Estimation of Energy Storage and Its Feasibility Analysis

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Additional information is available at the end of the chapter

1. Introduction

Storage significantly adds flexibility in Renewable Energy (RE) and improves energy management. This chapter explains the estimation procedures of required storage with grid connected RE to support for a residential load. It was considered that storage integrated RE will support all the steady state load and grid will support transient high loads. This will maximize the use of RE. Proper sized RE resources with proper sized storage is essential for best utilization of RE in a cost effective way. This chapter also explains the feasibility analysis of storage by comparing the economical and environmental indexes.

Most of the presently installed Solar PV or Wind turbines are without storage while connected to the grid. The intermittent nature of solar radiation and wind speed limits the capacity of RE to follow the load demand. The available standards described sizing and requirements of storage in standalone systems. However standards available for distributed energy resources (DER) or distributed resources (DR) to connect to the grid while considering solar photovoltaic (PV), wind turbine and storage as DR. Bearing this limitation, this chapter followed the sizing guidelines for standalone system to estimate the required storage for the grid connected RE applications.

Solar PV is unable provide electricity during night and cloudy days; similarly wind energy also unable to follow load demand. Moreover PV and/or wind application is not able to follow the load demand; when these RE generators are just in the stage to start generating energy and when these RE are in highest mode of generating stage while load demand falls to the lowest level. Therefore it can be said that RE is unable to generate energy by following the load demand which is a major limitation in energy management. Storage can play this critical role of proper energy management. Moreover storage helps in reducing the intermittent nature of RE and improve the Power Quality (PQ). This study considers regional Australia as the study area also considered residential load, solar radiation and

wind speed data of that location for detailed analysis. Figure 1 shows the daily load profile (summer: January 01, 2009 and winter: July 01 2009) of Capricornia region of Rockhampton, a regional city in Australia. Ergon Energy [1] is the utility operator in that area. However load demand of the residential load in that area depends on the work time patter which is different than the load profile of Figure 1. Overall electricity demand is very high in the evening and also in the morning for the residential load however PV generates electricity mostly during the day time therefore residents need to purchase costly electricity during peak demand in the evening. Similarly wind energy also unable to follow the residential load profile. Therefore properly estimated storage needs to be integrated to overcome this situation.
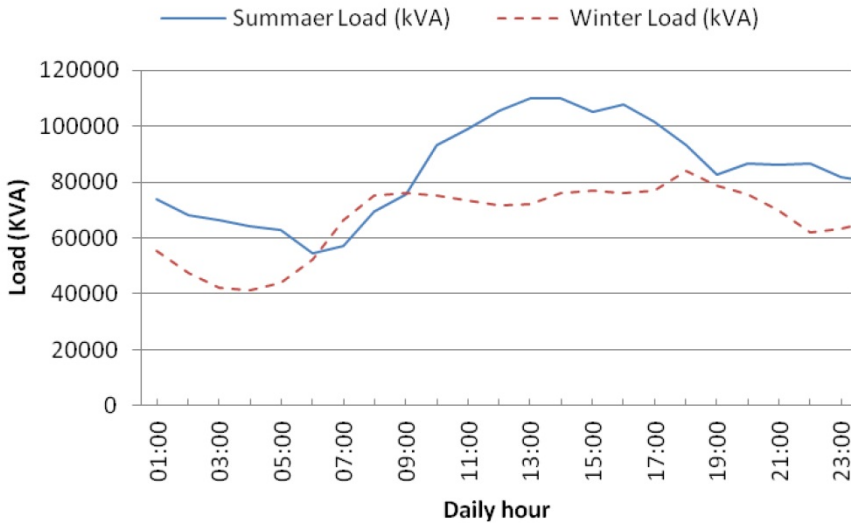

Figure 1. Daily load profile of Capricornia region in 2009 (Summer & Winter)

This chapter explores the need of storage systems to maximize the use of RE, furthermore estimates the required capacity of storage to meet the daily need which will gradually eliminate the dependency on conventional energy sources. Estimation of storage sizing is explained in section 3. This chapter also conducts the feasibility assessment of storage in terms of economic and environmental perspective which is explained in section 4.

2. Background

Solar and Wind are the two major sources of RE. Australia is one of best places for these sources. In regional areas of Australia, roof top Solar PV is installed in many residential houses either in off-grid or grid connected configurations and most residential wind turbine are for specific applications in off-grid configuration. In grid connected solar PV systems where storage is not integrated, the energy output from this system does not satisfy to the desired level. Currently installed most of the residential PV systems are designed in an

unplanned way that even with battery integrated system is not able to support the load in reliable way. Figure 2 illustrates a typical situation when whole system in jeopardize as the estimation of storage system was not done correctly.
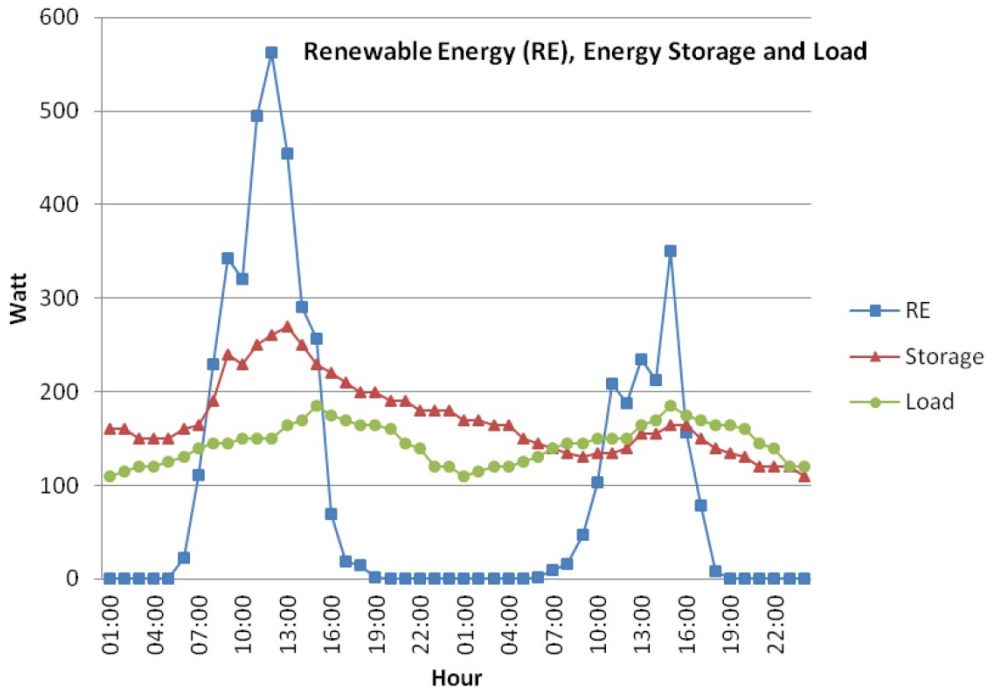

Figure 2. Typical condition of failure in storage integrated RE system

The adoption of storage with the PV system certainly incurs additional cost to the system but the benefits of adding storage has not been clearly assessed. Therefore this chapter aims to achieve two objectives. One is to estimate the required storage for the grid connected PV system or grid connected wind turbine or combination of grid connected PV and wind turbine system to achieve the maximum daily use of RE. Second objective is to identify the effects of storage on the designed system in terms of environment and economic by comparing the same system with and without storage. The feasibility of the designed system is expressed as, the Cost of Energy (COE) is closer to the present system while providing environmental benefits by reducing Greenhouse Gas (GHG) emission and improving the Renewable Fraction (RF).

Data was collected for the Capricornia region of Rockhampton city in Queensland, Australia. Load data was collected for a 3 bed room house by estimating all the electrical appliances demand and average usage period considering its ratings. Daily load profile drawn from hourly load data and total daily load was estimated by calculating the area under the daily load profile curve using trapezoidal method. Weather data was collected for the year 2009 from [2] for this location and calculated the energy output from PV array and

wind turbine. Figure 3 shows the solar radiation and wind speed of Rockhampton for the year 2009. Hourly energy output curve of PV and wind was drawn and compared with the load profile to estimate the required storage. For estimation, choice was taken considering the worst month weather data and it was observed that May to July is worst period when solar and wind have lower energy density as shown in Figure 3.
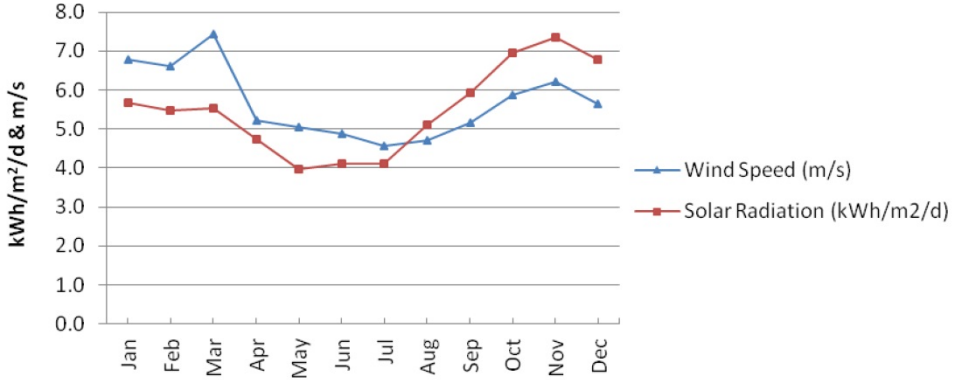
Figure 3. Solar radiation and wind speed in Rockhampton in 2009

Solar power

PV array considered as a device that produces DC electricity in direct proportion to the global solar radiation. Therefore, the power output of the PV array can be calculated by Equation 1[3-4].

$$P_{PV} = Y_{PV}f_{PV}\left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right)[1 + \alpha_P(T_C - T_{C,STC})] \tag{1}$$

If there is no effect of temperature on the PV array, the temperature coefficient of the power is zero, thus the above equation can be simplified as Equation 2 [3-4].

$$P_{PV} = Y_{PV}f_{PV}(\frac{\bar{G}_T}{\bar{G}_{T,STC}}) \tag{2}$$

where Y_{PV} - rated capacity of PV array, meaning power output under standard test conditions [kW]; f_{PV} - PV de-rating factor [%]; G_T - solar radiation incident on PV array in current time step [kW/m²]; $G_{T,STC}$ - incident radiation under standard test conditions [1 kW/m²]; α_P - temperature coefficient of power [%/ºC]; T_C - PV cell temperature in current time step [ºC]; $T_{C,STC}$ -PV cell temperature under standard test conditions [25ºC]. Performance of PV array depends on derating factors like temperature, dirt and mismatched modules.

Wind Power

Kinetic energy of wind can be converted into electrical energy by using wind turbine, rotor, gear box and generator. The available power of wind is the flux of kinetic energy, which the air is interacting with rotor per unit time at a cross sectional area of the rotor and that can be expressed [5] as per Equation 3:

$$P = \frac{1}{2}\rho A V^3 \tag{3}$$

where, P is Power output from wind turbine in Watts, ρ is the air density (1.225kg/m3 at 15°C and 1-atmosphere or in sea level), A is rotor swept area in m² and V is the wind speed in m/s.

The swept area of a horizontal axis wind turbine of rotor diameter (D) in meter (or blade length = D/2) can be calculated by Equation 4.

$$A = \pi(\frac{D}{2})^2 \text{ sq.m} \tag{4}$$

As power in the wind is proportional to the cube of the wind speed therefore increase in wind speed is very significant. One way to get more power is by increasing the tower height. Hourly wind speed at different height above ground level can be calculated by the vertical wind profile Equation 5 [6-7]:

$$V_2 = V_1(\frac{H_2}{H_1})^\propto \tag{5}$$

where v_1 and v_2 are the wind speeds at heights H_1 and H_2 and α is the wind shear component or power law exponent or friction coefficient. A typical value of α is 0.14 for countryside or flat plane area. Equation 5 commonly used in United States and the same is expressed in Europe by Equation 6 [7]:

$$V_2 = V_1(\frac{\ln(H_2/z)}{\ln(H_1/z)}) \tag{6}$$

where z is the roughness length in meters. A typical value of z for open area with a few windbreaks is 0.03m.

Temperature has effect on air density which changes the output of wind turbine. Average wind speed globally at 80m height is higher during day time (4.96m/s) than night time (4.85m/s) [8].

However German physicist Albert Betz concluded in 1919 that no wind turbine can convert more than 16/27 or 59.3% of the kinetic energy of the wind into mechanical energy by turning a rotor. This is the maximum theoretical efficiency of rotor and this is known as Betz Limit or Betz' Law. This is also called "power coefficient" and the maximum value is: C_P= 0.59. Therefore Equation-3 can be written as:

$$P = \frac{1}{2}C_p\rho A V^3 \tag{7}$$

The following subsections describe the residential load, solar & wind energy of Rockhampton area and also describe the importance of storage.

2.1. Estimation of daily residential load

Preferred method of determining load is bottom-up approach in which daily load is anticipated and summed to yield an average daily load. This can be done by multiplying the

power rating of all the appliances by the number of hours it is expected to operate on an average day to obtain Watt-hour (Wh) value as shown in Table 1. The load data collected from a 3 bed room house in Kawana, Rockhampton in Australia and total land area of the house is 700m² where 210m² is the building area with available roof space. For grid connected household appliances daily average load can also be obtained from monthly utility bills.

Appliances	Rating	Daily time of use	Qty	Daily use (Wh/day)
Refrigerator	602kWh/year (300W)	Whole day	1	1650
Freezer	88W	Whole day	1	880
Electrical Stove	2100W	Morning & Evening (1-2hrs)	1	2100
Microwave Oven	1000W	Morning & Evening (30 min to 1 hr)	1	500
Rice cooker	400W	Evening (30 minutes)	1	200
Toaster	800W	Morning (10 - 30 minutes)	1	80
Ceiling Fan	65W	Summer night (4 -5 hrs) & Holidays	5	1300
Fluorescent light	16W	Night (6 - 8 hours)	20	320
Washing machine (vertical axis)	500W	Weekends (1hr/week)	1	71
Vacuum Cleaner	1400W	Weekends (1hr/week)	1	200
Air conditioner (Window)	1200W	Summer night & Holidays (1hr)	3	1200
TV 32" LCD (Active/Standby)	150/3.5W	Morning & night (4 hrs)	1	670
DVD player (Active/Standby)	17/5.9W	Night (2 hrs)	1	50
Cordless phone	4W	Whole day	1	96
Computer (Laptop)	20W	Night (4 - 5hrs)	1	80
Clothe iron	1400W	Night & Holidays (15 - 30 minutes)	1	350
Heater (Portable)	1200W	Winter night & Holidays (30 minutes)	1	600
Hot Water System	1800W	Whole day(3- 4 hrs)	1	5400
Total:				**15,747**

Table 1. Daily load consumption of a house
Data source: Product catalogue and [7]

Load profile of a residential house varies according to the residents work time pattern. Working nature of the residents of Kawana suburb is such that most of the residents start for work between 7:00AM to 8:00AM and returns home between 5:00PM to 6:00PM during

weekday from Monday to Friday. A 24 hour load profile of a particular day as shown in Figure 4. It was found that maximum load demand was in the evening from 6:00PM to 10:00PM and in the morning 7:00AM to 9:00AM.
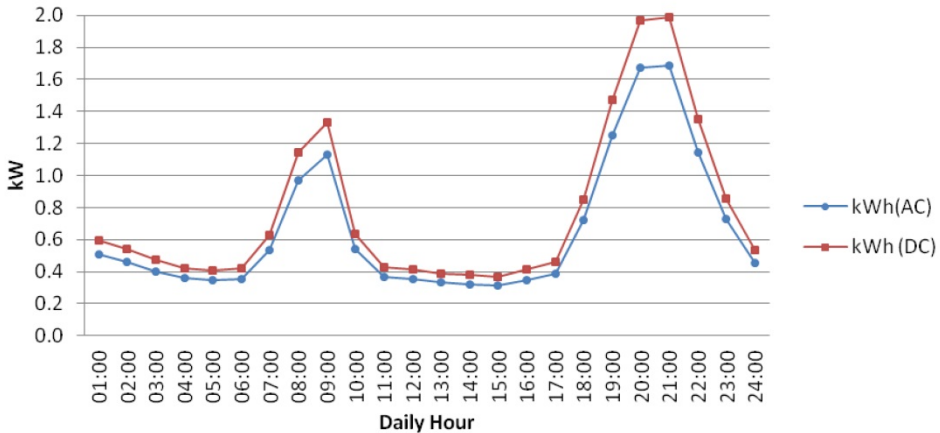
Figure 4. Daily load profile of a Residential house

Hourly load is a time series data and total daily load can be estimated by calculating the area under the load profile curve using Equation 8.

$$\text{Daily Load} = P_{Load} = \int_{t_1}^{t_{24}} f(x)dt \tag{8}$$

Where $f(x) = \frac{1}{2}(p_{t1} + p_{t2})T_{12}$

Where p_{t1} = Load (in kW) at time t_1 =1 in hour, p_{t2} = Load (in kW) at time t_2 = 2 in hour, T_{12} = time difference b/w t_1 and t_2 in hour.

Following Equation 8 total daily AC (Alternating current) load is the area under this load curve which is 15.7kWh and the equivalent DC (Direct current) load is shown considering efficiency of the converter as 85% which is 18.47kWh.
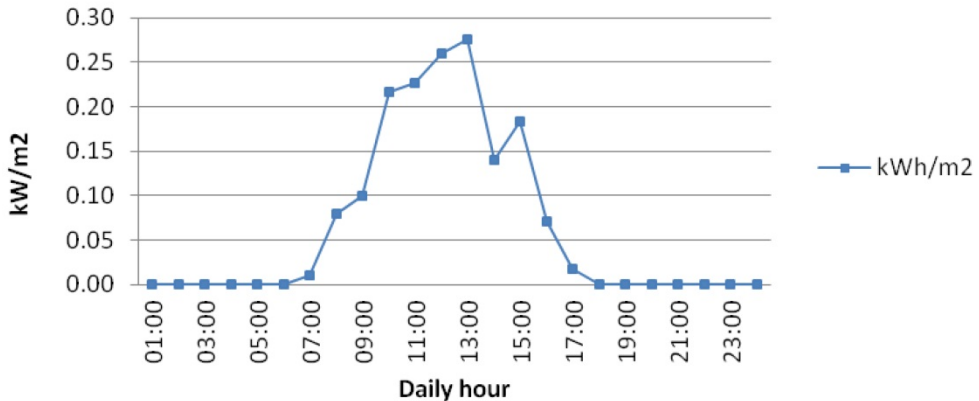
2.2. Estimation of daily available solar energy

Solar radiation varies with time and season. For estimation of available useful solar energy, worst month solar radiation was considered to ensure that the designed system can operate year-round. In Australia yearly average sunlight hours varies from 5 to 10 hours/day and maximum area is over 8 hours/day [2]. From the collected data it was found that in Rockhampton solar radiation over $5.0kWh/m^2/d$ varies from 08:00AM to 16:00PM i.e. sun hour is 8hrs/day.

The daily average solar radiation of Kawana suburb in the Capricornia region of Rockhampton city is as shown in the Figure 5. It was found that annual average solar radiation was 5.48kWh/m2/day. Lowest monthly average solar radiation was 4kWh/m2/day

on May and highest solar radiation was from October to December in 2009. PV system designed to supply entire load considering the worst month solar radiation, which will deliver sufficient energy during rest of the year.

For estimating daily solar energy, worst month (May) solar radiation was considered and Figure 5 shows hourly solar radiation for May 07, 2009. Daily total solar energy was estimated by calculating area under the solar radiation curve using Equation 8. Therefore total solar radiation in May 07, 2009 was 1.582975kWh/m^2/d. This energy generated by 1m^2 PV area. Total solar radiation will increase with the increased area of the PV array.

Figure 5. Daily solar radiation (May 07, 2009) in Rockhampton

## 2.3. Estimation of daily available wind energy

Wind speed varies with different natural factors, time and season. To estimate the available useful wind energy, worst month wind speed was considered to ensure that the designed system can operate year-round. From the collected data of Rockhampton it was found that July had the worst wind speed scenario as shown in Figure 3. It was found that in 2009, wind speed of Rockhampton was 6m/s or more for daily average duration of 10 hours. However for the month of July and August it was only 5 hours as shown in Table 2. Therefore wind speed data of July was considered for estimation of daily energy.

Three hourly wind speed data at 10.4m above sea level was collected from [2] for the year 2009, which was interpolated to get hourly data. At rotor height of 10m, 40m and 80m corresponding wind speed as shown in Figure 6. For energy estimation, July 03, 2009 wind speed data was considered and corresponding energy was calculated for 1m^2 of rotor wind area at 40m rotor height using Equation 7 as shown in Figure 7. Betz limit, gearbox, bearing and generator efficiency was considered and overall efficiency of the wind turbine was taken 25%. Total energy output from wind turbine on July 03, 2009 is the area under the curve of Figure 7 (11:00AM to 09:00PM) which is 0.232785kWh/m^2/d.

Month	Daily Time period	Time window (hrs)
Jan	06:00 - 20:00	14
Feb	03:00 - 17:00	14
Mar	00:00 - 15:00, 22:00 - 24:00	17
Apr	00:00 - 04:00, 20:00 - 24:00	8
May	16:00 - 24:00	8
Jun	12:00 - 19:00	7
Jul	10:00 - 15:00	5
Aug	07:00 - 12:00	5
Sep	01:00 - 10:00	9
Oct	00:00 - 06:00, 19:00 - 24:00	11
Nov	00:00 - 03:00, 15:00 - 24:00	12
Dec	13:00 - 24:00	11

Table 2. Wind speed period or window (6m/s or more)
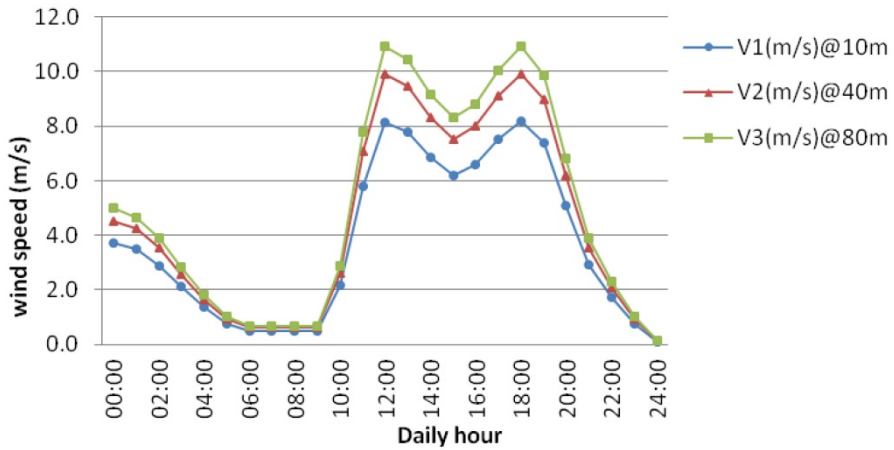
Figure 6. Wind speed at 10m, 40m and 80m height in Rockhampton
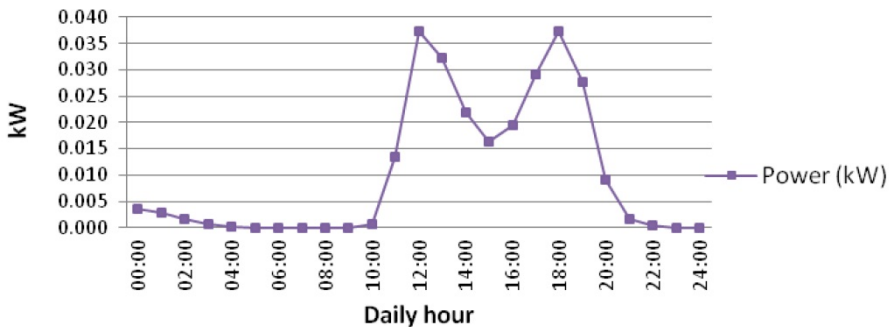
Figure 7. Energy converted per m² area at 40m height wind speed in Rockhampton

2.4. Importance of storage

The ability to store large amounts of energy would allow electrical utilities to have greater flexibility in their operation, because with this option the supply demand do not have to be matched instantaneously [9]. Table 3 shows the benefits and limitations of different storage systems.

Storage	Advantage			Limitations
	Efficiency (%)	*Life time (years)*	*Response time (S)*	
Pumped hydro	80	50	10	Location specific. Expensive to build.
Compressed air energy storage (CAES)	[a]f_{cef}=1.3 [b]f_{fhr}=4300kJ/kWh	25	360	Location specific. Expensive to build.
Flywheel	85	20	0.1	Low energy density. Large standby loss
Thermal energy storage(TES)	75	30	Tens of minutes	Storage tank is expensive
Batteries	80	10	0.01	Early stage technology. Expensive
Superconducting magnetic energy storage (SMES)	90	30	0.01	Low energy density. Expensive.
Capacitor	80	10	0.01	Low energy density. Expensive.
Hydrogen	50	25	360	Highly flammable

Table 3. advantage and limitations of few storage systems [12-14]
a. charge energy factor b. Fuel heat rate

The role of Energy Storage (ES) with Renewable Electricity generation is mentioned in[10] that the selection of ES system depends on application which is largely determined by the length of discharge. Based on the length of discharge, ES applications are often divided into three categories named power quality, bridging power and energy management applications. Although large scale storage is still expensive but research is going on for inexpensive and efficient batteries [11] suitable for large scale RE applications.

RE can be considered for different kinds of applications i.e. from small stand-alone remote systems to large scale grid-connected solar/wind power application. However development goes on to remote areas and brings the remote areas close to the grid network and eventually connected to the power grid and these RE generator are expected to operate as grid connected Distributed Generator (DG). Grid connected PV/wind with battery as storage can provide future-proof energy autonomy and allow home or office to generate clean energy and supply extra energy to the grid.

A recent study on high penetration of PV on present grid, mentioned that energy storage is the ultimate solution for allowing intermittent sources to address utility base load needs [15]. Storage integrated PV/Wind systems provides a combination of operational, financial and environmental benefits.

3. Estimation of storage sizing

Improper sized PV/Wind system is unable to meet the load requirements, sometimes electrical energy from RE wasted which neither can be used by the load nor can be stored in battery. This event occurs when the battery State of Charge (SOC) exceeds its maximum allowable value and the solar/wind power output exceeds load demand. The amount of wasted/lost energy can be avoided or reduced by proper choice of battery and PV/Wind generation sizes. G.B. Shrestha et.al. in [16] mentioned that PV panel size and the battery size have different impacts on the indices of performance and proper balance between the two is necessary. A proper match between the installed capacities with the load demand is essential to optimize such installation.

Brahmi Nabiha et. al. in [17] presents sizing of mini autonomous hybrid grid, including PV, wind, generator and battery. The performance of any battery, expressed essentially by the voltage, load capacity and SOC or the Depth of Discharge (DOD). The usable energy in a battery can be expressed by Equation 9.

$$E_{usable} = C \text{ x } V_{bat} \text{ x } DOD_{max} \tag{9}$$

where C is battery capacity and V_{bat} is the battery cell voltage.

IEEE Std-1013-2007 [18] provides the recommendations for sizing of lead-acid batteries for stand-alone PV systems. This recommended practice provides a systematic approach for determining the appropriate energy capacity of a lead-acid battery to satisfy the energy requirements of the load for residential, commercial and industrial stand-alone PV systems. IEEE Std-1561-2007 [19]provides guideline for optimizing the performance and life of Lead-Acid batteries in remote hybrid power systems; which includes PV, wind, batteries. It also explains the battery sizing considerations for the application. IEEE Std 1547-2003 [20] provides guideline to connect Distributed Resources (DR), such as PV, wind and storage with the power grid at the distribution level. Grid connected system sizing for storage integrated PV system also explained in [7].

Considering the above sizing practices and guidelines Figure 8 shows the steps for estimation of required storage for steady state residential load. For the easy of this analysis both PV and Wind turbine are considered to produce DC power which than converted to AC by inverter, also considered battery as storage device.

The following steps are summarized for estimation.

Step 1.   Determine the daily load of a residential house
Step 2.   Determine the required PV or Wind turbine rating for the load
Step 3.   Determine daily energy output from the PV array or Wind turbine

Step 4. Estimate PV array size and wind turbine rotor diameter

Step 5. Compare the daily energy output (from PV or wind turbine) with the daily load, find the required load that storage needs to support

Step 6. For the load on storage estimate the required Battery/Storage size in Ah.

The following sub-sections describe the estimation of required storage for grid connected PV, Wind and hybrid systems considering the residential load of Rockhampton as estimated in section 2.1.
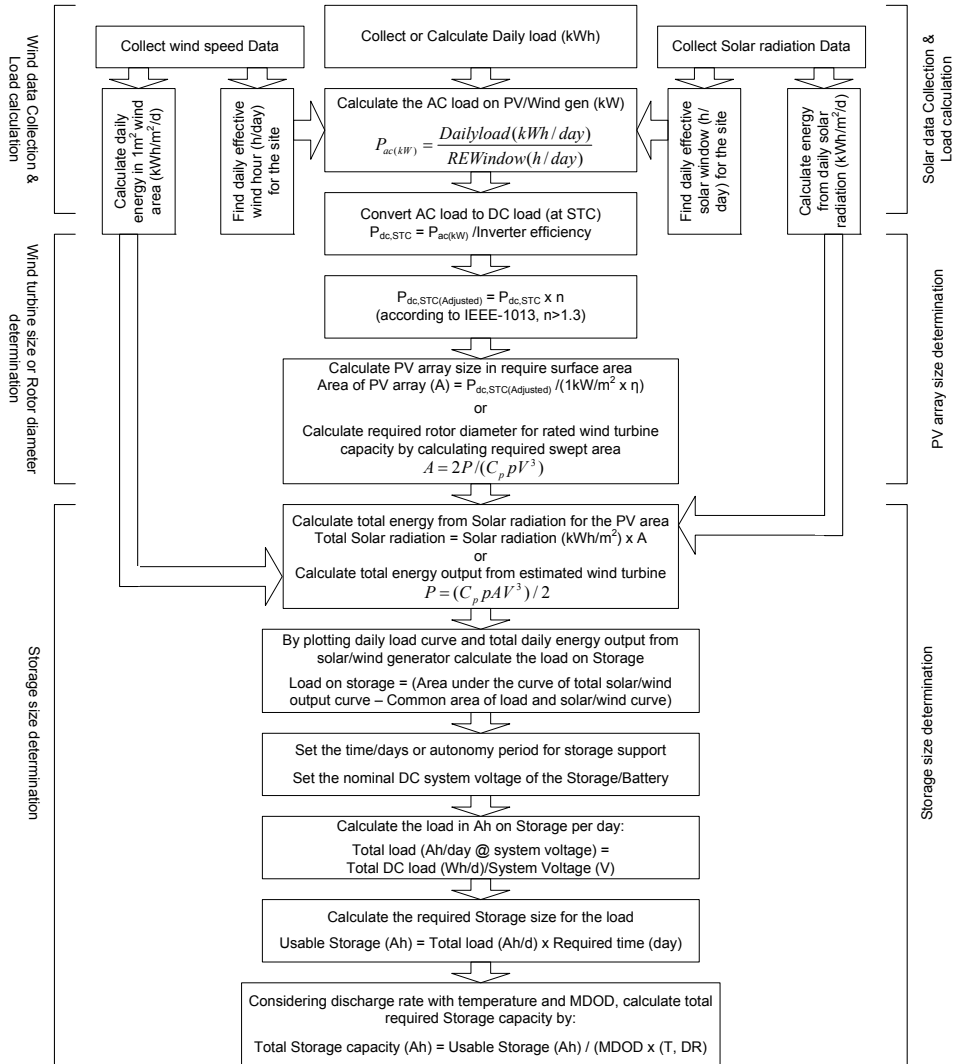
Figure 8. Storage size estimation steps

3.1. Estimation of storage for grid connected residential solar PV

The size of the PV array is determined by the daily average load divided by the available solar window or sun-hours per day. Generally, grid connected PV systems are designed to provide from 10% to 60% of energy needs with the difference being supplied from power utility[21]. However PV contribution can be increased to 100% of average steady state load. Following the steps in Figure 8, the estimation starts by calculating required PV size.

Daily extractable solar energy as calculated in section 2.2 was considered for the estimation of required PV size for the residential load. Daily load of a three bed room house as calculated in section 2.1 is 15.7kWh. Therefore the PV array should support at least 15.7kWh of load everyday at the solar energy rate of 1.582975kWh/m²/day. Solar window is 8 hours or more in Rockhampton [2], therefore the required PV array capacity for the AC load as:

$$P_{ac}(kW) = \frac{Energy\ (kWh/day)}{Solar\ window\ (h/day)} = \frac{15.7}{8} = 1.9625kW$$

Equivalent DC load on PV array can be found by considering the efficiency as:

η = inverter efficiency * dirty collector * mismatched modules = 85%

$$P_{dc,STC} = \frac{P_{ac}(kW)}{\eta} = \frac{1.9625}{0.85} = 2.31kW$$

To use battery as storage system, size of the PV array needs to be more than 1.3 times the load [18] in stand-alone configuration. But for the grid connected configuration 1.0 or 1.1 is good enough to avoid over design. For this designed residential load, it was considered 1.1. So the adjusted PV array size for the equivalent DC load becomes:

$$P_{dc,STC(Adjusted)} = 1.1xP_{dc,STC} = 1.1x2.31 = 2.541kW$$

Therefore, for this three bed room house 2.541kW capacity of PV array with proper sized storage required to support its load for 24 hours a day.

For known PV efficiency and for 1kW/m² rated PV module required surface area of the PV array can be calculated. The efficiency of crystal silicon PV module is 12.5% [7], however LG Polycrystalline PV module efficiency is 13.7% [22], therefore surface area becomes:

$$P_{dc,STC} = (1kW/m^2)insolation * A * \eta$$

$$A = \frac{P_{dc,STC}}{(1kW/m^2)\eta} = \frac{2.541}{1x0.125} = 20.328m^2$$

Therefore 20.328m² PV module with PV array efficiency of 12.5% will support the load with sufficient storage size. This PV area is much smaller than the area of the designed house roof area.

This PV size was considered to calculate the total energy from PV array and to estimate the required storage for the load. Batteries last longer if they are shallow cycled. The capacity of

the battery bank can be calculated by multiplying the daily load on battery by the autonomy day or the number of days it should provide power continuously. The ampere-hour (Ah) rating of the battery bank can be found after dividing the battery bank capacity by the battery bank voltage (e.g. 24V or 48V). It is generally not recommended to design for more than 12 days of autonomy for off-grid system and for grid connected system one day autonomy is good to design.

Total solar energy generated by the 20.328m² PV array at the solar radiation rate of Rockhampton is plotted in Figure 9 and calculated as 32.17872kWh which is the area under the PV output curve. Now superimpose the DC load curve on the PV output curve to find the load that needs to be supported by the storage as shown in Figure 9. The common area under the curve is 6.196kWh which is the area of the load that served by the PV array during day time while charging the batteries as well. The remaining load is (18.47 - 6.196) =12.274kWh/day that needs to be served by the storage. This is the daily minimum load on storage. However the design was based on to support total load, therefore the remaining energy from the PV array should be managed by the storage system which is (32.17872 - 6.196) = 25.98272kWh/day. This is the maximum load on storage, if total energy generated by PV array needs to be managed by the storage.
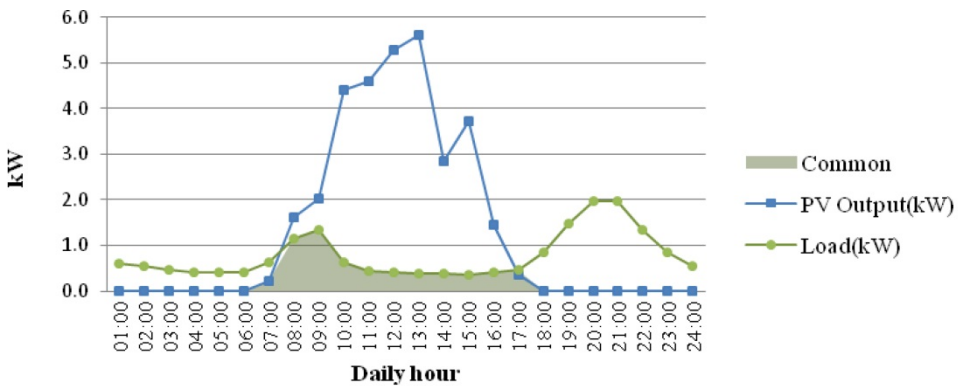

Figure 9. PV output and daily load curve shows the load on storage

Inverters are specified by their DC input voltage as well as by their AC output voltage, continuous power handling capability and the amount of surge power they can supply for brief periods of time. Inverter's DC input voltage which is the same as the voltage of the Battery bank and the PV array is called the system voltage. The system voltage usually considered as 12V, 24V or 48V. The system voltage for this designed DC system was considered 24V and this system was designed for one day. Considering inverter efficiency of 95% [23], the required battery capacity can be calculated.

$$\text{Daily minimum load in Ah @ system voltage =}$$

$$= \frac{\text{Load (Wh/day)}}{\text{System Voltage}} = \frac{12.274 \times 10^3}{24} = 511.416 \text{Ah/d}$$

$$\text{Daily maximum load in Ah @ system voltage} =$$

$$= \frac{\text{Load (Wh/day)}}{\text{System Voltage}} = \frac{25.98272 \text{x} 10^3}{24} = 1082.613 \text{Ah/d}$$

Energy storage in a battery typically given in Ah, at system voltage and at some specified discharge rate. Table 4 shows characteristics of several types of batteries.

Battery type	MDOD	Energy Density (Wh/kg)	Cycle Life (Cycles)	Calendar Life (Year)	Efficiencies	
					Ah%	Wh%
Lead-acid, SLI	20%	50	500	1-2	90	75
Lead-acid, golf cart	80%	45	1000	3-5	90	75
Lead-acid, deep-cycle	80%	35	2000	7-10	90	75
Nickel-cadmium	100%	20	1000-2000	10-15	70	60
Nickel-metal hydride	100%	50	1000-2000	8-10	70	65

Table 4. Comparison of Battery Characteristics[7]

The Ah capacity of a battery is not only rate-dependent but also depends on temperature. The capacity under varying temperature and discharge rates to a reference condition of C/20 at 25ºC is explained in [7]. Lead-acid battery capacity decreases dramatically in colder temperature conditions. However heat is also not good for batteries. In Rockhampton average temperature is above 20ºC. The Maximum depth of discharge (MDOD) for Lead-acid batteries is 80%, therefore for one day discharge the batteries need to store:

$$\text{Battery storage (minimum)} = \frac{\text{Load (Ah/day) x No of days}}{\text{MDOD}} = \frac{511.416 \text{x} 1}{0.80} = 639.27 \text{Ah}$$

$$\text{Battery storage (maximum)} = \frac{\text{Load (Ah/day) x No of days}}{\text{MDOD}} = \frac{1082.613 \text{x} 1}{0.80} = 1353.26 \text{Ah}$$

The rated capacity of battery is specified at standard temperature. At 25ºC, the discharge rate of C/20 type battery (i.e. discharge for 20 hours), becomes 96% [7], therefore finally required battery capacity becomes:

$$\text{Required minimum Battery storage}(25^\circ\text{C,20hour-rate}) =$$

$$= \frac{\text{Battery storage}}{\text{Rated capacity}} = \frac{639.27}{0.96} = 665.90 \, Ah$$

$$\text{Required maximum Battery storage}(25^\circ\text{C,20hour-rate}) =$$

$$= \frac{\text{Battery storage}}{\text{Rated capacity}} = \frac{1353.26}{0.96} = 1409.64 \, Ah$$

3.2. Estimation of storage for grid connected residential wind power

Following the similar steps in section 3.1, required wind turbine capacity was calculated and then required storage was estimated for the same load of 15.7kWh/day.

Energy generated by wind turbine at 40m height for 1m² rotor wind area was calculated in section 2.3, which is 0.232785kWh/m²/d. The output of the wind turbine needs to be improved such that at least 15.7kWh of load should be supported each day. It was found that in July, wind speed was 6m/s or above only for 5hrs/day at 10m height, however at 40m height wind speed was 6m/s or above for 10hrs/day, therefore the rotor height was considered 40m. The required wind turbine size for the load can be calculated as:

$$P_{ac}(kW) = \frac{Load\ (kWh/day)}{Windwindow\ (h/day)} = \frac{15.7}{10} = 1.57kW$$

This estimation is for required storage which is a DC component; it requires inverter to support the load. DC capacity of the wind turbine can be calculated considering inverter efficiency of 90%.

$$P_{dc,STC} = \frac{P_{ac}(kW)}{\eta} = \frac{1.57}{0.90} = 1.744kW$$

Likewise PV assumption, wind turbine capacity is considered 1.1 times the required load in grid connected configuration, to charge batteries while supporting load.

$$P_{dc,STC(Adjusted)} = 1.1xP_{dc,STC} = 1.1x1.744 = 1.92kW$$

Energy generated by wind turbine on July 03, 2009 was 0.232785kWh/m²/d. To support total load, rotor swept area needs to be adjusted. Equation 7 shows that power output is not linear for increase in rotor diameter. It was found that at 40m rotor height, wind speed varied b/w 6.17m/s to 9.92m/s, therefore average wind speed of 8m/s was considered to calculate the rotor diameter for the rated wind turbine capacity of 1.92kW. The rotor diameter was calculated as 5.58m and calculated total energy is 26.355kWh which is the area under the wind turbine output curve as shown in Figure 10.

Daily load curve was plotted on the daily energy output curve and calculated the common area to estimate the required load on storage to support for the day. It was found that 7.736kWh of load was supported by the wind turbine while charging the storage. The remaining (18.47 - 7.736) = 10.734kWh of load needs to be supported by the storage each day. This is the minimum load on storage. However the design was considering to manage 100% load therefore remaining (26.355 - 7.736) = 18.619kWh of energy must be managed by the storage. This is the maximum load on storage.

Considering the DC system voltage as 24V, load on battery in Ah can be calculated for one day as:
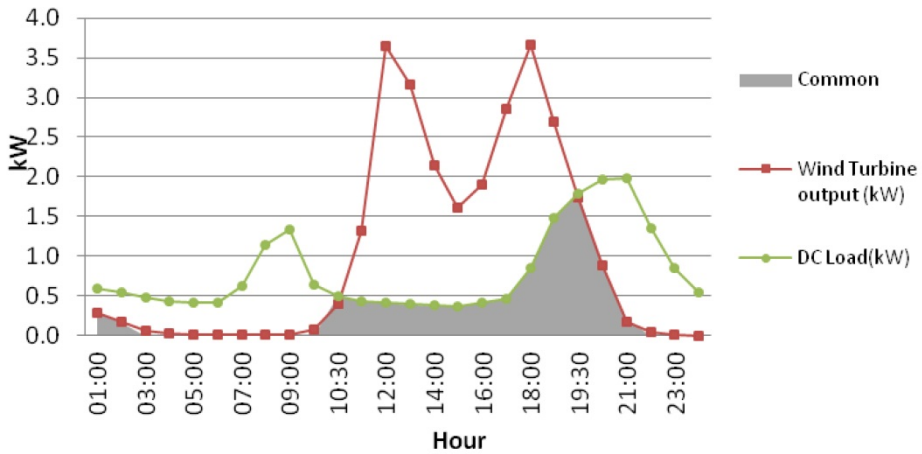
Figure 10. Wind turbine output and daily load curve shows the load on storage

Daily minimum load in Ah @ system voltage =

$$= \frac{\text{Load (Wh/day)}}{\text{System Voltage}} = \frac{10.734 \times 10^3}{24} = 447.25 \text{Ah/d}$$

Daily maximum load in Ah @ system voltage =

$$= \frac{\text{Load (Wh/day)}}{\text{System Voltage}} = \frac{18.619 \times 10^3}{24} = 775.79 \text{Ah/d}$$

Energy storage in a battery typically given in Ah, at system voltage and at some specified discharge rate. Consider MDOD for Lead-Acid batteries is 80%, therefore for one day discharge the battery needs to store the energy as:

Battery storage (minimum) =

$$= \frac{\text{Load (Ah/day) x No of days}}{\text{MDOD}} = \frac{447.25 \times 1}{0.80} = 559.0625 \text{Ah}$$

Battery storage (maximum) =

$$= \frac{\text{Load (Ah/day) x No of days}}{\text{MDOD}} = \frac{775.79 \times 1}{0.80} = 969.7375 \text{Ah}$$

The rated capacity of battery is specified at standard temperature. At 25ºC, the discharge rate of C/20 (i.e. discharge for 20 hours), becomes 96% [7], therefore finally required battery capacity becomes:

Required minimum Battery storage(25°C,20hour-rate)=

$$= \frac{\text{Battery storage}}{\text{Rated capacity}} = \frac{559.0625}{0.96} = 582.356 \, Ah$$

Required maximum Battery storage(25°C,20hour-rate)=

$$= \frac{\text{Battery storage}}{\text{Rated capacity}} = \frac{969.7375}{0.96} = 1010.143\,Ah$$

3.3. Estimation of storage for grid connected residential hybrid system

Many studies indicated that hybrid system is always better than any single RE system. However the practical implementation depends on the availability of adequate solar radiation, wind speed and their seasonal variation. Other critical point is adequate space for hybrid system installation and moreover the overall cost of the installation. The study location of this analysis is suitable for both solar and wind energy. It was found that for little variation of wind speed, convertible energy variation is much higher therefore wind energy fluctuation is higher than solar energy. Considering all the scenarios and for the easy of analysis it was considered that 50% of load to be supported by solar and 50% by wind energy.

Following the steps in Figure 8 and earlier sections, required storage is estimated.

For Solar PV: 50% AC Load is (15.7/2) = 7.85kWh/d

Required PV array capacity becomes:

$$P_{ac}(kW) = \frac{\text{Energy (kWh/day)}}{\text{Solar window (h/day)}} = \frac{7.85}{8} = 0.98125kW$$

Equivalent DC load can be found by considering the efficiency of the PV system as:

η = inverter efficiency * dirty collector * mismatched modules = 85%

$$P_{dc,STC} = \frac{P_{ac}(kW)}{\eta} = \frac{0.98125}{0.85} = 1.1544kW$$

For this designed house load, PV capacity considered 1.1 times the load. So the adjusted PV array size for the equivalent DC load becomes:

$$P_{dc,STC(Adjusted)} = 1.1xP_{dc,STC} = 1.1x1.1544 = 1.27kW$$

Therefore it requires 1.27kW capacity of PV array with proper sized storage to support 50% load for 24 hours a day.

Considering the crystal silicon PV module whose efficiency is 12.5% [7], therefore the surface area of PV module becomes:

$$P_{dc,STC} = (1kW/m^2)\text{insolation} * A * \eta$$

$$A = \frac{P_{dc,STC}}{(1kW/m^2)\eta} = \frac{1.27}{1x0.125} = 10.16m^2$$

Therefore 10.16m² of PV area required for this hybrid system. The output energy from this PV module is plotted in Figure 11. For the remaining load the required wind turbine is estimated as:

For Wind turbine: 50% AC Load is (15.7/2) = 7.85kWh/d

Required wind turbine capacity becomes:

$$P_{ac}(kW) = \frac{Load\ (kWh/day)}{Windwindow\ (h/day)} = \frac{7.85}{10} = 0.785kW$$

The inverter considered with this wind turbine of efficiency 90%, therefore the DC capacity becomes:

$$P_{dc,STC} = \frac{P_{ac}(kW)}{\eta} = \frac{0.785}{0.90} = 0.872kW$$

For this designed house load, wind turbine capacity considered 1.1 times the load. So the adjusted wind turbine size for the equivalent DC load becomes:

$$P_{dc,STC(Adjusted)} = 1.1xP_{dc,STC} = 1.1x0.872 = 0.9592kW$$

Average wind speed of 8m/s was considered to calculate the rotor diameter for the required capacity of wind turbine. For the 0.9592kW capacity wind turbine, the rotor diameter becomes 3.95m and daily energy generated by this wind turbine was plotted in Figure 11.

Total energy generated from this hybrid system is 28.12kWh and compared with the DC load it was calculated that the Hybrid system support directly 8.45kWh of load as shown the common area in Figure 11. Therefore the minimum (18.47 - 8.45) = 10.02kWh of load needs
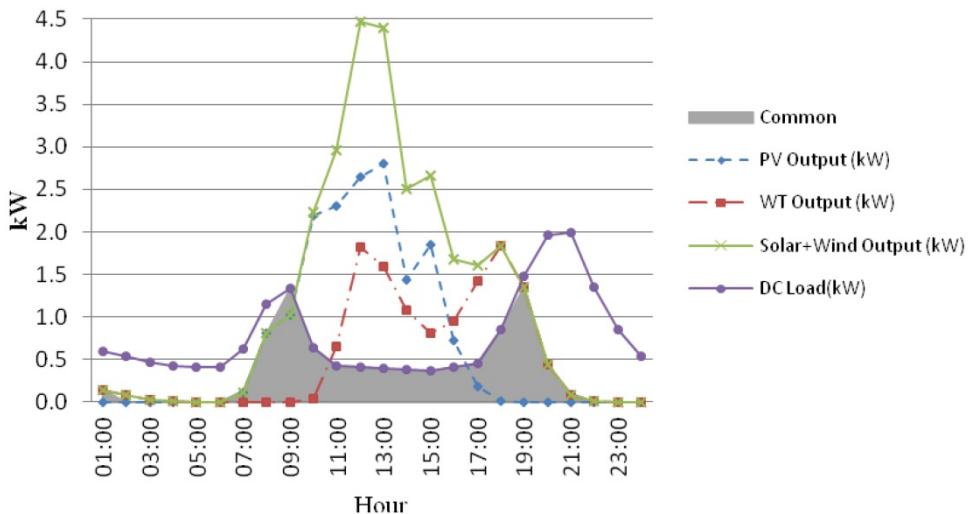
Figure 11. Hybrid system output and daily load curve shows the load on storage

to be supported by the storage system. However the hybrid system was designed to support 100% load therefore remaining generated energy (28.12 - 8.45) = 19.67kWh from hybrid system must be managed by the storage. This is the maximum load on storage.

Considering the DC system voltage as 24V, load on battery in Ah can be calculated for one day as:

$$\text{Daily minimum load in Ah @ system voltage =}$$

$$= \frac{\text{Load (Wh/day)}}{\text{System Voltage}} = \frac{10.02 \times 10^3}{24} = 417.50 \text{Ah/d}$$

$$\text{Daily maximum load in Ah @ system voltage =}$$

$$= \frac{\text{Load (Wh/day)}}{\text{System Voltage}} = \frac{19.67 \times 10^3}{24} = 819.58 \text{Ah/d}$$

Considered MDOD of Lead-Acid batteries is 80%, therefore for one day discharge the battery needs to store the energy as:

$$\text{Battery storage (minimum) =}$$

$$= \frac{\text{Load (Ah/day) x No of days}}{\text{MDOD}} = \frac{417.50 \times 1}{0.80} = 521.875 \text{Ah}$$

$$\text{Battery storage (maximum) =}$$

$$= \frac{\text{Load (Ah/day) x No of days}}{\text{MDOD}} = \frac{819.875 \times 1}{0.80} = 1024.843 \text{Ah}$$

Temperature effects are considered in the storage requirements for the hybrid systems. At 25°C for C/20 (i.e. 20 hours discharge) the discharge rate is 96%, therefore finally required battery capacity becomes:

$$\text{Required minimum Battery storage}(25^\circ\text{C,20hour-rate)=}$$

$$= \frac{\text{Battery storage}}{\text{Rated capacity}} = \frac{521.875}{0.96} = 543.62 \, Ah$$

$$\text{Required maximum Battery storage}(25^\circ\text{C,20hour-rate)=}$$

$$= \frac{\text{Battery storage}}{\text{Rated capacity}} = \frac{1024.843}{0.96} = 1067.544 \, Ah$$

Therefore in grid connected configuration to support 15.7kWh/day load the required minimum and maximum storage with solar PV, Wind turbine and hybrid system are shown in Table 5. Minimum storage indicates the required storage that needs to support the daily load. However PV, wind turbine or hybrid system generates more energy than the daily required therefore maximum storage is required to manage total generated energy by supporting load or supplying to the grid in suitable time. This design considered PV array

efficiency 12.5% with solar window 8 hours and overall wind turbine efficiency 25% with wind window 10 hours.

Designed system	Required system capacity	Required Storage (at 24V DC system voltage)	
		Minimum (Ah)	Maximum (Ah)
Solar PV system	2.541kW PV with 20.328m² PV array	665.90Ah	1409.64Ah
Wind turbine system	1.92kW wind turbine with 5.58m rotor diameter	582.356Ah	1010.143Ah
Hybrid system	1.27kW PV with 10.16m² PV array and 0.9592kW wind turbine with 3.95m rotor diameter	543.62Ah	1067.544Ah

Table 5. Required storage in different configurations

4. Feasibility analysis of storage

Previous section described the required storage for the residential load in different configurations and this section describes feasibility of the storage in those configurations.

G.J. Dalton et al. in [24] compared HOMER and Hybrids as RE optimization tool and found that HOMER is better in representing hourly fluctuations in supply and demand. This chapter explains the feasibility of storage by analyzing the model output. A model was developed in HOMER version 2.68 [25] as shown in Figure 12. PV array, wind turbine, storage, inverter, grid and diesel generator were used in different size and combinations. The model identified the optimized configuration of storage, PV, wind turbine with grid or diesel generator for the residential load and investigated environmental and economical benefits due to the storage systems. The model was evaluated considering the project life time of 25 years. The performance matrices considered are NPC, COE as economical factor, Renewable Fraction (RF) and greenhouse gas (GHG) emission as environmental factor. The model compared in off-grid and grid connected configurations.
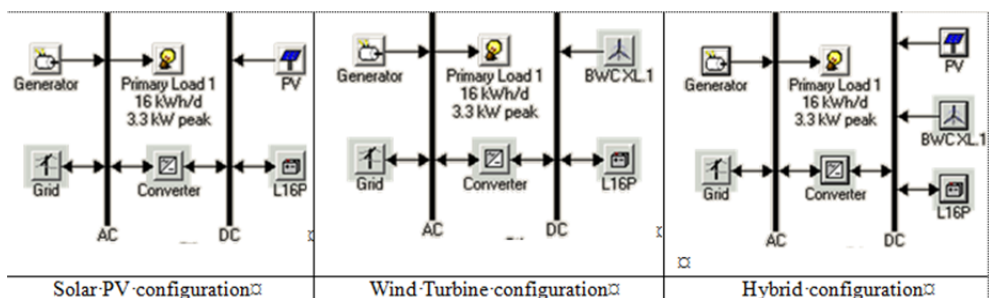
Figure 12. Model simulation in different configurations

Net Present Cost (NPC): The total net present cost of a system is the present value of all costs that it incurs over its lifetime minus the present value of all the revenue that it earns over its lifetime. NPC is the main economic output and ranked all systems accordingly. NPC can be represented [24-25] by Equation 10:

$$NPC(\$) = \frac{TAC}{CRF} \tag{10}$$

where *TAC* is the total annualized cost (which is the sum of the annualized costs of each system component). The capital recovery factor (CRF) is given by Equation 11:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{11}$$

where *N* denotes number of years and *i* means annual real interest rate (%). Model considered annual interest rate rather than the nominal interest rate. The overall annual interest rate considered as 6%.

Cost of Energy (COE): It is the average cost per kWh of useful electrical energy produced by the system. COE can be calculated by dividing the annualized cost of electricity production by the total useful electric energy production and represented [25] in Equation 12:

$$COE = \frac{C_{ann,tot} - C_{boiler} E_{thermal}}{E_{prim,AC} + E_{prim,DC} + E_{def} + E_{grid,sales}} \tag{12}$$

where $C_{ann,tot}$ is total annualized cost of the system (\$/yr), C_{boiler} is boiler marginal cost (\$/kWh), $E_{thermal}$ is total thermal load served (kWh/yr), $E_{prim,AC}$ is AC primary load served (kWh/yr), $E_{prim,DC}$ is DC primary load served (kWh/yr), E_{def} is deferrable load served (kWh/yr) and $E_{grid,sales}$ is total grid sales (kWh/yr).

Emission: Emission is widely accepted and understood environmental index. Greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF6) are the main concern for global warming. In addition SO_2 is another pollutant gas released by coal fired energy system. Emission is measured as yearly emission of the emitted gases in kg/year and emissions per capita in kg/kWh. Model used it as input when calculating the other O&M cost. It was represented in [25] as shown in Equation 13:

$$C_{om,other} = C_{om,fixed} + C_{cs} + C_{emission} \tag{13}$$

where $C_{om,fixed}$ is system fixed O&M cost (\$/yr), C_{cs} is the penalty for capacity shortage (\$/yr) and $C_{emission}$ is the penalty for emission (\$/yr).

Renewable Fraction (RF): It is the total annual renewable power production divided by the total energy production. RF can be calculated [26] using Equation 14:

$$f_{pv} = \frac{E_{PV}}{E_{TOT}} \tag{14}$$

where E_{PV} and E_{TOT} are the energy generated by RE and total energy generated respectively. The overall RF (f_{ren}) can also be expressed [25] in Equation 15:

$$f_{ren} = \frac{E_{ren} + H_{ren}}{E_{tot} + H_{tot}} \qquad (15)$$

where E_{ren} is renewable electric production, H_{ren} is renewable thermal production, E_{tot} is total electrical production and H_{tot} is total thermal production.

Battery dispatch: Ideally battery charging should be taken into account for future load supply. Battery dispatch strategies explained by Barley and Winn [27], named 'load following' and 'cycle charging'. Under load following strategy, a generator produces only enough power to serve the load, which does not charge the battery. Under cycle charging strategy, whenever a generator operates it runs at its maximum rated capacity, charging battery bank with any excess electricity until the battery reaches specified state of charge. Load following strategy was considered for this analysis for the better utilization of RE.

4.1. Data collection

For the simulation of the optimization model, residential load data were considered as Rockhampton resident's average load consumption. Solar radiation and wind speed data were collected from [28]. All required system components are discussed in the following sub-sections.

4.1.1. Electric load

Daily average steady state load of a 3 bed room house was estimated in section 2.1 which is 15.7kWh/d. Daily load profile of the distribution network of Capricornia region was collected from [1] and according to the electricity bill information [29] the daily average electricity consumption per house is 15.7kWh/day. Model takes a set of 24 hourly values load data or monthly average or hourly load data set of 8,760 values to represent average electric load, therefore yearly residential load (AC) becomes 5730kWh/yr. The load profile is shown in Figure 4.

4.1.2. Solar radiation data

Solar radiation data is the input to the model and hourly solar radiation data of Rockhampton was collected from [28]. Daily average extractable energy from this solar radiation is explained in section 2.2.

4.1.3. Wind speed data

Three hourly wind speed data was collected from [28] which was interpolated to generate hourly data and used as input data in the model. The extractable energy from the wind speed is explained in section 2.3.

4.1.4. Storage

For this analysis Trojan L16P Battery (6V, 360Ah) at system voltage of 24V DC is used in the model. The efficiency of this battery is 85%, min State of Charge (SoC) 30%.

4.2. System components cost

Table 6 lists the required system components with related costs in Australian currency. PV array, Wind turbine, Battery charger, Inverter, deep cycle battery, diesel generator and grid electricity costs are included for the analysis. PV array including inverter price is available, and found that 1.52kW PV array with inverter costs $3599 [30], also it is found that 1.56kW PV with inverter costs is $4991[31]. However model considered battery charger is included with PV array therefore the PV array cost is listed accordingly in Table 6 and inverter costs considered separately.

Description	Value/Information
PV array	
Capital cost	$3100.00/kW
Replacement cost	$3000.00/kW
Life Time	25 years
Operation & maintenance cost	$50.00/year
Wind Turbine (BWC XL.1 1 kW DC)	
Capacity	1kW DC
Hub Height	40m
Capital cost	$4000.00
Replacement cost	$3000.00
Life time	25 years
Operation & maintenance cost	$120/yr
Grid electricity	
Electricity price (Off peak time)	$0.30/kWh
Electricity price (Peak time)	$.42/kWh
Electricity price (Super Peak time)	$0.75/kWh
Emission factor	
CO_2	632.0 g/kWh
CO	0.7 g/kWh
Unburned hydrocarbons	0.08 g/kWh
Particulate matter	0.052 g/kWh
SO_2	2.74 g/kWh
NOx	1.34 g/kWh
Inverter	
Capital cost	$400.00/kW
Replacement cost	$325.00/kW
Life time	15 years
Operation & maintenance cost	$25.00/year
Storage (Battery)	
Capital cost	$170.00/6V 360Ah
Replacement cost	$130.00/6V 360Ah
System Voltage	24 volts

Description	Value/Information
Generator	
Capital cost	$2200.00/kW
Replacement cost	$2000.00/kW
Operation & maintenance cost	$0.05/hr
Life time	15000hrs
Fuel cost	$1.53/ltr

Table 6. Technical Data and Study assumptions

SMA Sunny Boy Grid Tie Inverter (7000Watt SB7000US) price is $2823 [32], however Sunny Boy 1700W inverter price is $699 [33]. 1kW BWC XL.1 wind turbine with 24V DC charge controller price is $3560 [34] and 10kW Bergey BWC Excel with battery charging or grid tied option wind turbine cost is $29,250 [35]. Grid electricity cost in Rockhampton is found from Ergon Energy's electricity bill [36] and for Tariff-11, it is $0.285/kWh (including GST & service). However Government's decision to impose carbon tax at the rate of $23/ton of GHG emission which will increase this electricity bill as well as the cost of conventional energy sources, therefore off-peak electricity cost is considered as $0.30/kWh for analysis. Trojan T-105 6V, 225AH (20HR) Flooded Lead Acid Battery price is $124.79 [37]. Fuel cost for generator is considered at the current price available in Rockhampton, Australia.

The significance of storage was analyzed from the optimized model to evaluate environmental and economical advantages of storage in off-grid and grid-connected configurations in fourteen different cases. All these cases were analyzed considering same load 15.7kWh/d or 5730kWh/yr.

Category-1: Off-grid Configuration

Case-1: Diesel Generator only
Case-2: PV with Diesel Generator
Case-3: PV with Storage and Diesel Generator
Case-4: Wind turbine with Diesel Generator
Case-5: Wind turbine with Storage and Diesel Generator
Case-6: Hybrid (PV & Wind turbine) with Diesel Generator
Case-7: Hybrid (PV & Wind turbine) with Storage and Diesel Generator

Category-2: Grid-connected Configuration

Case-1: Grid only
Case-2: PV with Grid and Diesel generator
Case-3: PV with Storage, Grid and Diesel generator
Case-4: Wind turbine with Grid and Diesel generator
Case-5: Wind turbine with Storage, Grid and Diesel generator
Case-6: Hybrid (PV & Wind turbine) with Grid and Diesel generator
Case-7: Hybrid (PV & Wind turbine) with Storage, Grid and Diesel generator

5. Results and discussion

Simulation was conducted to get optimized configuration of RE resources. Simulation results and findings are discussed below.

5.1. Category - 1(Off grid configuration)

Case 1. Diesel Generator only

In this configuration 10kW Diesel generator was used to support total load of 5730kWh/yr which consumed enough fuel (8440L/yr) and emitted significant amount of GHG & pollutant gas to the air. Generator required frequent maintenance and fuel cost was also high therefore NPC was high and COE was $5.342/kWh. This configuration was the costliest and environmentally most vulnerable.

Case 2. PV with Diesel Generator configuration

In this off-grid configuration, model used 12kW PV with 5kW Inverter and 10kW Diesel generator as required resources. Results showed that, although PV generates electricity more than the total load demand but could not meet the load demand during night. Total 12,781kWh/yr electricity was generated from PV and diesel generator. PV alone generates 8908kWh/yr i.e. RF became 69.7% but most of the energy from PV array was wasted. Diesel generator directly supplied 3873kWh/yr to the load which was 67.6% of load demand, although compared to the total production; generator contribution was only 30.3%. The remaining load demand, (5730 -3873) = 1857kWh/yr was supported by PV array through inverter. Therefore a significant amount of electricity from PV array was wasted. Wasted electricity was (8908 - 1857/0.94) = 6932.46kWh/yr which is 54.2% of total electricity production but compared to the total PV electricity production, the wasted electricity was 77.82%. To reduce this great amount of loss, this system should have some way to store the energy and could reduce the use of diesel generator.

Case 3. PV with Storage and Diesel Generator configuration

In this off-grid configuration model 11kW PV, 48 number of Trojan L16P Battery (@ 6V, 360Ah) at 24V system voltage with 5kW Inverter was used. The optimized configuration shaded out diesel generator, therefore 100% load supported by PV and storage. Results showed that, PV generates electricity more than the load demand and battery stored the excess electricity to maintain the load demand.

PV generates 8166kWh/yr of electricity from which a good amount of energy was stored in the battery and used at other time. Total AC load supported directly by PV array during day time and by battery during morning & night. Inverter converts 6096kWh/yr of DC electricity to AC. Battery stored 4281kWh/yr of energy and supplied 3692kWh/yr to support the load. Battery stored 52.42% of PV generated energy and supported 64.43% of load while PV directly supports 35.56% of load. However still 1480kWh/yr of excess energy generated by the PV array and was wasted that could be sold to the grid. This model configuration supports 100% load by PV array and storage which makes it environment friendly off-grid configuration.

Case 4. Wind turbine with Diesel Generator configuration

This off-grid configuration used 10kW BWC XL.1 wind generator with 5kW inverter and 10kW diesel generator as required resources to support 5730kWh/yr of load. Result showed that, wind turbine generates much more electricity than the total load demand but could not meet the load demand for 24 hours period.

Total 41,023kWh/yr of electricity was generated from wind turbine and diesel generator, where 38,781kWh/yr from wind turbine i.e. 94.5% of total production from RE but most of it was wasted as wind turbine supports 3488kWh/yr of load, which is 60.87% of load demand. Diesel generator contributes 2242kWh/yr or 39.13% of load demand, although compared to the total production; diesel generator contribution was only 5.5%. Total 35,070kWh/yr or 85.5% of total electricity production was wasted but compared to the total wind turbine output 90.43% was wasted. By adding storage this huge loss of electricity could be minimized and that could reduce the use of diesel generator.

Case 5. Wind turbine with Storage and Diesel Generator configuration

This off-grid configuration model used 3kW BWC XL.1 wind generator, 40 numbers of Trojan L16P Battery (@ 6V, 360Ah) at 24V system voltage and 5kW Inverter. This optimized configuration shaded out diesel generator, therefore 100% load was supported by wind turbine and storage. Result showed that, wind turbine generates electricity more than the load demand and battery stored the excess electricity to support at other time.

Wind turbine generates 11,634kWh/yr of electricity. Inverter converts 6096kWh/yr of DC electricity to AC. Battery stored 2364kWh/yr of energy and supplied 2037kWh/yr to the load. Battery stored 20.32% of wind turbine generated energy and supported 35.55% of load. However still 5211kWh/yr of excess energy generated by the wind turbine, i.e 44.79% of total generated energy was wasted that could be sold to the grid.

Case 6. Hybrid system with Diesel generator configuration

This off-grid hybrid configuration model used 3kW PV, 5kW BWC XL.1 wind generator, 5kW Inverter and 4kW diesel generator. Result showed that, although PV and wind turbine generates much more electricity than the total load demand but could not meet the load demand for 24 hours period.

Total electricity generated from RE (PV and Wind turbine) and diesel generator was 24,434kWh/yr where 2,227kWh/yr from PV, 19,390kWh/yr from wind turbine and 2,817kWh/yr from diesel generator. PV contributed 9.1%, wind turbine 79.35% and diesel generator 11.53% of total production, therefore overall RE contribution was 88.5% of total production. Diesel generator contributed 49.16% of load demand. Inverter converts 3,099kWh/yr of DC electricity to 2,913kWh/yr of AC electricity from RE generation which was 50.84% of load demand. A significant amount of electricity (18,518kWh/yr) from RE was wasted which is 75.78% of total electricity production and 85.66% compared to the total RE production. Storage could be used to reduce this huge energy loss and to minimize the use of diesel generator.

Case 7. Hybrid system with Storage and Diesel Generator configuration

This off-grid hybrid configuration model used 1kW PV, 3kW BWC XL.1 wind generator, 5kW Inverter and 32 Trojan L16P batteries at 24V system voltage to support the same load. Hybrid system (PV and wind turbine) output with storage supports 100% load and shaded out the use of diesel generator. Result showed that, storage managed the electricity from hybrid system and met the load demand 24 hours a day, but a significant amount of energy was wasted that could be sold to the grid.

Total 12,376kWh/yr of electricity was generated from hybrid system, where 742kWh/yr or 6% from PV and 11,634kWh/yr or 94% from wind turbine. Battery stored 2073kWh/yr and supported 1,788kWh/yr or 31.20% of load demand. This configuration supplied 100% load demand from RE, however 5,995kWh/yr was wasted which could be sold to the grid.

Summary of Category-1 or Off-grid configurations

The results of standalone configurations can be summarized that storage minimized the use of resources which reduced the project cost, improved load support that reduced GHG emission and reduced the loss of generated RE and showed the scope to sell excess energy to the grid. Table 7 summarizes these findings. Load support describes, percentage of load supported by RE and storage. Energy loss describes percentage of energy loss compared to total RE production.

5.2. Category-2 (Grid connected configuration)

Case 1. Grid only configuration

This is the present configuration of most residential electricity connection. Grid supplies total load demand of 5730kWh/yr. Grid electricity tariff varies with time, season and application [36, 38]. This configuration model considered 3 different price of grid electricity, depending on demand time. These are off-peak (0.30$/kWh), peak (0.42$/kWh) and super peak rate (0.75$/kWh). 6:00PM to 7:00PM considered super peak, 8:00PM to 10:00PM and 8:00AM to 9:00AM considered peak time and rest are off peak time. In this case yearly average COE becomes $0.422/kWh. As grid electricity mainly comes from conventional sources therefore a good amount of GHG and pollutant gas emits to the air.

Case 2. PV in Grid connected configuration

In this optimized model configuration diesel Generator was shaded out, however PV array still contributed a small portion of load demand. To meet load demand this model used 3kW PV, 5kW Inverter and grid supply. Total 7,182kWh/yr electricity was produced, where grid supplied 4,955kWh/yr or 69% of total production or 86.47% of total load demand. PV array produced 2,227kWh/yr or 31% of total production or 13.53% of the load demand. Total 549kWh/yr of energy was sold back to the grid and 818kWh/yr of PV generated electricity was wasted due to mismatch in timely demand which could be stored and supplied to the load.

	PV	Wind	Inverter	Storage	RE use	
				(at 24V DC system voltage)	Load support	RE energy loss
Case-2 (PV +Gen)	12kW	-	5kW	-	32.40%	77.82%
Case-3: (PV+Storage+Gen)	11kW	-	5kW	48 nos. (103.68kWh)	100%	18.12%
Case-4 (Wind turbine+Gen)	-	10kW	5kW	-	60.87%	90.43%
Case-5 (Wind turbine+Storage+Gen)	-	3kW	5kW	40 nos. (86.4kWh)	100%	44.79%
Case-6 (Hybrid +Gen)	3kW	5kW	5kW	-	50.84%	85.66%
Case-7 (Hybrid+Storage+Gen)	1kW	3kW	5kW	32 nos. (69.12kWh)	100%	48.44%

Table 7. Category-1 or off-grid configuration results

Case 3. PV with Storage in Grid connected configuration

This configuration model is very interesting compared to the earlier case that, by adding sufficient amount of storage, system improved PV contribution for same load demand. To meet load demand this model used 5kW PV, 12 numbers of Trojan L16P battery, 5kW inverter and grid supply. Total 6208kWh/yr of electricity produced where grid supplied 2496kWh/yr or 40% of total production or 43.56% of total load demand. PV array produced 3712kWh/yr or 60% of total production. Loss of energy was very insignificant. Battery stored 1918kWh/yr and supplied 1648kWh/yr to the load or 28.76% of total load. However PV array directly supported (5730-2496-1648) = 1586kWh/yr of load which was 27.68% of total load demand.

Case 4. Wind turbine in Grid connected configuration

In this configuration model, wind turbine generates enough electricity but was unable to meet the timely load demand therefore consumed sufficient amount of grid electricity. To meet the load demand this optimized model used 3kW BWC XL.1 wind turbine, 5kW inverter and grid supply. Total 14,389kWh/yr of electricity was produced where wind generator produced 11,634kWh/yr or 80.9% of total production. Grid supplied 2755kWh/yr or 19.1% of total production or 48.08% of load demand. Wind turbine supported (5730 - 2755) = 2975kWh/yr or 51.92% of load demand and 7121kWh/yr of electricity was sold back to the grid. Total 894kWh/yr of electricity was unused.

Case 5. Wind turbine with Storage in Grid connected configuration

This configuration model used 3kW BWC XL.1 wind generator, 16 numbers of Trojan L16P battery, 5kW inverter and grid supply. Total 11,784kWh/yr of electricity was produced where grid supplied only 150kWh/yr or 1.3% of total production or only 2.6% of total load demand. Wind turbine produced 11,634kWh/yr which was 98.7% of total production. Battery stored 2202kWh/yr and supplied 1895kWh/yr or 33.07% of total load demand. However wind turbine directly supported (5730-1895-150) = 3685kWh/yr or 64.31% of total load demand. Total 5068kWh/yr or 53.65% of wind production was sold back to the grid. Significant amount of electricity was sold back to the grid therefore overall GHG emission was reduced.

Case 6. Hybrid system without Storage in Grid connected configuration

In this configuration both PV and wind turbine was used. This hybrid configuration model used 1kW PV, 1kW BWC XL.1 wind generator, 1kW inverter and grid supply for the same load of 5730kWh/yr. Results showed that, the hybrid system was optimized such that minimum RE components were required but could not met the load demand for 24 hours period. Total 9,021kWh/yr of electricity was produced where grid supplied 4,401kWh/yr or 76.80% of load demand or 48.78% of total production. PV and wind hybrid system produced 4,620kWh/yr or 51.21% of total production. Hybrid system supplied 1329kWh/yr of electricity or 23.19% of load demand. However hybrid system generated enough electricity and sold 1,236kWh/yr to the grid, still 1,891kWh/yr of electricity wasted which was 40.93% of total RE production. This wasted electricity could be utilized and grid use could be minimized by adding storage.

Case 7. Hybrid system with Storage in Grid connected configuration

This hybrid configuration model used 1kW PV, 3kW BWC XL.1 wind generator, 3kW inverter, 12 Trojan L16P battery and grid supply. This configuration improved RE contribution in supporting load. Total 12,546kWh/yr of electricity was produced where grid supplied only 170kWh/yr which is 1.4% of total production or 2.96% of load demand. PV generates 742kWh/yr and wind turbine 11,634kWh/yr i.e. RE production was 98.6% of total electricity generation. This hybrid system sold back 5,527kWh/yr of electricity to the grid. Storage helped in improving RE utilization & minimized loss. Battery stored 1911kWh/yr and supported 1642kWh/yr of load or 28.65% of load demand.

Summary of Category-2 or Grid-connected configurations

The results of grid connected configurations can be summarized that storage improved load support which reduced GHG emission. Storage optimized the RE sources by minimizing grid use and reduced loss of energy. Table 8 summarizes these findings. Load support describes, percentage of load supported by RE and storage. Energy loss describes percentage of energy loss compared to total RE production. Grid sales describes, energy sold to grid compared to total RE production.

	PV	Wind	Inverter	Storage (at 24V DC system voltage)	RE use		
					Load support	Grid sales	RE energy loss
Case-2 (PV +Grid)	3kW	-	5kW	-	38.86%	24.65%	36.73%
Case-3 (PV+Storage+Grid)	5kW	-	5kW	12 nos. (25.92kWh)	56.44%	0.027%	0.0%
Case-4 (Wind turbine + Grid)	-	3kW	5kW	-	51.92%	61.19%	7.68%
Case-5 (Wind turbine + Storage +Grid)	-	3kW	5kW	16 nos. (34.56kWh)	97.38%	43.56%	0.0%
Case-6 (Hybrid +Grid)	1kW	1kW	1kW	-	23.19%	26.75%	40.93%
Case-7 (Hybrid+Storage +Grid)	1kW	3kW	3kW	12 nos. (25.92kWh)	97.03%	44.66%	2.53%

Table 8. Category-2 or grid connected configuration results

5.3. Findings

The optimization was done in two configuration categories and seven cases in each category. Four different factors were compared in each case. These factors were GHG & Pollutant gas emission, RF, COE and NPC. The comparative findings of these factors are explained below.

GHG & Pollutant gas emission

Figure 13 shows GHG and pollutant gas emissions in different case configurations. It was found that by adding storage in stand-alone system, emission of GHG and other pollutant gas was eliminated. In Grid connected configuration, it was also evident that storage minimized emission by improving RE utilization. By selling excess energy back to the grid storage with wind and hybrid system further helped in reducing GHG emission from grid which is shown in negative values in Figure 13.

Renewable Fraction (RF)

RF is the measuring index of how much electricity produced from RE, out of total production. In stand-alone system it was found that storage eliminates the use of diesel generator therefore RF became 100%. In Grid connected configuration Storage again improves the RE utilization and RF became as high as 98.7% as shown in Figure 14.
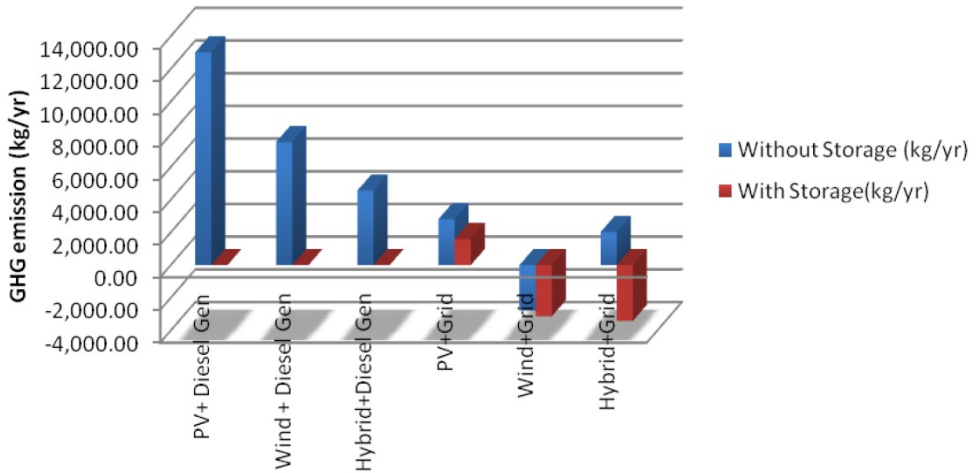
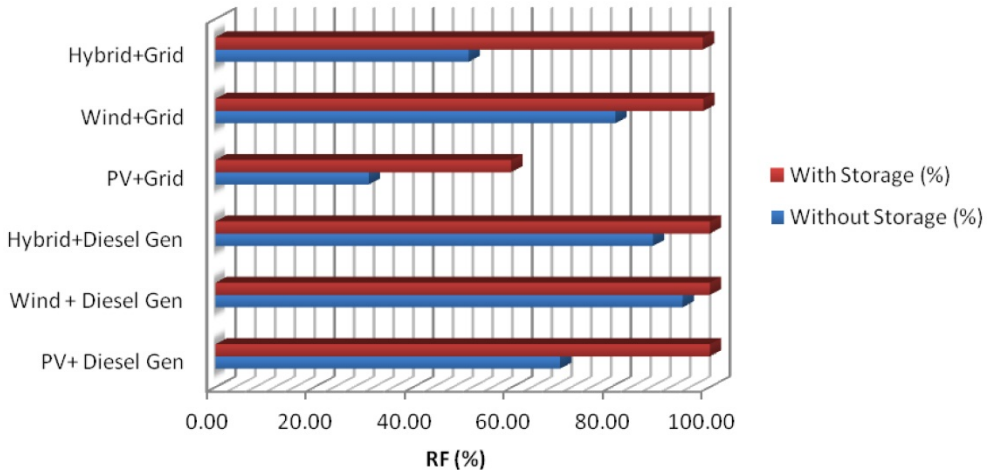**Figure 13.** GHG and pollutant gas emission in different cases

Figure 14. Renewable fraction (RF) in different cases

Cost of Energy (COE)

COE is the cost of per unit energy in $/kWh. Stand-alone configuration involving diesel generator was costly therefore COE was very high; however adding storage reduced COE to a reasonable level. In Grid connected configuration in all combination of RE sources, storage reduced the COE and in hybrid system storage reduced COE close to the grid only energy cost as shown in Figure 15.
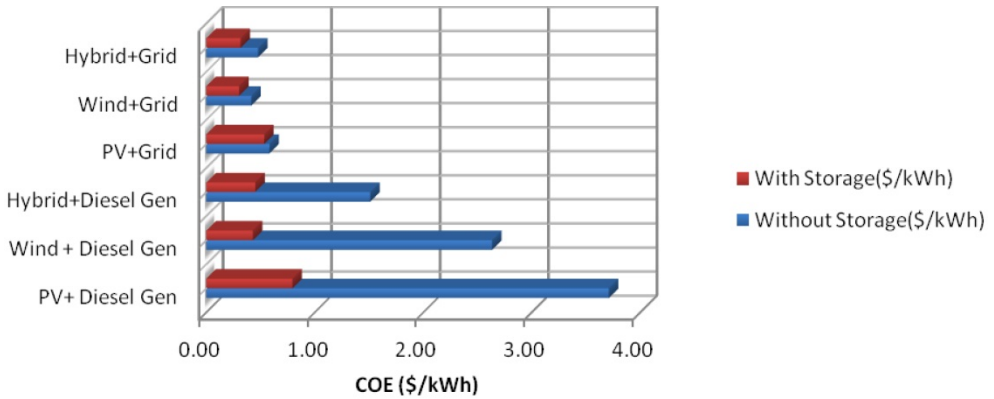
Figure 15. Cost of energy (COE) in different cases

Net Present Cost (NPC)

NPC represents present cost of the system. In standalone configuration NPC was very high however storage helped in reducing NPC to an acceptable level by improving the utilization of RE. In Grid connected configuration, storage helped in reducing NPC in every combination of RE used as shown in Figure 16.
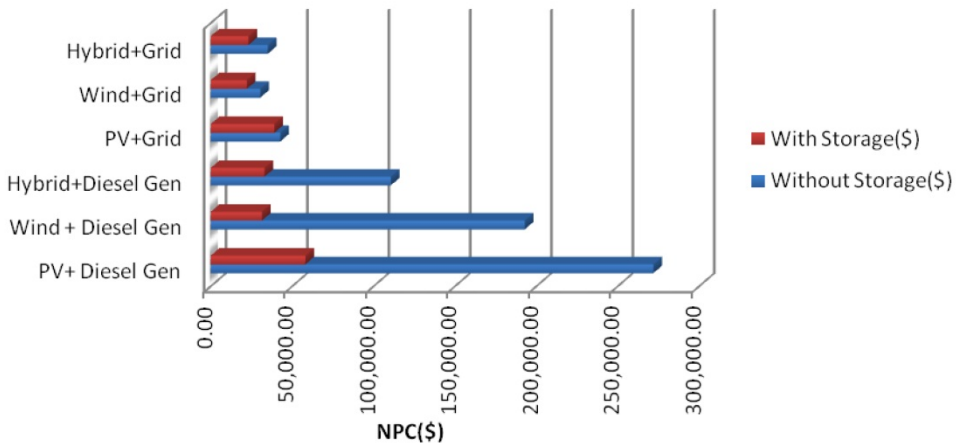

Figure 16. Net present cost (NPC) in different cases

5.4. Payback period

In this model payback was calculated by comparing one system with another. Payback is the number of years in which the cumulative cash flow switches from negative to positive by comparing storage integrated model with without storage model in grid connected configuration. Cash flow in grid connected PV with storage system compared with grid connected PV base system and it was found that payback period is 4.15 year. Similarly grid

connected wind generator with storage compared with without storage system and found that payback period is 2.67 years. In case of grid connected Hybrid (PV & wind turbine) system with storage compared with same without storage system and found that payback period is 2.05 years. Storage helped in RE utilization that minimizes the use of grid electricity and increased energy sell back to the grid. Therefore it was confirmed that the investment cost of storage integration returns in very short period of time as shown in Figure 17. In Australia solar bonus scheme awards the price of electricity fed into the grid from RE at a rate of $0.44/kWh [39-40] which is much higher than the utility rate. This ensures that the payback period will be much shorter in Australia.
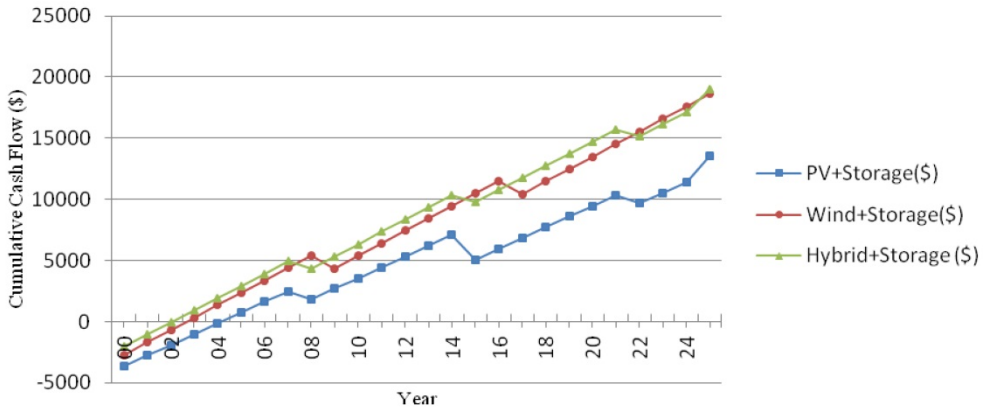
Figure 17. Payback period of storage in three different cases

6. Conclusion

Storage integrated RE system was analyzed for a residential load in Rockhampton, Australia. Estimation of required storage for the RE system was calculated. Estimation steps were developed and estimation of required storage was done in grid connected PV, wind and hybrid systems. It was found that to support daily load of 15.7kWh/day in grid connected PV system minimum 665.90Ah of storage, in grid connected wind turbine minimum 582.356Ah of storage and in hybrid system minimum 543.62Ah of storage required at 24V DC system voltage.

Model was developed for feasibility analysis of storage with RE. Model was analyzed in standalone and grid connected configurations. Analysis was conducted to observe the storage influences over the GHG emission, RF, COE and NPC indexes. It was found by analyzing the output data from the optimized model that storage has great influence on improving RE utilization.

It was evident from the analysis that storage helped significantly in reducing GHG & other pollutant gas emission, reduced COE, improved RF and reduced NPC. Comparing without and with storage system model, it was found that in grid connected PV system, storage

reduced 43.35% of GHG and pollutant gas emission and in all standalone systems it was 100%. In grid connected wind and hybrid system, storage reduced GHG emission more than 100% by selling extra energy to the grid. In grid connected configuration storage improved RF where with PV, wind turbine and hybrid system RF was 59.8%, 98.7%, 98.6% respectively. Storage reduced COE and in grid connected configuration it was as low as presently available grid electricity cost. In hybrid and wind system COE was $0.316/kWh and $0.302/kWh respectively. Similarly Storage reduced NPC by 8.3%, 27.13% and 33.95% in grid connected PV, wind and hybrid configurations respectively. Moreover payback time of storage is very short therefore storage integrated RE system is more feasible for implementation.

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