.08 | $45,297 |

Now, based on the main objective of this study, both PV and battery are applied to scenarios to evaluate the cost-effective option at the end.

### 5.1.3 Grid connected house with PV for electricity and gas consumption

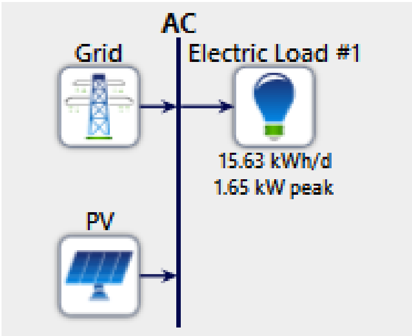


Figure 25 Grid connected PV system for electricity and gas connected house

For the system with electricity and gas connections the average electricity consumption is 15.63kWh/day with Grid and PV connected. During the day, Photovoltaic panels produces electricity which is used by the house to run appliances but during evenings or in the absence of sunlight power is taken from the Grid. Three sizes of PV panels are tested, and their net present cost is compared as shown in table 5.

Table 5 Consumption and cost parameters of Grid tied PV system

| PV size (kW) | NPC | PV production (kW/yr) | Energy purchased from grid (kWh) | Energy sold to grid (kWh) | CO2 emisions (kg/yr) | System O&M costs ($/yr) | Operating cost ($) |
|---|---|---|---|---|---|---|---|
| **7kW** | $18,701 | 10494 | 3255 | 8044 | 2057 | $584.75 | $753.58 |
| **5kW** | $18928 | 7496 | 3364 | 5155 | 2126 | $929.47 | $1050 |
| **3kW** | $19528 | 4497 | 3580 | 2373 | 2263 | $1308 | $1381 |

The results of all three PV systems shows that 7kW PV produce the maximum amount of power. Figure 26,31 and 36 shows the NPC by component which is PV and Grid in this case. It shows that grid costs are maximum in case of 3kW PV and minimum in 7kW. Therefore, lower the PV size, lower would be the production and the costs would be more as the system will require more power from grid. Maximum amount of power is generated by 7kW PV which leads to more and more electricity sold to the grid at a sale price of $0.11/kWh which results in benefits that leads to low NPC for whole system. Operating costs doesn’t include capital costs while it includes only annualised cost which is maximum in case of 3kW PV.

- **Results of grid tied 7kW PV system**

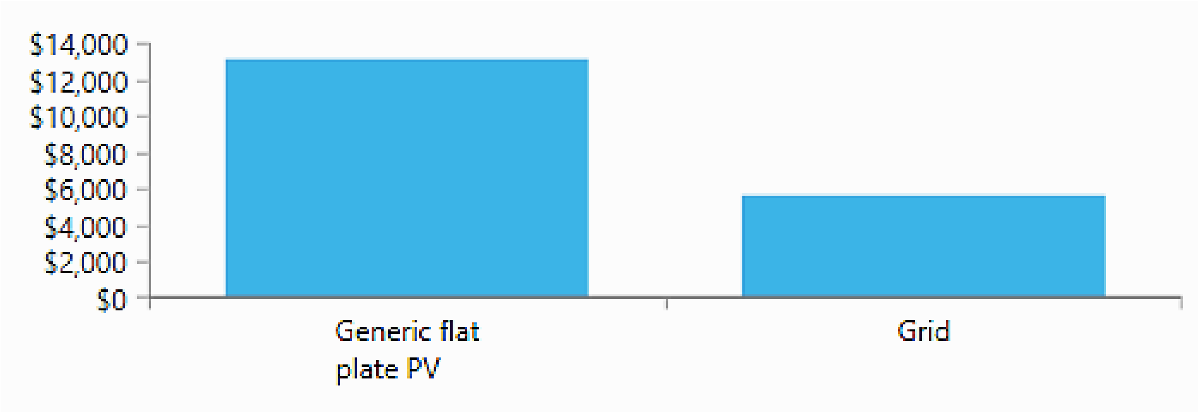


Figure 26 Net present cost by component type for 7kW PV panel

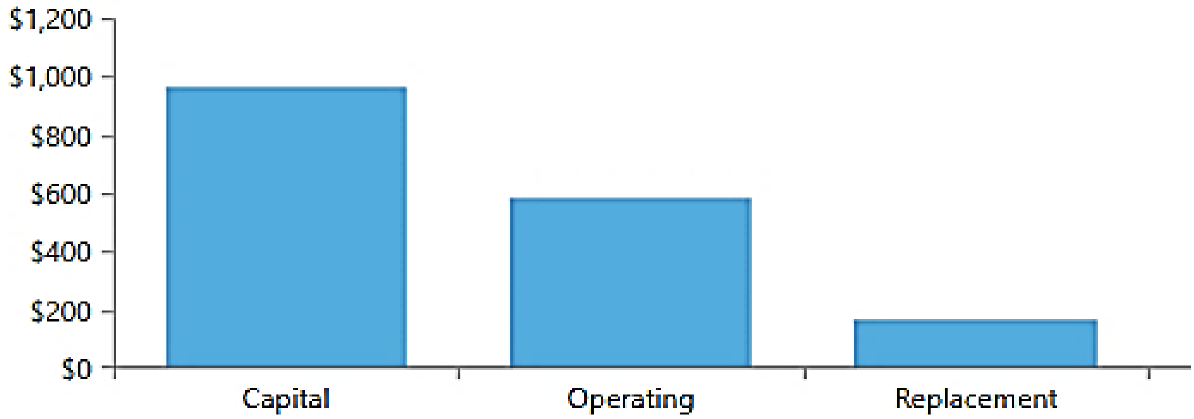


Figure 27 Annualized costs by cost type for grid tied 7kW PV system

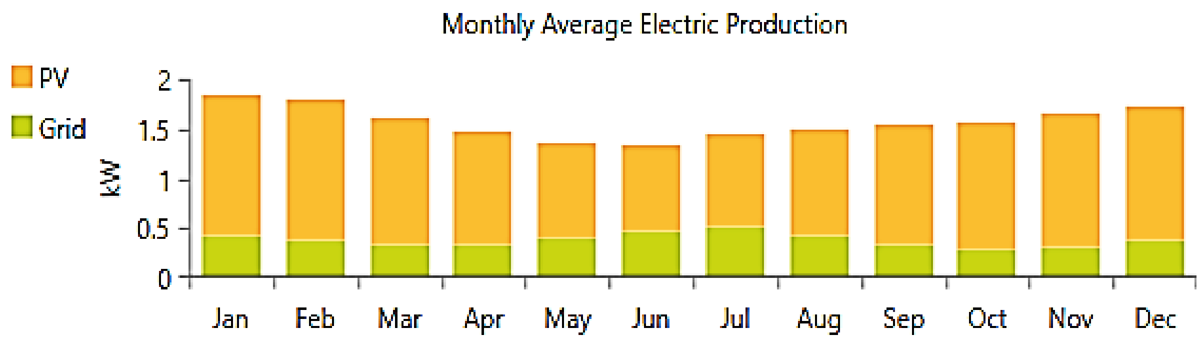


Figure 28 Monthly average electricity production for grid tied 7kW PV system

HOMER Pro generates Dmap (see figure 29) which basically means data map that shows time series data for one whole year [33]. These Dmaps are generated for many parameters including grid purchased power, PV generated power, battery state of charge, power sold to grid, solar isolation and renewable penetration with time of the day on one axis and months on other. The parameter values are represented by different colours with the help of a colour ribbon on one axis as shown in figure 29.

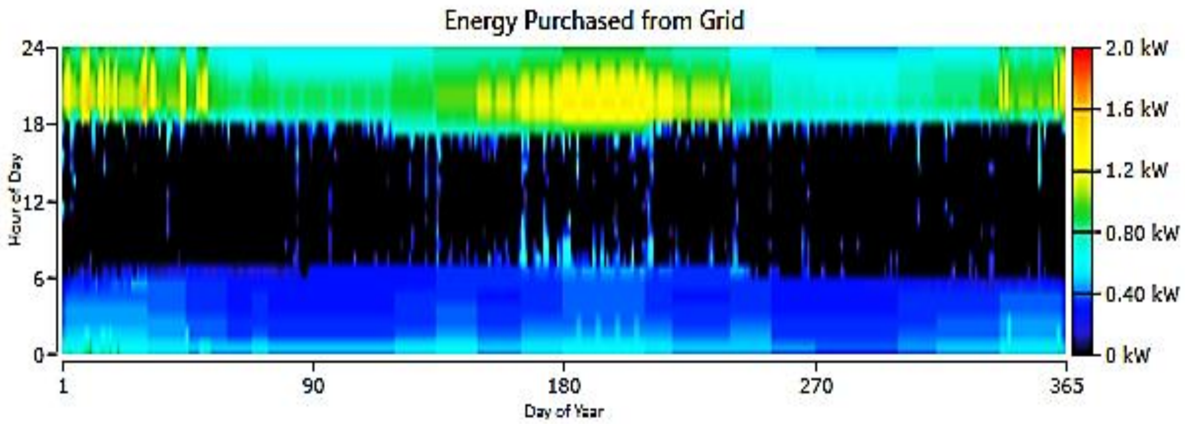


Figure 29 Dmap showing electricity purchased from the Grid when PV stops producing power during nights

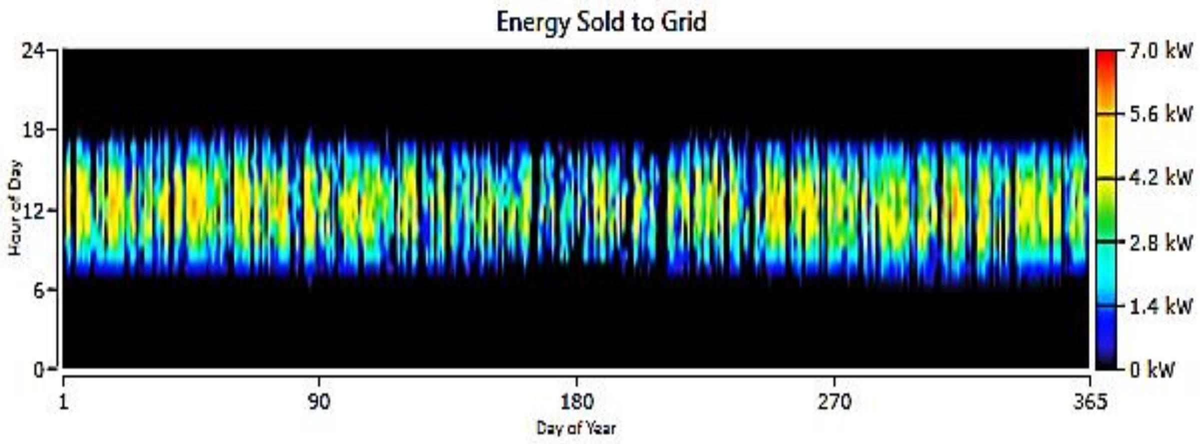


Figure 30 Dmap showing energy sold to the grid generated by 7kW PV panel

Figure 29 shows the black region during the day as PV panels produce power during daytime and power is not required to be purchase from the grid and from morning 12 am to approximately 7 am and evening 18 pm to 11:59pm power is taken from the grid. During daytime from approximately 7 am to 17 pm electricity is produced by panels and used for household load.

- **Results of grid tied 5kW PV system**

In this scenario, the net present costs of component including grid and PV is less as compared to 7kW system. The monthly average electricity production of 5 kW PV panels is more in comparison with electricity purchased from the grid [see figure 33].

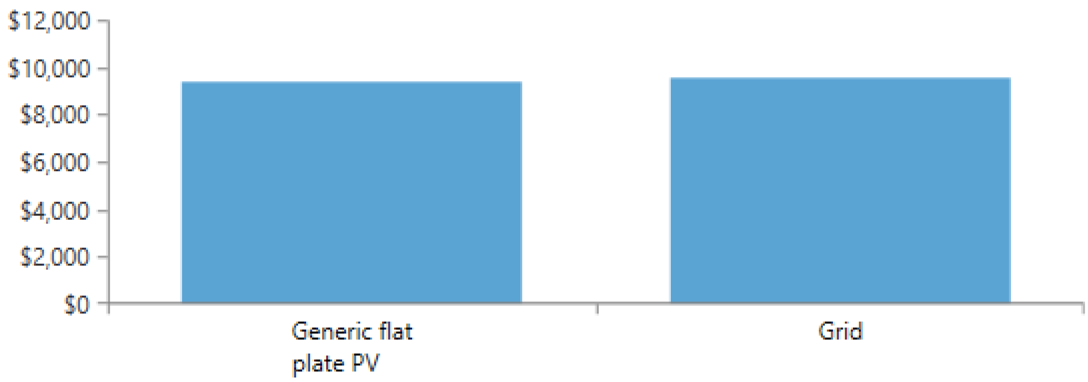


Figure 31 Net Present cost by component for Grid tied 5kW PV panel

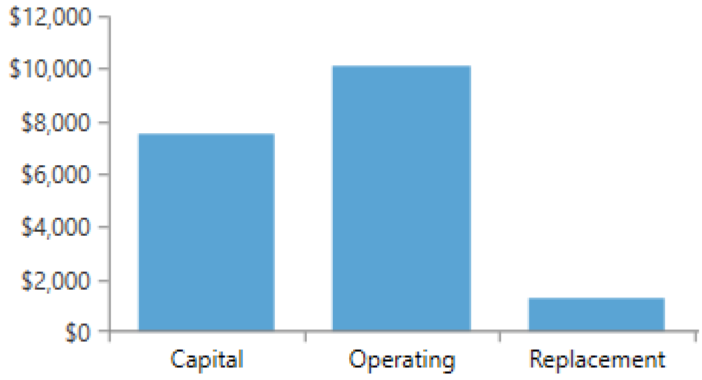


Figure 32 Annualized costs by cost type for Grid tied 5kW PV system

The annualised costs in figure 32 includes the sum of capital costs, operating costs and replacement costs of electricity produced by panels and operating costs in the figure also includes the costs incurred in purchasing power from the grid.

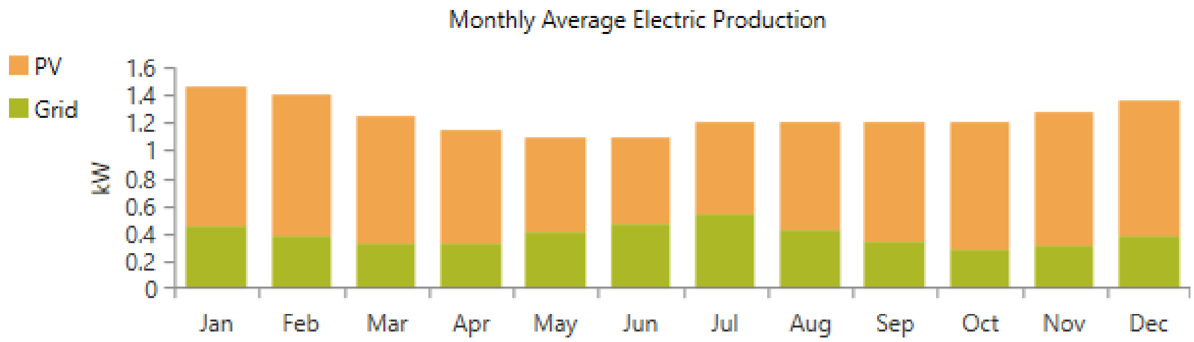


Figure 33 Monthly average electricity production for Grid tied 5kW PV system

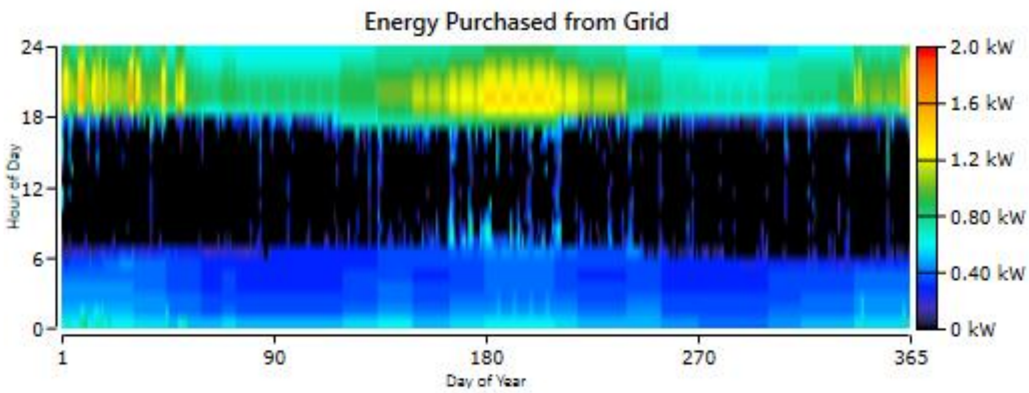


Figure 34 Dmap showing energy purchased from the grid

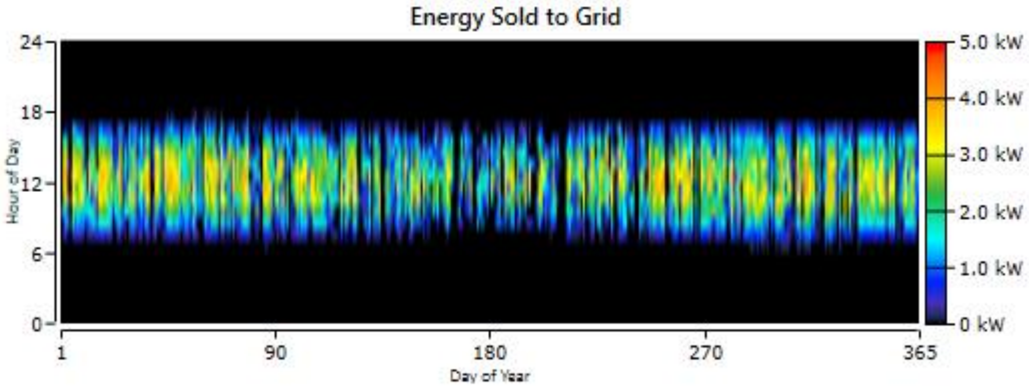


Figure 35 Dmap showing electricity sold to Grid

Dmaps similar to 7kW system are also generated for 5kW system which shows that during daytime from 7am to 16 pm, PV panels produce excessive power and after fulfilling the load power is fed to Grid [see figure 35] at a sell back price. The generation cost less in this case, but more power is required to purchase from the grid as compared to 7kW PV system.

- **Results of grid tied 3kW PV panel**

In case of 3kW PV panel, the electricity produced by 3kW system is less and therefore more power is required to purchase from the grid to fulfil load. Figure 36 shows the grid NPC which is more than the PV panel as system is buying more power from the grid. In case of annualised costs, capital cost is less and operating cost is more as operating costs includes the PV operating cost i.e. $30 per year and costs paid to the Grid for buying electricity (see figure 37).

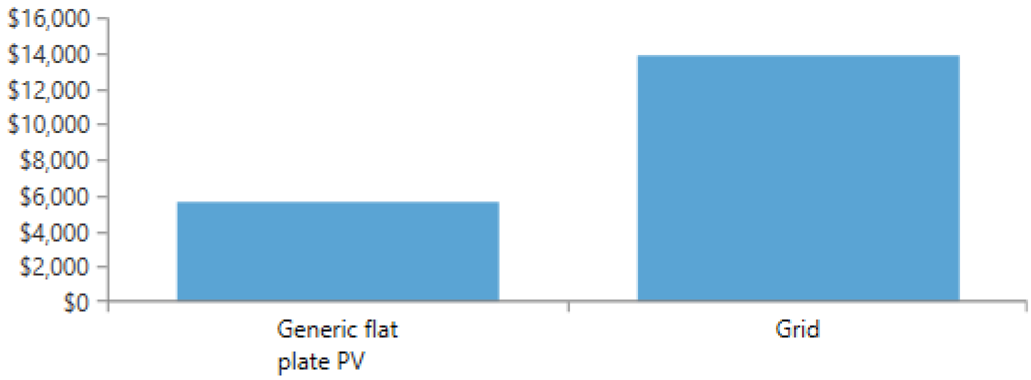


Figure 36 Net present cost comparison by component for 3kW PV panel

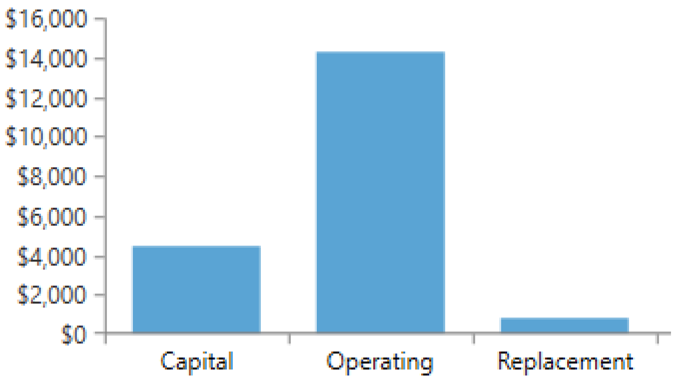


Figure 37 Annualised cost comparison by different costs included in grid connected 3kW PV panel system

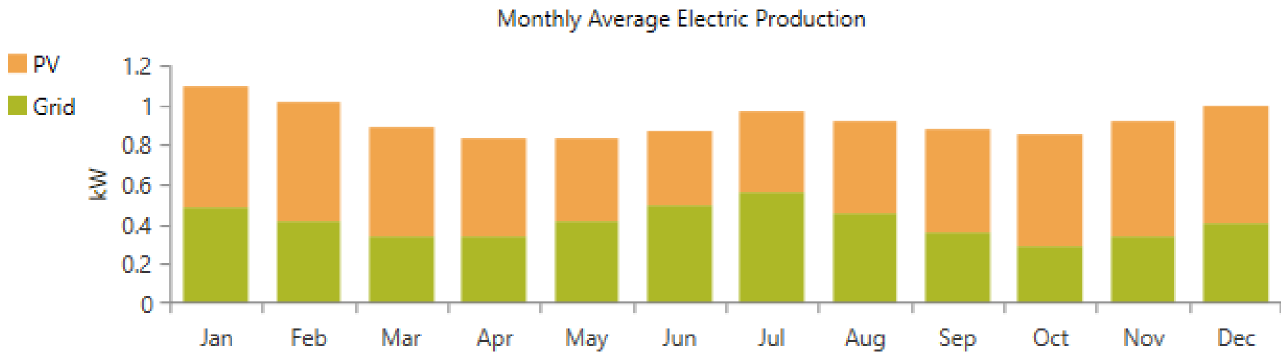


Figure 38 Monthly average electricity production from PV and purchased power from Grid

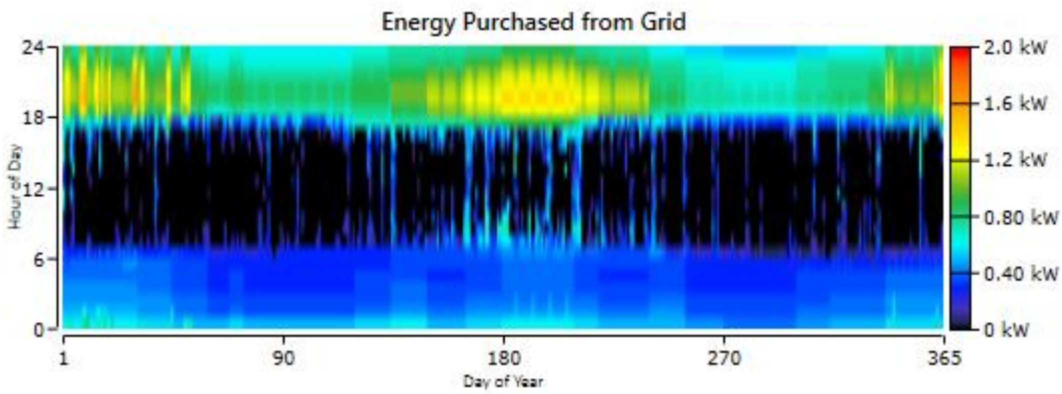


Figure 39 Dmap showing power purchased from the Grid

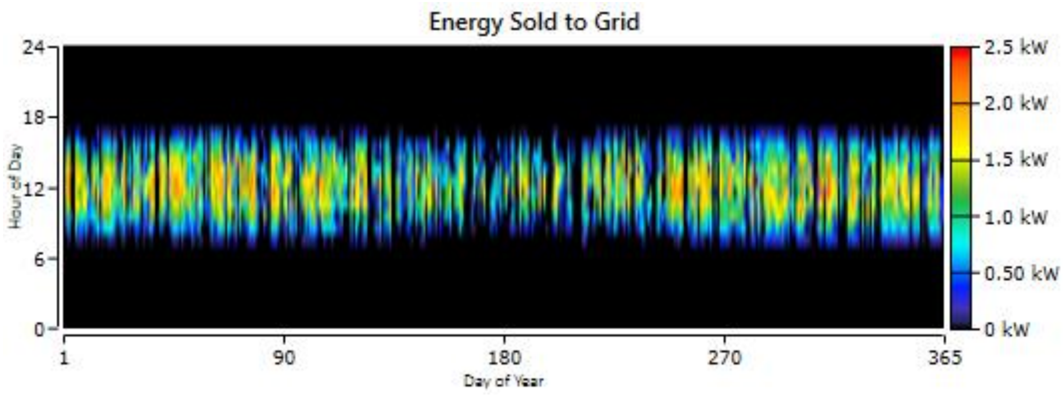


Figure 40 Dmap showing power sold to the grid for 3kW PV system

Dmaps showing power purchased and sold to the grid (see figure 39 and 40) between 8 am to 16 pm for selling as power produced by the PV panels and during night time and evenings power is purchased from the grid. The overall costs of the system is maximum in this case due to small PV size. During winters the production is least and more power is required from the grid and less power is sold to the grid that is why Dmaps in the figures 39 and 40 are narrow in the middle of the year and broad for the other months.

Moreover, renewable fraction is also calculated in HOMER Pro which basically defined as factor of energy generated from PV which is required to fulfil load [33]. The comparison of renewable fraction for all three different PV sizes as shown in the figure 41 which shows the grid purchase and PV production. Here, PV production is the electricity generated by PV panels. Less amount of electricity is required to be purchased from Grid in case of 7kW PV panel followed by 5kW panel.

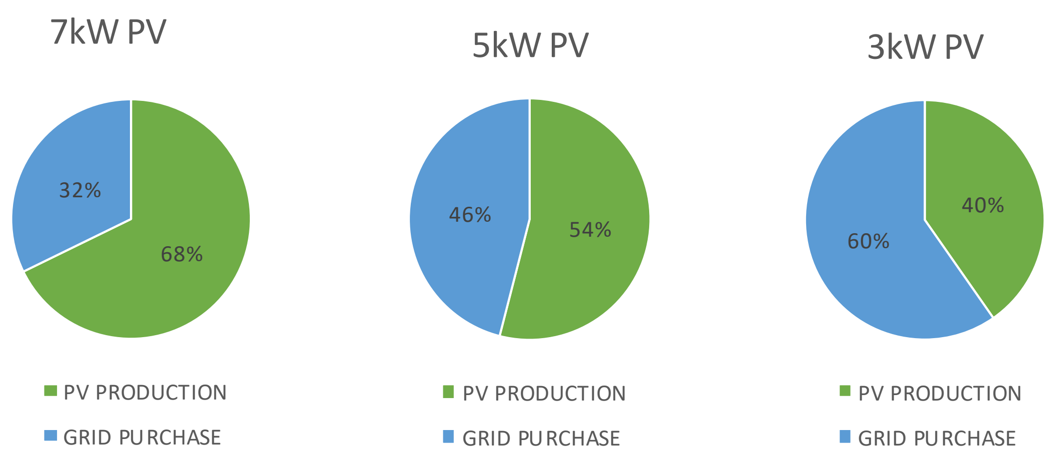


Figure 41 Renewable fraction of all three PV panel sizes

### 5.1.4 Grid connected house with PV for electricity only energy consumption

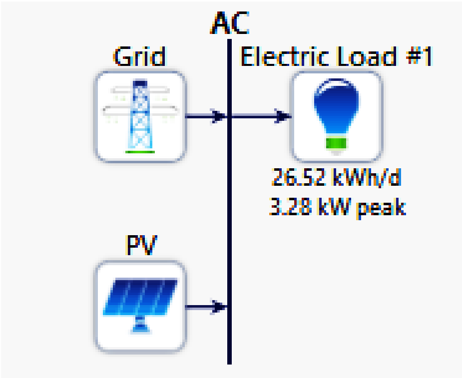


Figure 42 Schematic of grid connected PV system for electricity only connected house

This system includes dwellings connected with electricity only energy system. No gas appliances are used in these systems. PV panels are connected to the system to produce power to run the house during day and during evenings, dwellings purchase power from the grid. Different production and consumption pattern-based graphs are generated in HOMER Pro for three different sizes of PV panels so that on the basis of their net present costs, a least expensive and favourable option can be found.

Table 6 Costs and production comparison of different PV panel sizes

| PV size (kW) | NPC ($) | PV production (kW/yr) | Energy purchased from grid (kWh) | Energy sold to grid (kWh) | System CO2 emisions(kg/yr) | System O&M costs ($/yr) | Operating costs ($/yr) |
|---|---|---|---|---|---|---|---|
| **7kW** | $34,471 | 10494 | 6417 | 7232 | 4055 | $2034 | $2203 |
| **5kW** | $35,132 | 7496 | 6651 | 4467 | 4203 | $2418 | $2539 |
| **3kW** | $36,583 | 4497 | 7111 | 1930 | 4500 | $2876 | $2948 |

From table 7, it is clear that grid connected 7kW PV panel system for only electricity house has least NPC as the production is maximum as compared to 5kW and 3kW PV panels (see figures 45, 50 and 55).

- **Results of grid tied 7kW PV system**

In case of electricity only energy consumption, cooking and heating appliances runs on electricity which increases the overall consumption of electricity. In case of 7kW PV panel, NPC of grid includes the power purchased from grid which is more than the NPC of PV panels used as given in figure 43. Operating costs are maximum as in Homer pro power purchased from grid is given as operating costs.

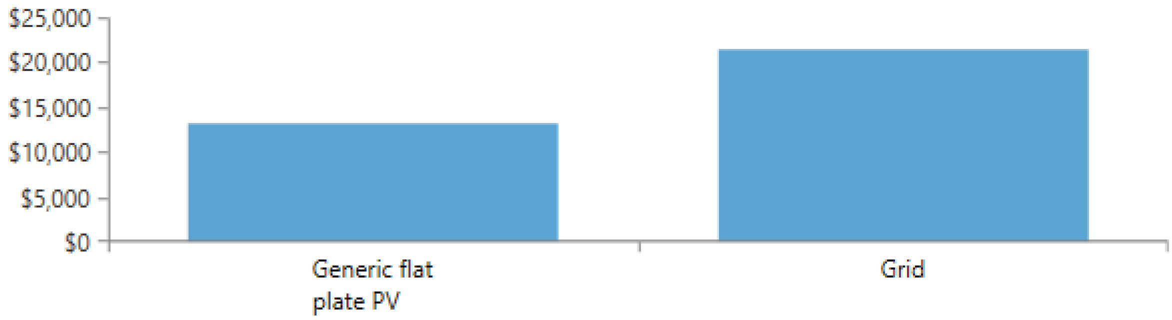


Figure 43 Net present cost comparison by component for 7kW PV panel

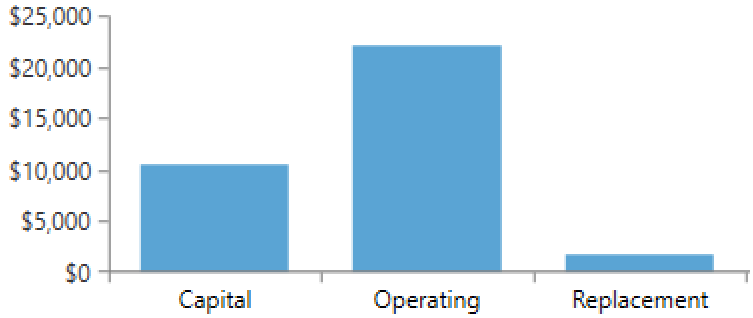


Figure 44 Annualised cost comparison of all costs included in the project for 7kW PV panel

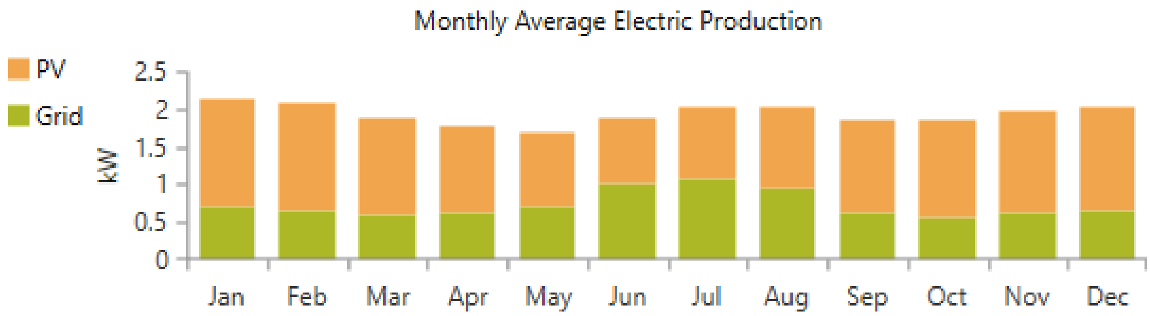


Figure 45 Monthly average electricity production from 7kW PV and grid purchased power

During daytime in weekdays, people usually do not stay at home but the panels produce maximum electricity in those hours which is only used for some appliances which runs whole day such as refrigerator, lights etc. and the excess power is fed to the grid which gives feed in tariff between 7 am to 17 pm approximately (see figure 47). In winters, due to the heating appliances, more electricity is required by dwelling in evening hours as people stay at home in the evening which results in more power from the grid which is shown by blue colour in the mid of year in the figure 46.

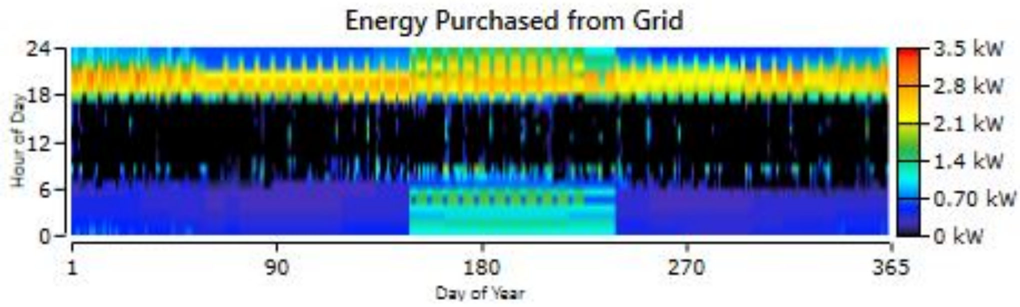


Figure 46 Dmap showing power purchased from the Grid for 7kW PV system

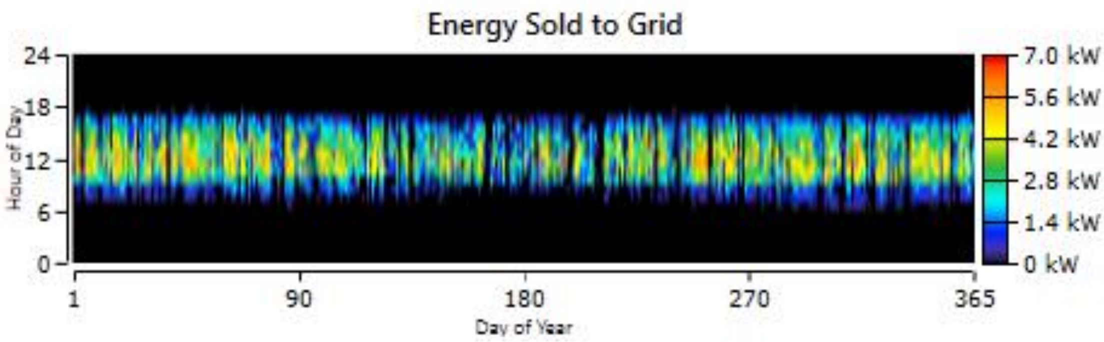


Figure 47 Dmap showing power sold to the Grid for 7kW PV system

- **Results of grid tied 5kW PV system**

NPC of grid is more in this case as compared to 7kW PV system as the panel size is small which requires more power purchased from the grid. But the capital costs are less as compare to 7kW PV system. Energy sold to the grid in 5kW system is less as compared to 7Kw system.

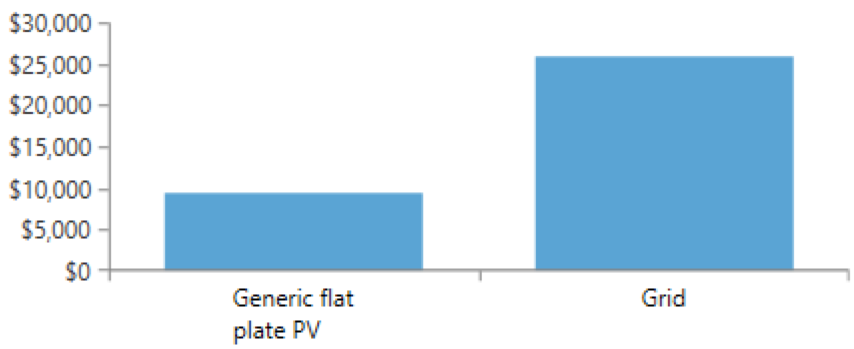


Figure 48 Net present cost comparison by component for 5kW PV panel

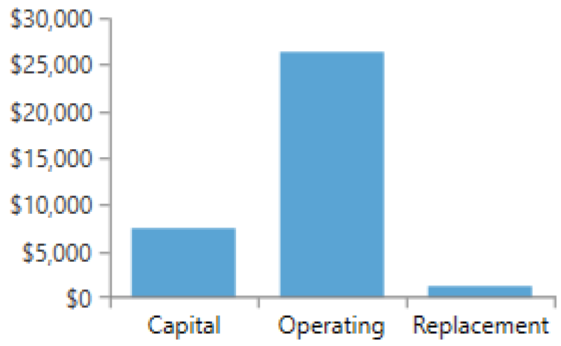


Figure 49 Annualised cost comparison of all costs included in the project for 5kW PV panel

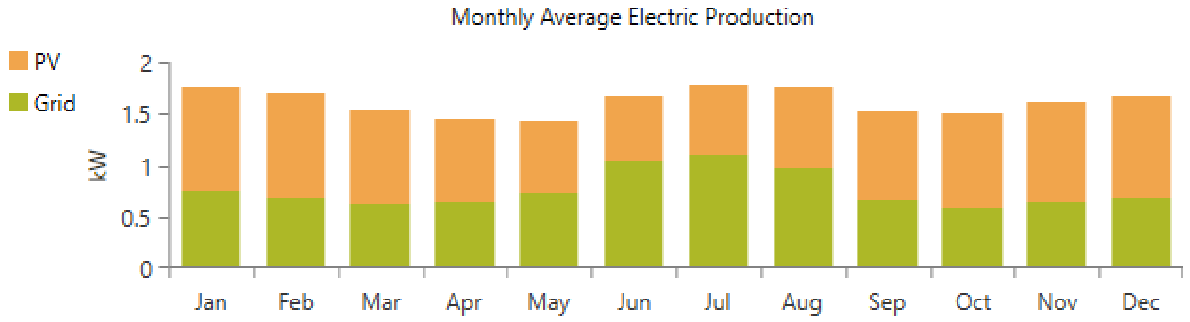


Figure 50 Monthly average electric production for 5kW PV panel

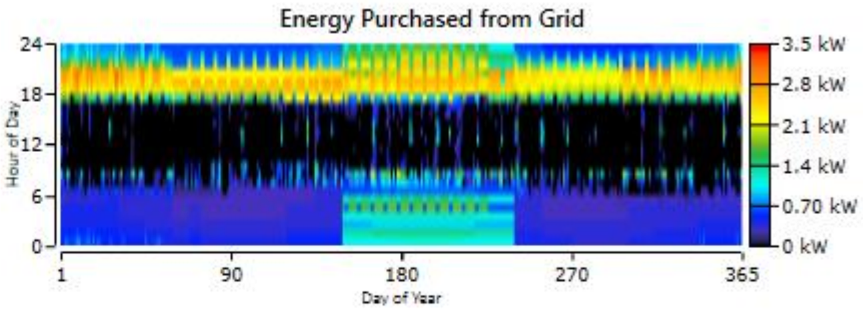


Figure 51 Dmap showing power purchased from the Grid for 5kW PV system

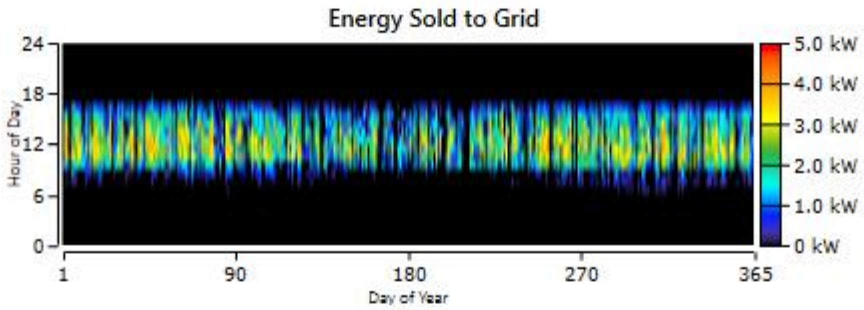


Figure 52 Dmap showing power sold to the Grid for 5kW PV system

- **Results of grid tied 3kW PV system**

3kW PV panel size is the smallest size with least capital cost and least production. This leads to more Grid NPC (see figure 53) as the panel size cannot fulfil the residential load fully during day as at peak hours between 12pm to 2pm panels produce maximum which fulfil the load and excess is fed to the grid. During evening hours or sometimes during day, power is taken from the grid (see figure 56) which shows some colours in black region that indicated the power purchased from the grid.

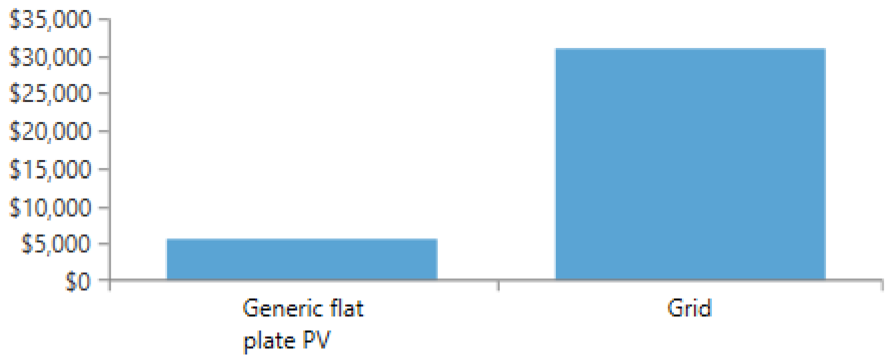


Figure 53 Net present cost comparison by component for 3kW PV panel

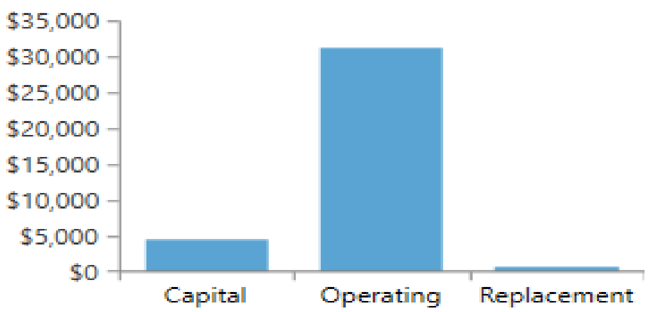


Figure 54 Annualised cost comparison of all costs included in the project for 3kW PV panel

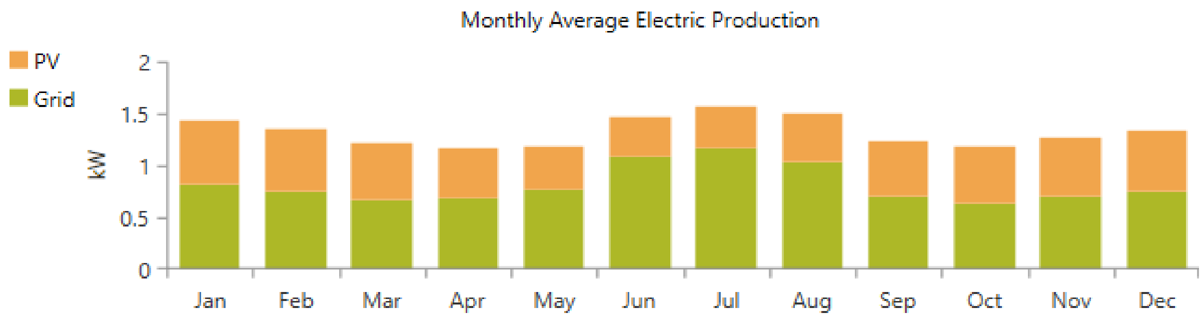


Figure 55 Monthly average electric production for 3kW PV system

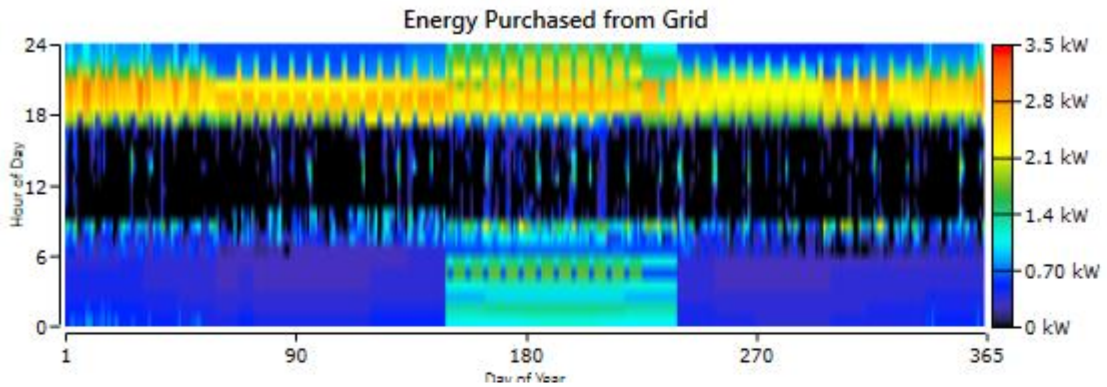


Figure 56 Dmap showing power purchased from the Grid for 3kW PV system

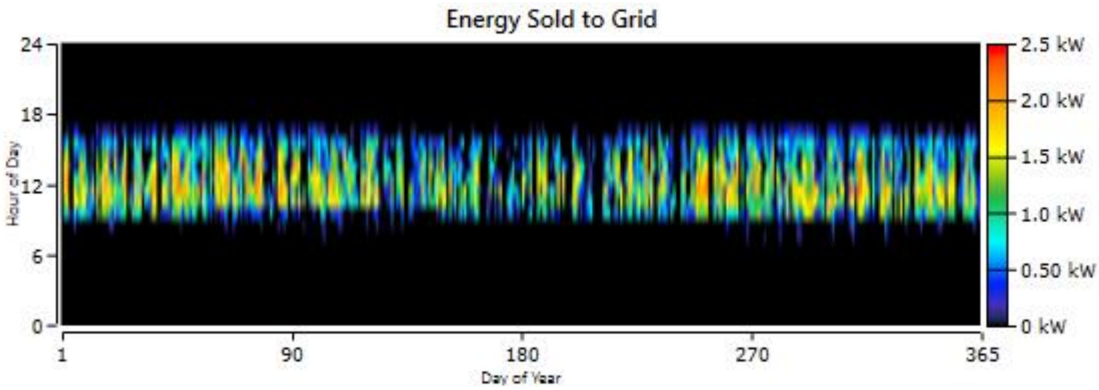


Figure 57 Dmap showing power sold to the Grid for 3kW PV system

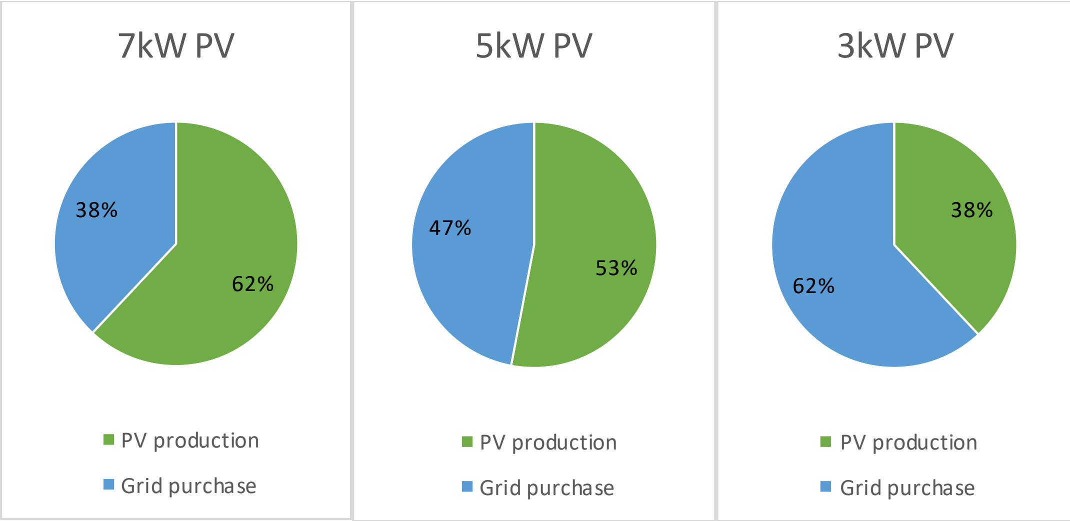


Figure 58 Renewable fraction comparison of all three sizes of panels

On comparing two systems i.e. Grid tied PV electricity and gas connected and only electricity connected house it is noticed that Grid and PV connected house with only electricity has more NPC as compared to the house with electricity and gas for a lifetime of 20 years. For 7kW PV and grid connected house with electricity and gas connection, the NPC of gas is $7203 (see table 3 ) and electricity is $18701 (see table 5) which is overall $25904 which is greater than the NPC of only electricity house i.e. $34471 (table 6). Net present costs decrease with the increase in PV sizes and $CO_2$ emissions from the whole system also reduces with increase in PV sizes. Therefore, most cost-effective system is grid tied 7kW PV with electricity and gas house as it has least net present cost and less $CO_2$ emissions as compared to a house with only electricity. This is because of the reduced prices of gas and in electricity and gas connected house, most of the appliances are on gas like gas water heaters, space heaters and cooktops. The renewable fraction for 7Kw PV system in electricity and gas connected house is 76.3% while for electricity only its value is 62.1% which shows that grid and PV connected house with electricity and gas is a more economic approach. For 3kW and 5kW NPC costs are maximum which are not considered as cost-effective as compared to 7kW PV system.

### 5.1.5 Grid connected house with PV and battery for electricity and gas consumption

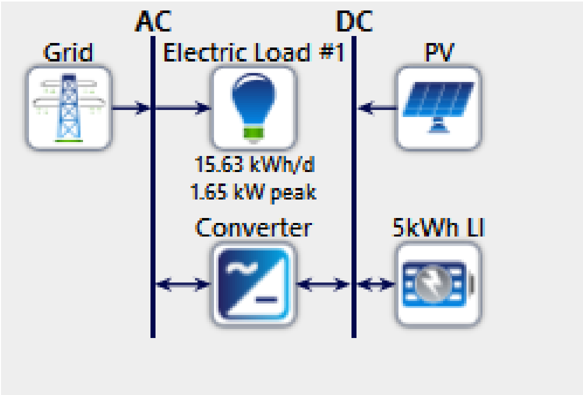


Figure 59 Schematic of grid tied PV and battery system for electricity and gas connected house

In the above two sections, battery is not connected to the system and PV panels work only in day light which required power from the grid. Therefore, rather than purchasing power from the grid, battery storage is used. During daytime, PV panels produce energy which is fed to the grid as seen in above sections but in this case that energy is stored in the battery after passing through inverter. This stored power will be used in the evening hours which has more electricity consumption patterns as compared to morning. This will increase the overall benefits as very less amount of power will be taken from the grid if the battery discharge completely.

Table 7 Cost and power production comparison of different PV sizes with different battery sizes for grid tied PV-Battery system with electricity and gas connections

| PV size (kW) | Battery size (kWh) | Converter (kW) | NPC | Initial capital System ($) | PV production (kW/yr) | Energy purchased from grid (kWh) | Energy sold to grid (kWh) | CO2 emisions (kg/yr) | System O&M costs ($/year) | Operating costs ($/year) |
|---|---|---|---|---|---|---|---|---|---|---|
| **7kW** | 5kWh | 5kW | $10,825 | $12,000 | 10,494 | 2019 | 5961 | 1276 | -$363.66 | -$108 |
| | 10kWh | | $15240 | $15,500 | 10,494 | 902 | 4737 | 570 | -$351.95 | -$23.93 |
| | 15kWh | | $19571 | $19,000 | 10,494 | 418 | 4217 | 264 | -$347.90 | $52.47 |
| **5kW** | 5kWh | 5kW | $12058 | $10000 | 7496 | 2188 | 3475 | 1383 | -$18.31 | $189.11 |
| | 10kWh | | $16525 | $13,500 | 7496 | 1190 | 2370 | 752 | -$1.78 | $227.99 |
| | 15kWh | | $20899 | $17,000 | 7496 | 750 | 1887 | 475 | $6.14 | $358.28 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **3kW** | 5kWh | 5kW | $17273 | $8000 | 4497 | 2585 | 1073 | 1634 | $692.89 | $852.07 |
| | 10kWh | | $21889 | $11,500 | 4497 | 1917 | 305 | 1212 | $723.07 | $954.61 |
| | 15kWh | | $26257 | $15,000 | 4497 | 1727 | 98.1 | 1091 | $730.42 | $1034 |

For a system with electricity and gas, the NPC of 7kW PV with 5kWh battery is least, followed by 5kW PV with 5kW battery as the capital cost of smaller sized batteries is less which decreases the overall costs. For a system with 3kW PV panel with 15kWh battery, NPC is maximum because of high cost of bigger battery size i.e. 15kWh. For 7kWh PV-Battery system, on comparing all three battery sizes, 5kWh battery equipped systems has least cost but maximum amount of $CO_2$ emissions are released while with 15kWh battery $CO_2$ emissions are least but the NPC is high. More amount of electricity is required to purchase from grid in case of small battery size systems. Therefore, more the battery size, less power is purchased from the grid with high NPC. As smaller sized can't store much power and some of power discharges which results in more selling power to the grid at a sale price of $0.11/kWh which provides benefits that leads to lower net present costs of the system.

- Results of grid tied 7kW PV and battery system

In all the results of 7kW PV and 5kW PV, the grid net present costs are negative (see figures 60, 62, 64, 66, 68 and 70) which shows that more power is sold to the grid than purchasing from the grid. Monthly average electricity production shows PV generated power usage for residential load and power purchased from grid. PV met the maximum residential load in case of 7kW PV with 15kWh battery because the battery size is large to store energy which can be used to fulfil maximum load requirement. As shown in the figure 65, only during winter months and summer months, some amount of power is purchased from grid but in remaining seasons stored energy fulfil the load. But as the system has extra benefits but the main disadvantage of this system is high NPC value due to the higher costs of batteries. 7kW/ 5kWh combination of PV and battery has least

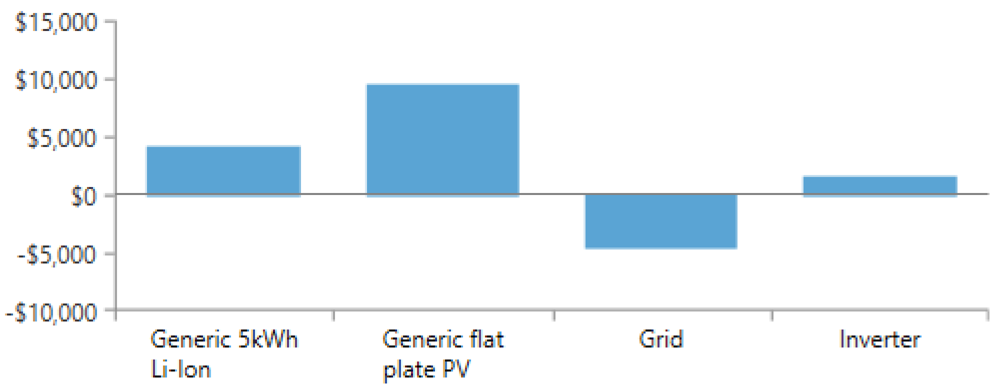


Figure 60 Net present cost comparison by component for 7kW PV and 5kWh battery system

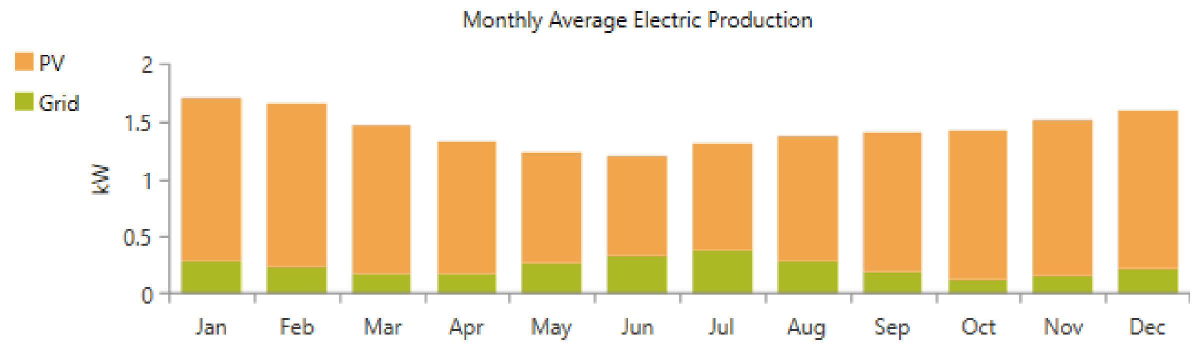


Figure 61 Monthly average electricity production for grid tied 7kW and 5kwh battery system

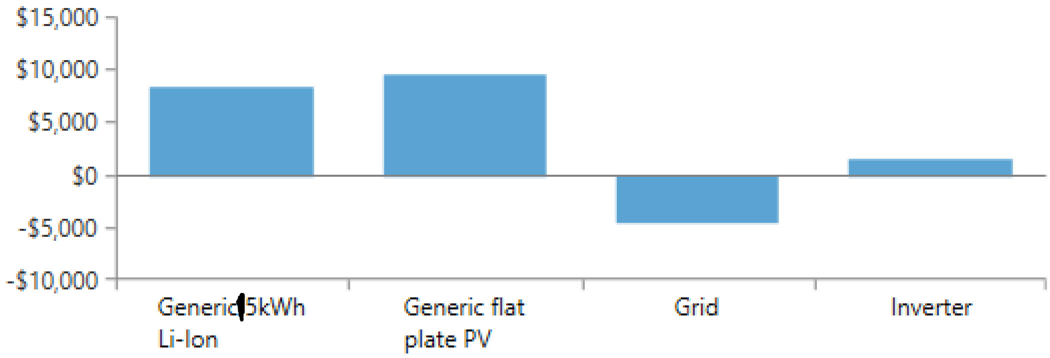


Figure 62 Net present cost comparison by component for 7kW PV and 10 kWh battery system

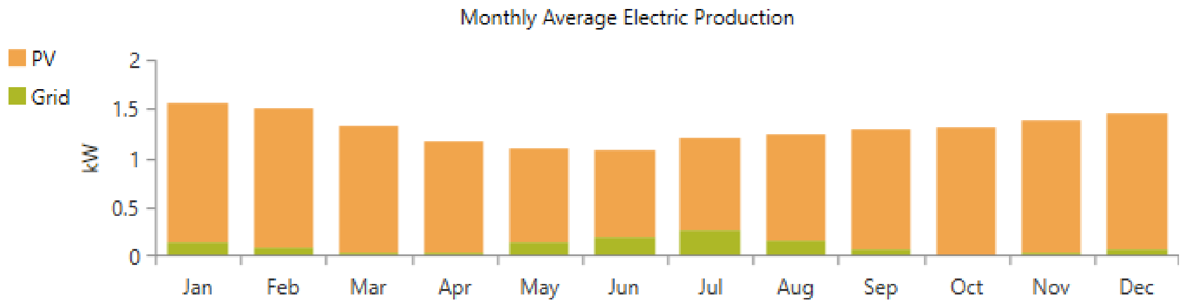


Figure 63 Monthly average electricity production for grid tied 7kW and 10kwh battery system

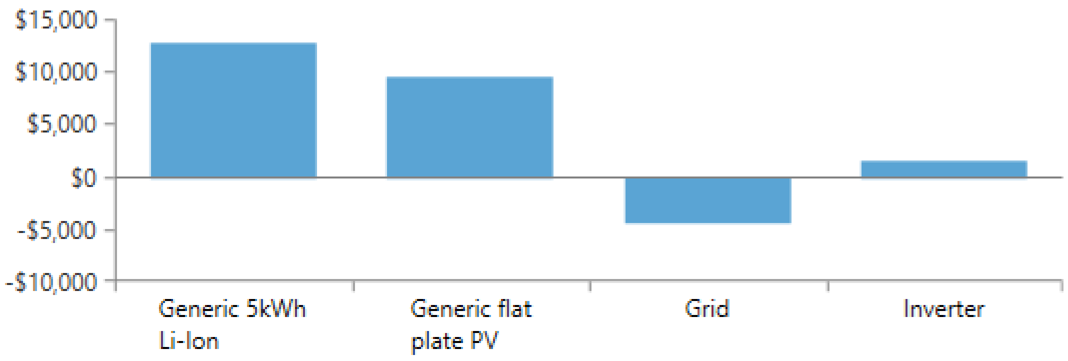


Figure 64 Net present cost comparison by component for 7kW PV and 15 kWh battery system

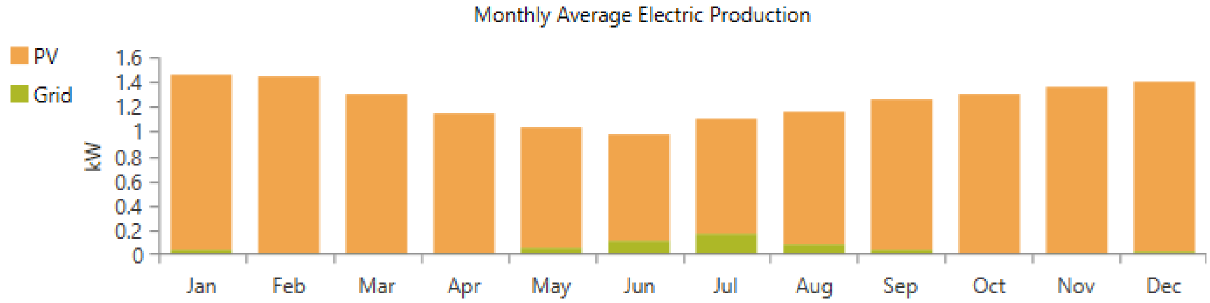


Figure 65 Monthly average electricity production for grid tied 7kW and 15 kwh battery system

- **Results of grid tied 5kW PV with battery system**

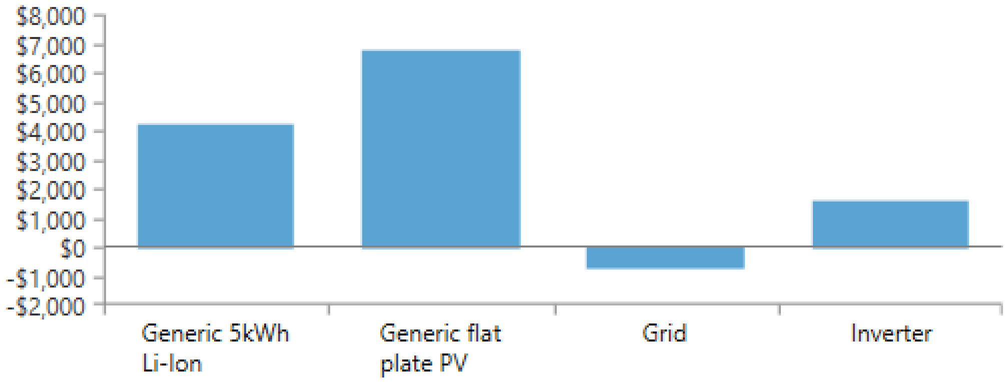


Figure 66 Net present cost comparison by component for 5kW PV and 5 kWh battery system

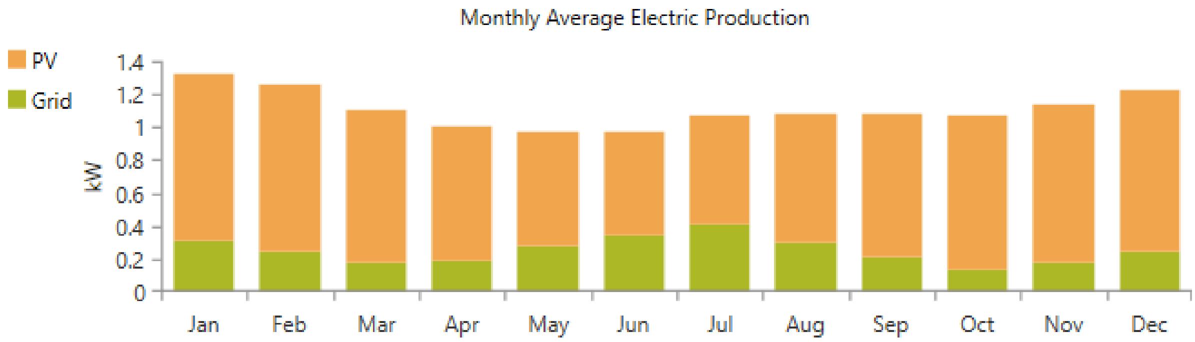


Figure 67 Monthly average electricity production for grid tied 5kW and 5 kwh battery system

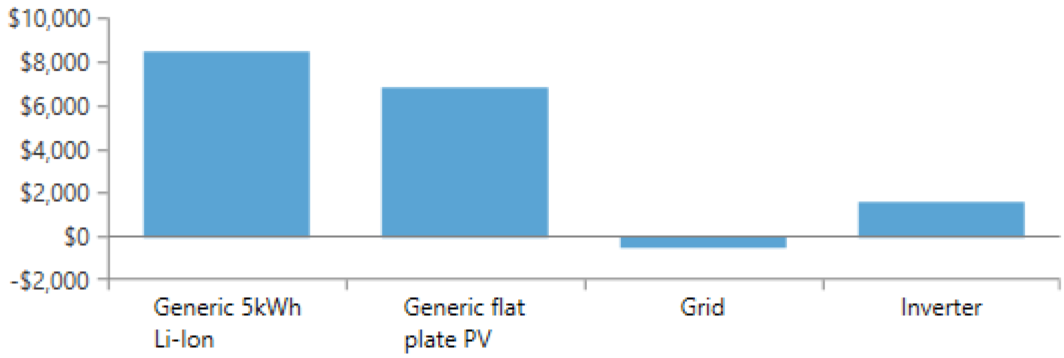


Figure 68 Net present cost comparison by component for 5kW PV and 10 kWh battery system

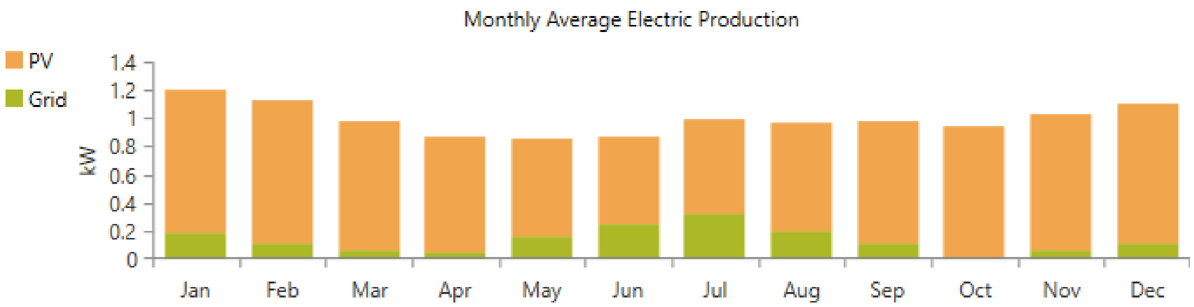


Figure 69 Monthly average electricity production for grid tied 5kW and 10kwh battery system

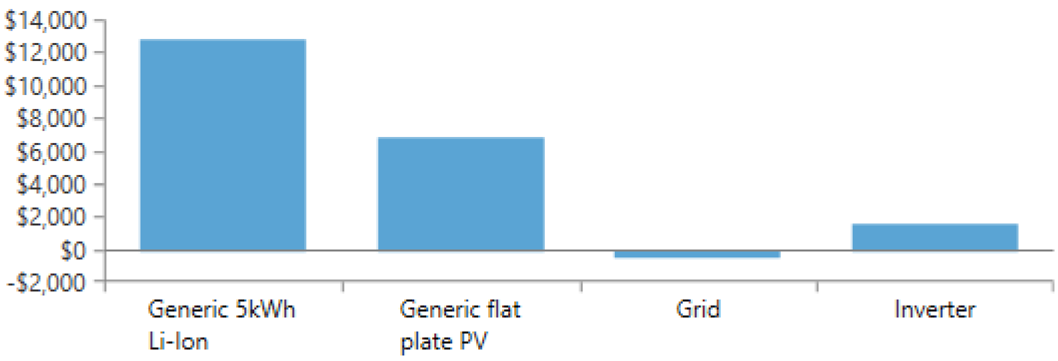


Figure 70 Net present cost comparison by component for 5kW PV and 15 kWh battery system

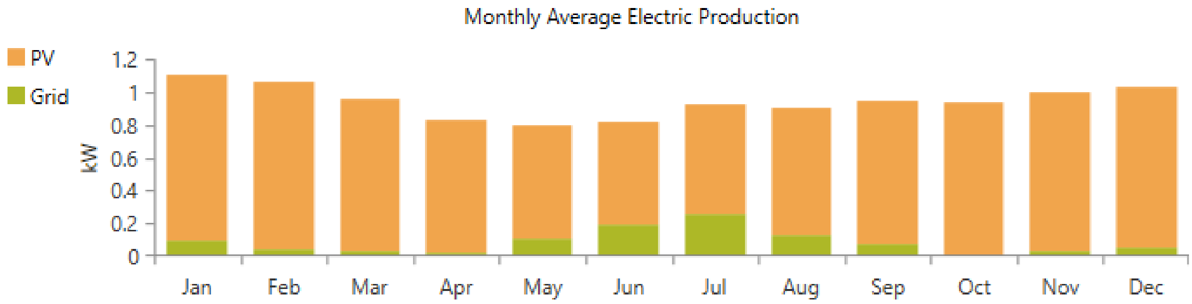


Figure 71 Monthly average electricity production for grid tied 5kW and 15 kwh battery system

- **Results of grid tied 3kW PV with battery system**

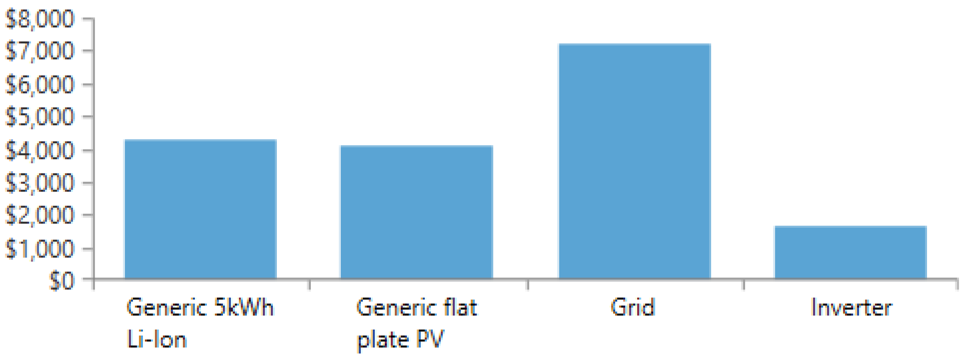


Figure 72 Net present cost comparison by component for 3 kW PV and 5 kWh battery system

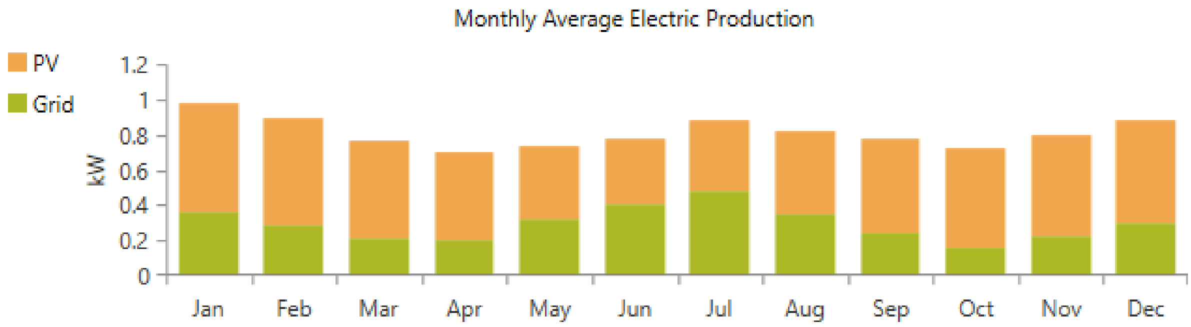


Figure 73 Monthly average electricity production for grid tied 3kW and 5 kwh battery system

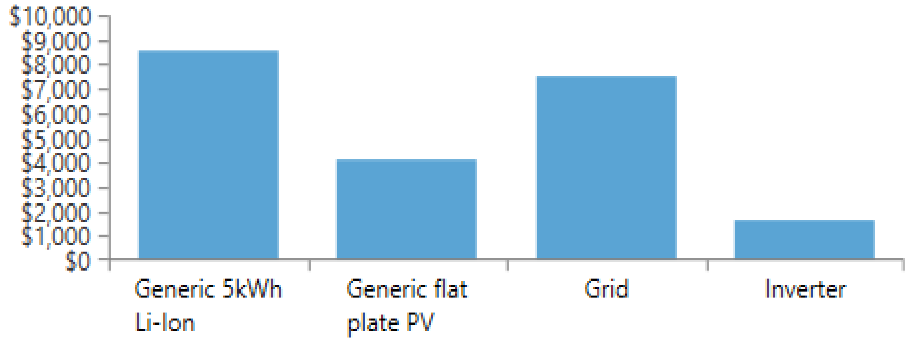


Figure 74 Net present cost comparison by component for 3kW PV and 10 kWh battery system

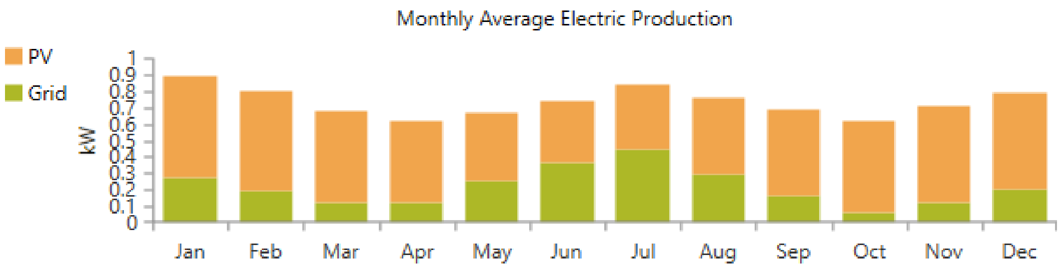


Figure 75 Monthly average electricity production for grid tied 3kW and 10kwh battery system

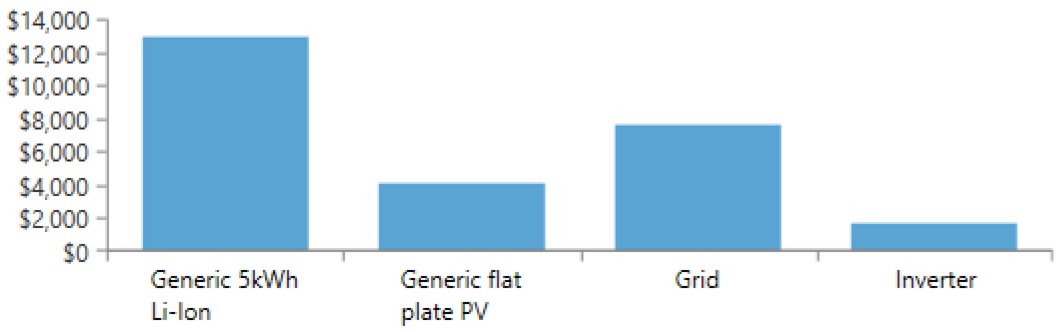


Figure 76 Net present cost comparison by component for 3kW PV and 15 kWh battery system

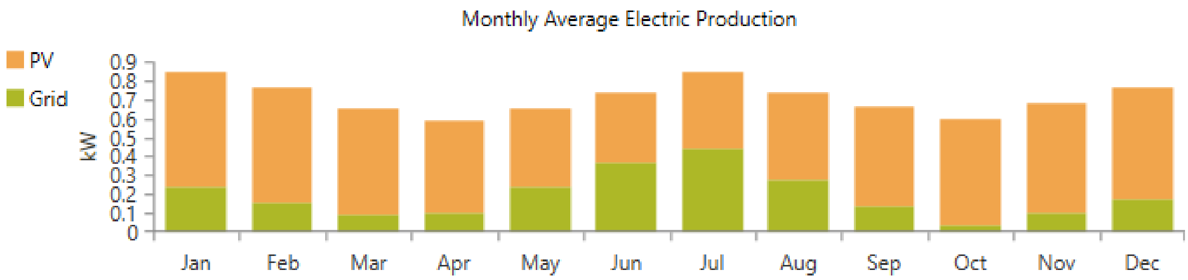


Figure 77 Monthly average electricity production for grid tied 3kW and 15kwh battery system

Figures 73,74 and 76 shows the monthly production which shows that in case of 7kW with 15kWh battery, very less amount of electricity is purchased from the grid and that is during winters and some amount in summers. The renewable fraction for 7kW PV with 15kWh battery is maximum i.e. 95% followed by 91.1% for 7kW with 10kWh battery and 90% for 5kW PV with 15kWh battery. In 3kW PV with 5kWh battery, the renewable fraction is least among all cases discussed in this section i.e. 61.7% which means that maximum amount of power is taken in this case. Moreover, annual throughput for 7kW PV with 5kWh battery is maximum while its value is minimum in case of 3kW PV with 5kWh battery. Therefore, in terms of NPC, more the battery size, more will be the NPC but less power is required to purchase from the Grid.

### 5.1.6 Grid connected house with PV and battery for only electricity consumption

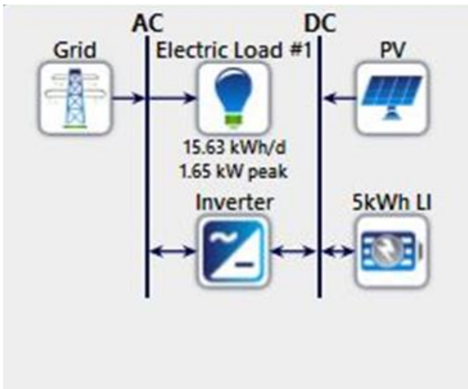


Figure 78 Schematic of Grid tied PV and battery system for electricity only connected house

In this scenario, as all the appliances in dwellings are electric and then consumption is more in the evening hours which leads to sufficient storage requirement. Therefore, battery is connected to the house to store power generated by PV panels during day and discharge power during night to fulfil demand.

Table 8 Cost and power production comparison of different PV sizes with different battery sizes for grid tied PV-Battery system with electricity only connections

| PV size (kW) | Battery size (kWh) | Conv. (kW) | NPC | Initial capital cost ($) | PV production (kW/yr) | Energy purchased from grid (kWh) | Energy sold to grid (kWh) | CO2 emisions (kg/yr) | System O&M costs ($/year) | Operating costs ($/year) |
|---|---|---|---|---|---|---|---|---|---|---|
| **7kW** | 5kW | 5kW | $19,384 | $12,000 | 10494 | 5212 | 5183 | 3294 | $422.79 | $678.45 |
| | 10kW | | $23,895 | $15500 | 10494 | 4099 | 3975 | 2590 | $434.05 | $771.39 |
| | 15kW | | $28320 | $19000 | 10,494 | 3109 | 2939 | 1965 | $455.99 | $856.36 |
| **5kW** | 5kW | 5kW | $25,365 | $10,000 | 7496 | 5519 | 2834 | 3488 | $1204 | $1,412 |
| | 10kW | | $30,857 | $30,133 | 7496 | 4558 | 1771 | 2881 | $1249 | $1528 |
| | 15kW | | $34,795 | $17,000 | 7496 | 3802 | 934 | 2403 | $1283 | $1635 |
| **3kW** | 5kW | 5kW | $35845 | $8000 | 4497 | 6192 | 682 | 3914 | $2399 | $2559 |
| | 10kW | | $40,381 | $11,500 | 4497 | 5679 | 116 | 3589 | $2422 | $2654 |
| | 15kW | | $46141 | $15000 | 4497 | 5572 | 0.601 | 3521 | $2426 | $2730 |

In this case, the NPC costs of the system with smallest PV size and highest battery size i.e. 3kW/15kWh is maximum. In case 7kW PV with different battery sizes, NPC of the system with 5kWh battery is least followed by 10kWh and 15kWh battery. Battery size puts a great impact on NPC, CO2 emissions, purchased power from the grid and sold power to the grid. NPC is maximum because of higher battery costs which increases with the increase in battery size but with larger battery size, least amount of power is purchased from the grid. CO2 emissions are minimum in case of larger battery size as shown in the table 9.

- **Results of grid tied 7kW PV with battery system**

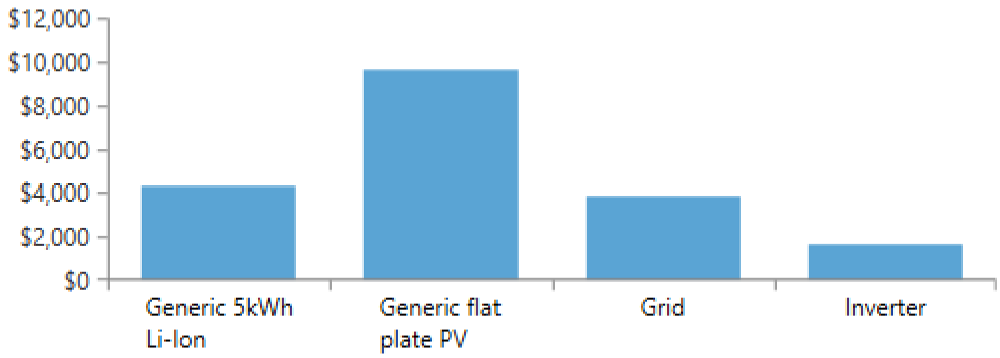


Figure 79 Net present cost comparison by component for 7kW PV and 5 kWh battery system

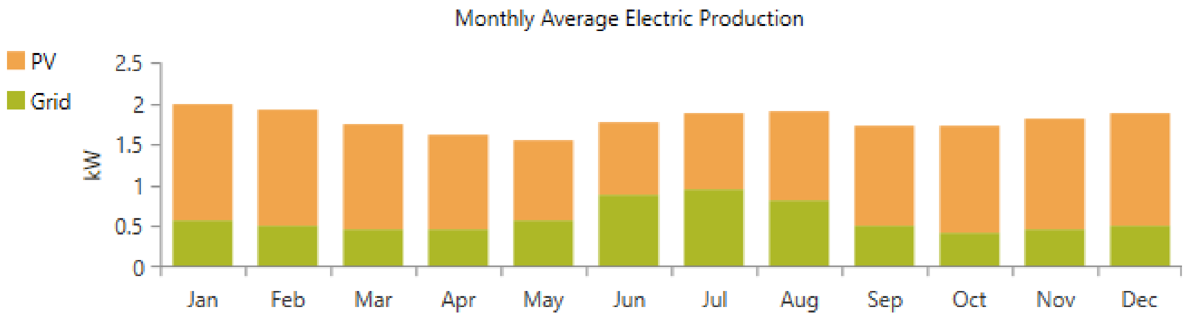


Figure 80 Monthly average electricity production for grid tied 7kW and 5kwh battery system

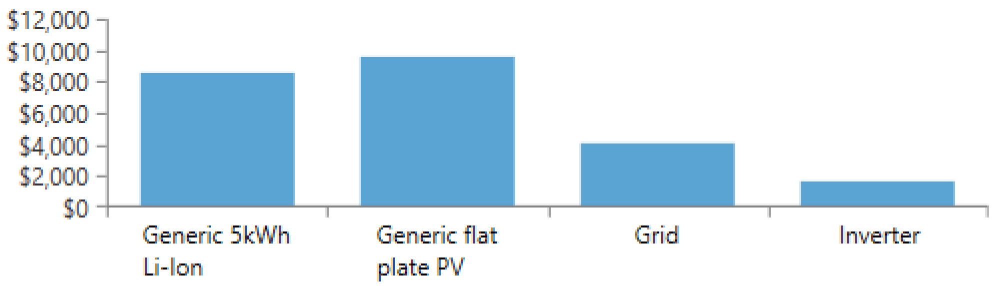


Figure 81 Net present cost comparison by component for 7kW PV and 10 kWh battery system

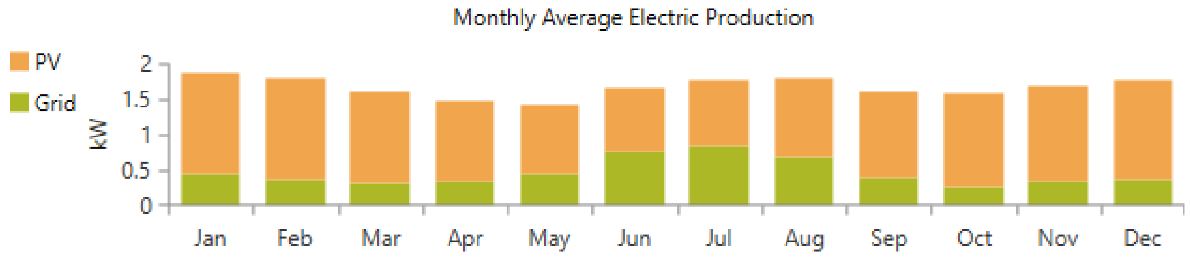


Figure 82 Monthly average electricity production for grid tied 7kW and 10kwh battery system

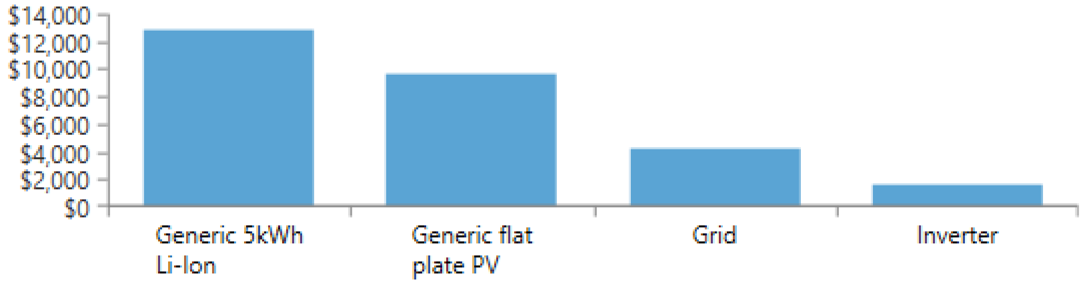


Figure 83 Net present cost comparison by component for 7kW PV and 15 kWh battery system

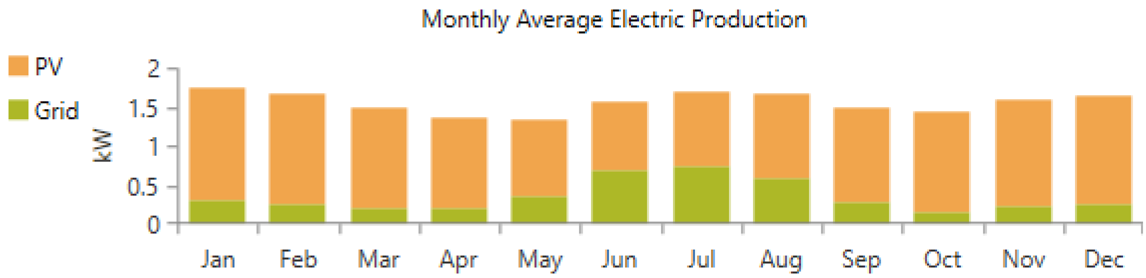


Figure 84 Monthly average electricity production for grid tied 7kW and 15kwh battery system

- **Results of grid tied 5kW PV with battery system**

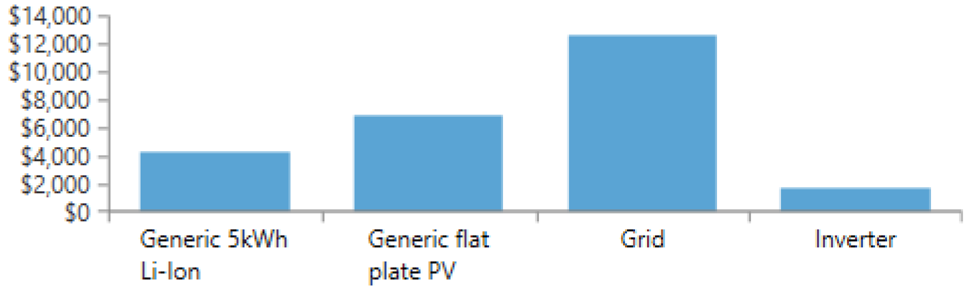


Figure 85 Net present cost comparison by component for 5kW PV and 5 kWh battery system

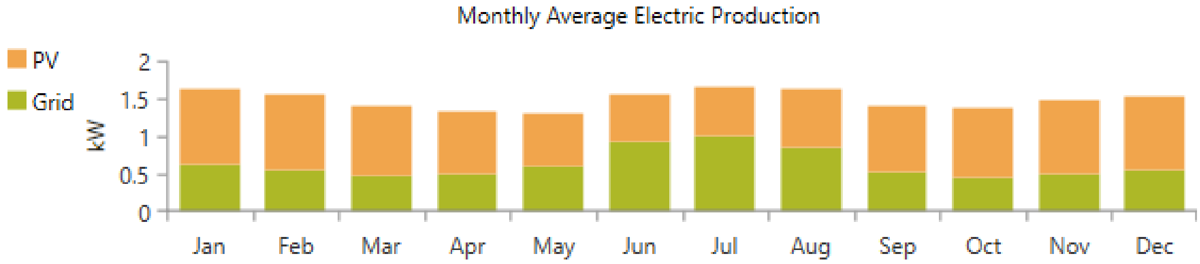


Figure 86 Monthly average electricity production for grid tied 5kW and 5kwh battery system

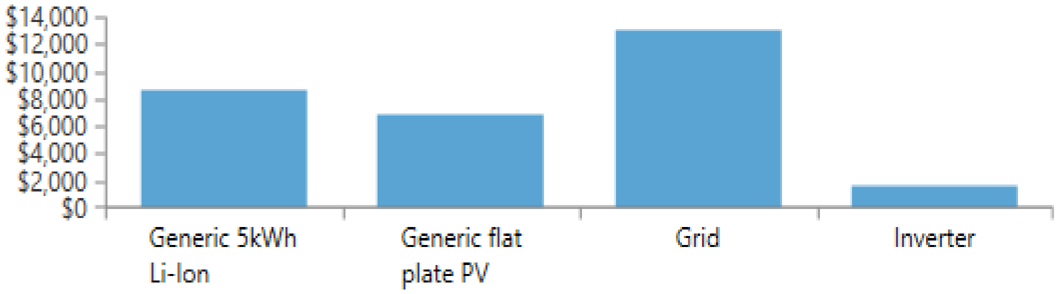


Figure 87 Net present cost comparison by component for 5kW PV and 10 kWh battery system

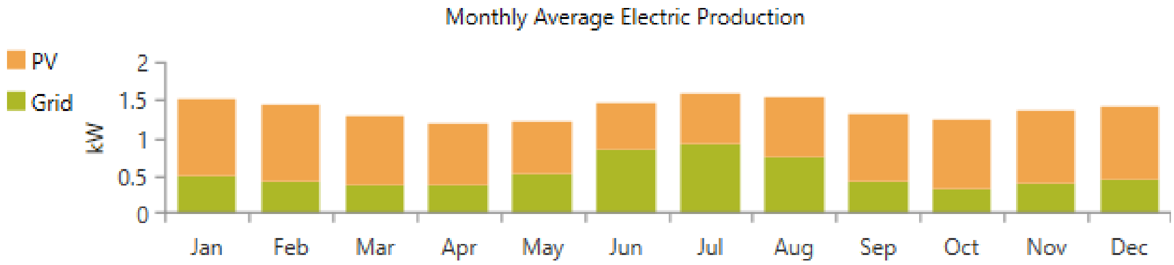


Figure 88 Monthly average electricity production for grid tied 5kW and 10kwh battery system

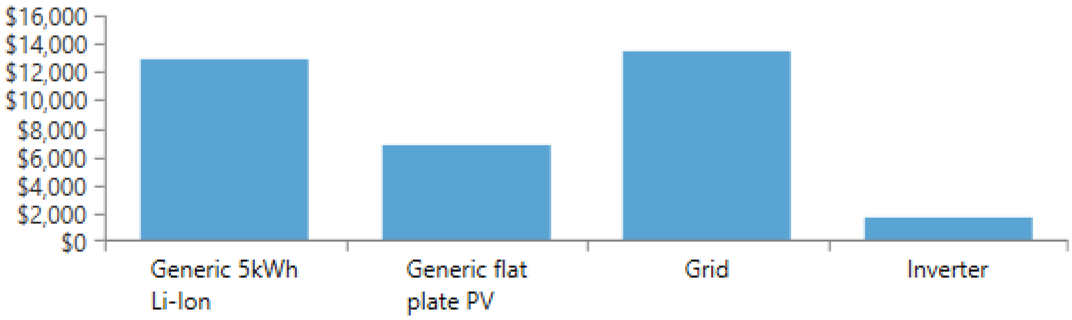


Figure 89 Net present cost comparison by component for 5kW PV and 15 kWh battery system

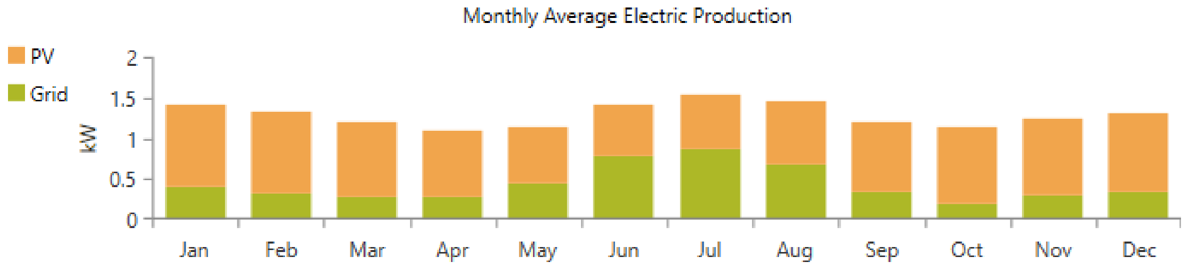


Figure 90 Monthly average electricity production for grid tied 5kW and 15kwh battery system

- **Results of grid tied 3kW PV with battery system**

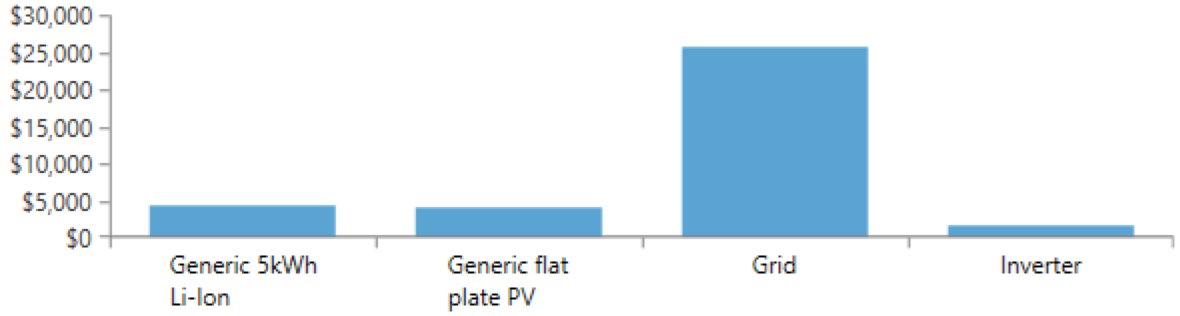


Figure 91 Net present cost comparison by component for3kW PV and 5kwh battery system

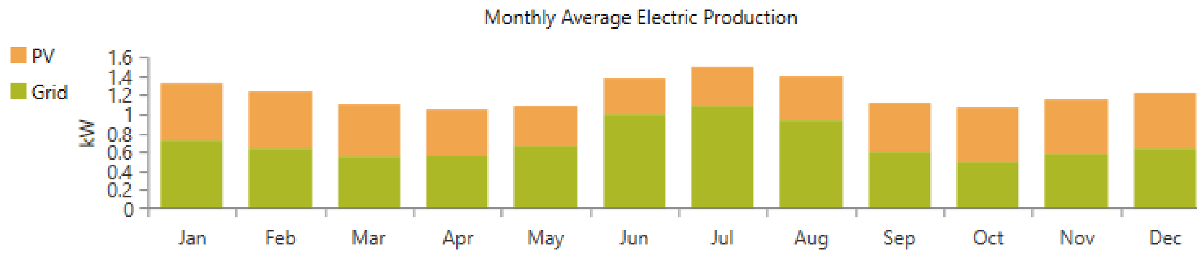


Figure 92 Monthly average electricity production for grid tied 3kW and 5kwh battery system

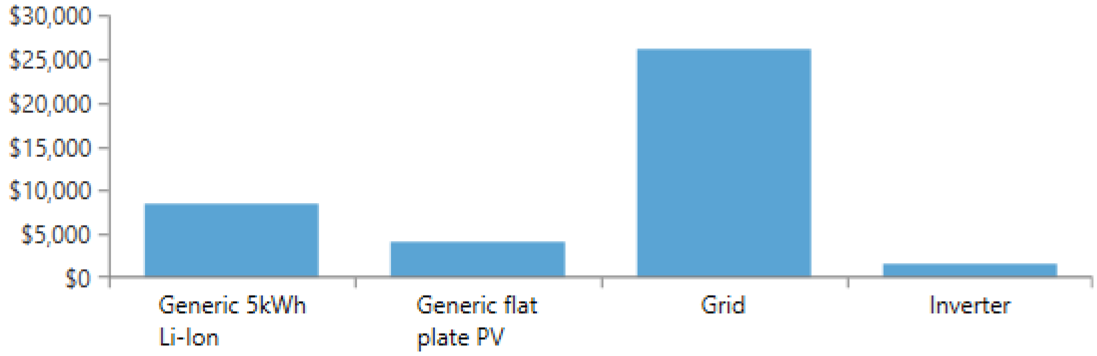


Figure 93 Net present cost comparison by component for grid tied 3kW PV and 10kwh battery system

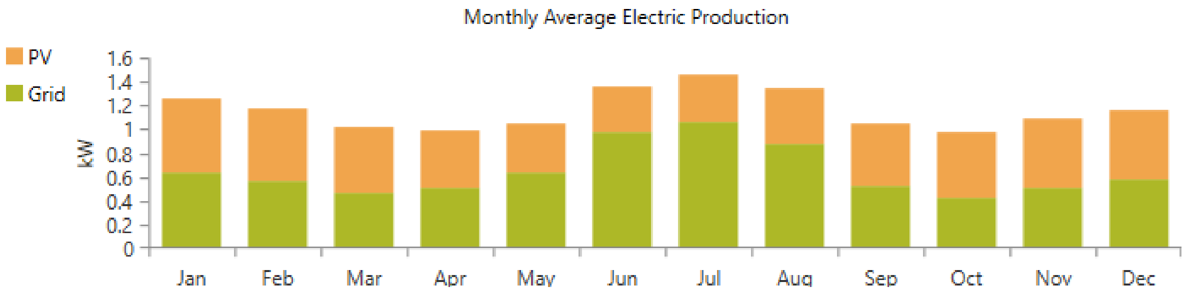


Figure 94 Monthly average electricity production for grid tied 3kW and 10kwh battery system

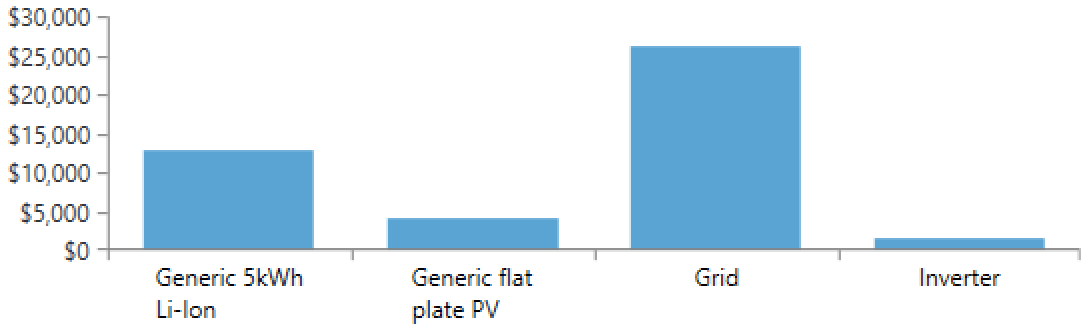


Figure 95 Net present cost comparison by component for grid tied 3kW PV and 15kwh battery system

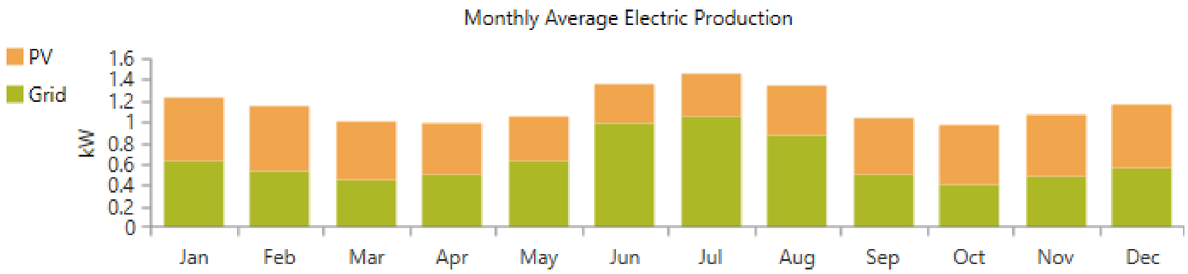


Figure 96 Monthly average electricity production for grid tied 3kW and 15kwh battery system

Figure 79, 81,83 represents costs by component which involves the costs of all components i.e. LI-ion battery, PV panel, grid and inverter. Here, grid involves the power purchased from the grid which is least in case of larger battery size i.e. 15kWh. In 3kW PV system, the renewable fraction for 3kW PV with 5kWh battery is 40.2% and for 15kWh battery its value is 42.4%. For 7kW PV with 15kWh PV, renewable fraction is maximum i.e. 75.4% which means least amount of power is taken from the grid as shown in the figure, 84. Therefore, larger the PV with smaller sized battery, least will be NPC and operating costs.

On comparing both systems, house with electricity and gas and house with electricity only, it is clear that, house with electricity and gas has lower costs in every single case. For example, 7kW PV and 5kWh battery has $18,701 NPC for electricity and gas connected house while for the same PV and battery NPC for electricity only house is $19,384. If these two systems are compared with without battery connected systems, then the results show that grid tied PV without battery with electricity and gas has least NPC i.e. $10,825 and for electricity only connected house its value is $19,384.

## 5.2 Sensitivity Analysis

Sensitivity analysis is basically performed in order to test the system on various values like PV sizes, battery sizes, electricity prices, PV and battery prices and retail prices and the system is tested by putting these values to one variable i.e. sensitivity variable. As the most optimal case in optimisation results was with electricity and gas, therefore the same case is used to perform sensitivity analysis. For this case, three different variables are analysed.

### 5.2.1 When retail price and sell back of electricity is increased

Retail price put a huge impact on overall energy system costs. The research has covered the analysis based on $0.43/kWh. To perform sensitivity analysis, suppose, power price is varied between $0.35/kWh to $0.50/kWh. Here, sensitivity variable is electricity price. NPC i.e. net present cost is calculated at all these prices for the system with 7kW PV and grid with electricity and gas connected house and overall consumption per day 15.63kWh. At $0.43, NPC was $18701 while in case of $0.35, it value drops to $15,867. For higher retail prices, like $0.46, NPC is $19,764. This shows that with the increase in electricity prices, NPC increases but other factors like PV production, renewable fraction remain same.

Sell back price is the price at which grid provides the household, a credit for sending surplus power to grid. The increase in feed in tariff prices benefits the customer. But for NPC calculations, suppose, sell back price is varied from $0.8/kWh to $0.15/kWh. For a normal case as considered in this study, the NPC is $18,701 at $0.11/kWh while at $0.15, NPC value gets reduced i.e. $15,200.

### 5.2.2 When battery prices reduced

Battery price is one of the main reason due to which battery connected systems are not optimal. If battery price is reduced to some values then it will affect the NPC of the system. For a normal case as discussed in this study, for smallest battery size i.e. 5kWh battery, capital cost is $3500 with $1500 replacement cost then the NPC was $10,825. Suppose, the prices are lowered to values with capital cost $2000 and replacement is $800 then the NPC of the system is calculated which shows $8797 least amount of NPC as compared to all systems discussed so far. More the battery size, less would be the benefits and more would be the NPC. As renewable energy demand is increasing by day, therefore reduction in battery prices is expected.

# CHAPTER 6

## CONCLUSION AND FUTURE WORKS

After analysing all the results, this research has successfully found a reliable system for Adelaide based residential household with least costs and maximum benefits. As PV panels of 3kW, 5kW and 7kW with and without battery are analysed and based on given load patterns, NPC and renewable fraction of all three systems with and without battery are evaluated for electricity and electricity and gas energy consumption.

In terms of net present costs of the system, 7kW has least NPC i.e. $10,825 when it is connected with 5kWh battery in a dwelling equipped with electricity and gas energy consumption. As the gas price is less that leads to lowering costs of the systems. But smaller battery size has lower value of renewable fraction and maximum amount of renewable fraction is found out in case of 7kW PV with 15kWh battery i.e. 95% which means that 95% electricity demand is fulfilled by PV/BES system and only 5% is taken from grid. Bigger battery size results in more storage which benefits the dwelling to buy least amount of power from the grid. The NPC of this system is $19,571 which is almost doubled by increasing battery size.

A new approach of testing gas data leads to following conclusions,

- Grid tied PV dwelling with electricity and gas connected has least Net present costs as compared to house with electricity only because of the reduced retail price of gas as compared to electricity
- Battery costs play a great role in overall cost of the system and both the system connected with battery are expensive which leads to a conclusion that adding battery to PV system is not a reliable approach
- The main objective of the study also includes reduced greenhouse gas emissions which shows that if bigger size PV panel is used for a system then $CO_2$ emissions will be reduced as for those cases least amount of power would be required from the grid.

The most difficult issue with the research was collection of electricity and gas data. One of the main limitations of research is that, consumption patterns depends upon individual usage which can be different for different dwellings that leads to change in many values. Electricity prices are different for different hours in a day or even during different seasons, which can be considered for further study to find optimal cases for those systems.

## NOMENCLATURE

| | |
|---|---|
| $\alpha_p$ | power temperature coefficient |
| Ac | alternating current |
| BES | battery energy storage |
| c | grid demand rate ($/kW/month) |
| $c(pv)$ | capacity of PV array (kW) |
| $C_{npc,tot}$ | total net present cost |
| $C_t$ | net cash inflow at ‘t’ ($) |
| $C_o$ | total initial costs i.e. inflows ($) |
| $C_{an,tot}$ | total annualised cost |
| $C_{an,cap}$ | annual capital cost ($) |
| $C_{op}$ | operating cost ($) |
| $CHP$ | combined heat and power unit |
| CRF | capacity recovery factor |
| cp | purchase price ($/kWh) |
| cps | grid sell back rate ($/kWh) |
| Dc | direct current |
| $d(pv)$ | PV derating factor |
| $DOD$ | depth of discharge |
| DG | distributed generation units |
| $E_{gridp}$ | electricity purchased from grid |
| $E_{grids}$ | electricity sold to grid |
| $E$ | overall generated electricity |
| $E_{served}$ | total load served (kWh) |
| EC | energy charge ($) |
| $F$ | fuel costs |
| $f(pv)$ | derating factor of PV (%) |
| $GAs$ | genetic algorithm |
| $G_t$ | radiation incident on PV panels (kW/$m^2$) |
| $G_{t,stc}$ | radiation incident on PV panels at stc (kW/$m^2$) |
| $i$ | interest rate (%) |
| $l$ | project lifetime (years) |
| LCC | life cycle cost |
| $M$ | operation and maintenance costs |
| MG | micro grid |
| MILP | mixed-integer linear programming |
| $n$ | number of years |
| $NPC$ | net present cost ($) |
| $\eta_{bat,c}$ | battery charge efficiency |
| $P_{bat,cmax}$ | maximum charge power for battery |
| $P_{bat,dmax}$ | maximum discharge power for battery |

| | |
|---|---|
| $P_{gridp,j}$ | peak hourly grid demand in j month |
| $P_{out}$ | generated power from PV (kWh) |
| $PSO$ | particle swarm approach |
| r | discount rate or interest rate (%) |
| SSR | self-sufficiency ratio |
| $SOC$ | state of charge for battery (%) |
| $stc$ | standard test conditions |
| $T_c$ | cell temperature for PV for current time step (°) |
| $T_{c,stc}$ | cell temperature at standard test conditions (°) |
| T | number of time periods (years) |

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