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Research Article

Investigation of Energy Storage Systems, Its Advantage and Requirement in Various Locations in Australia

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Storage minimizes the intermittent nature of renewable sources. Solar and wind are the two fostered source of renewable energy. However, the availability of useful solar radiation and wind speed varies with geographical locations, and also the duration of this energy sources varies with seasonal variation. With the available vast open land and geographical position, Australia has great potential for both solar and wind energies. However, both these sources require energy buffering to support load demand to ensure required power quality. Electricity demand is increasing gradually, and also Australia has target to achieve 20% electricity from renewable sources by 2020. For effective utilization of solar and wind energy potential location of these sources needs to be identified, and effective size of storage needs to be estimated for best utilization according to the load demand. Therefore this paper investigated wind speed and solar radiation data of 210 locations in Australia, identified the potential locations, and estimated required storage in various potential locations to support residential load demand. Advantages of storage were analyzed in terms of loading on distribution transformer and storage support during energy fluctuation from renewable energy. Further analysis showed that storage greatly reduces greenhouse gas emission and reduces overall cost of energy by maximizing the use of solar and wind energies.

1. Introduction

Storage significantly adds flexibility in renewable energy (RE) by minimizing intermittent nature of RE, also improves energy management. Solar and wind are the two most endorsed source of RE in recent years. However due to natural factors these sources cannot provide steady energy for the whole day and introduce potential unbalance in energy generation and demand. Australia is one of best places for these sources although level of solar radiation and wind speed varies from location to location. Therefore proper investigation is required to know the potential locations and required PV or wind turbine or storage capacity for certain RE application.

Electricity generation varies with the variation of solar radiation, wind speed and duration of these sources. Therefore to maximize the use of RE, properly sized storage needs to be added with designed solar or wind system. Presently installed most of the solar PV systems are intended to support the residential load and that are also connected with the distribution network (DN). However load profile and the electricity generation profile does not synchronize most of the time which keeps the dependency on the conventional grid power for major load demand time.

This paper investigates the RE potential of different locations, also investigates available standards to estimate the required storage to support residential load in various locations in Australia. The analysis considered that RE will support the steady state load and grid will support transient high loads. Furthermore storage influence on RE was analyzed and found that storage maximizes the use of RE, reduces load on distribution transformer and supports load during energy fluctuations. Therefore proper sized RE resources with proper sized storage is essential for best utilization of RE in different potential locations in Australia.

2. Background

RE is the alternative source for future energy demand. Traditionally stationary energy sector use coal and different forms of hydrocarbon to generate electricity that causes greenhouse gas (GHG) emission. Australia's reliance on coal-fired power makes it one of the world's highest per-capita GHG emitting countries [1]. Currently, RE sources fulfill 15%–20% of world's total energy demand [1] and in Australia around 7% electricity generates from RE. Australia set national RE target of 20% electricity from RE by 2020 [1] and national GHG emission target of 60% below 2000 level by 2050 [2]. Therefore it is urgent to maximize the use of RE by bringing higher percentage of RE into the national energy mix. Among various RE sources, solar and wind are easily available and everlasting source of energy.

Photovoltaic (PV) array produces DC electricity in direct proportion to the global solar radiation. Therefore, the power output from PV array can be calculated by (1) [3, 4]

$$P_{\mathrm{PV}} = Y_{\mathrm{PV}} f_{\mathrm{PV}} \left(\frac{G_T}{G_{T,\mathrm{STC}}} \right) \left[1 + \alpha_P \left(T_C - T_{C,\mathrm{STC}} \right) \right] \quad (1)$$

where Y_{PV}—rated capacity of PV array, meaning power output under standard test conditions [kW]; f_{PV}—PV derating factor [%]; G_T—solar radiation incident on PV array in current time step [kW/m^2]; $G_{T,\mathrm{STC}}$—incident radiation under standard test conditions [1 kW/m^2]; α_P—temperature coefficient of power [%/°C]; T_C—PV cell temperature in current time step [°C]; $T_{C,\mathrm{STC}}$—PV cell temperature under standard test conditions [25°C]. Performance of PV array depends on de-rating factors like temperature, dirt and mismatched modules.

Kinetic energy of wind can be converted into electrical energy by using wind turbine, rotor, gear box and generator. Wind turbine can convert maximum 59.3% of the kinetic energy of the wind into mechanical energy which is known as Betz limit or "power coefficient" and the value is: $C_p = 0.59$. Available power from wind turbine can be expressed [5] as per (2):

$$P = \frac{1}{2} C_p \rho A V^3 \quad (2)$$

where, P is Power output from wind turbine in Watts, ρ is the air density (1.225 kg/m^3 at 15°C and 1-atmosphere or in sea level), A is rotor swept area in m^2, V is the wind speed in m/s.

Basic characteristics of solar radiation and wind speed influence the output from these sources. Output from solar PV is directly proportional to the solar radiation and output from wind turbine is proportional to the cubic of wind speed as shown in (1) and (2). Therefore, fluctuation in solar radiation and wind speed has great impact on energy output.

Energy storage can provide critical role in integrating RE into the grid by load shifting and storing about one day average load demand [6]. Again how much storage is required for any application is a great concern for effective utilization of solar and wind energy. Energy output from solar and wind is critically dependent on the location where these applications are installed. Therefore identification of suitable location and estimation of required capacity of RE and storage is essential for any particular load demand. Presently installed small PV or wind system, especially residential grade PV or wind system are not integrated with storage system just to cut the cost of the total system. Compared to the initial cost, continuous presence of storage for energy buffering is more beneficial. Although large scale storage is still expensive but significant research is underway for inexpensive and efficient large scale storage systems [7] suitable for large scale RE applications.

This paper illustrates applications of energy storage system (ESS), identifies potential location of RE in Australia and estimates the required size of energy storage in different locations considering weather data of the location to support residential load. Moreover benefits of storage were analyzed to see the influence of storage in RE utilization.

3. Applications of Energy Storage Systems

Demand of ESS is increased due to the technological development to use with intermittent renewable energy sources. Large storage lets RE producers to store surplus energy and supply when demand goes high. In Queensland, Australia, approximately 10% electricity network has been built to support only the extreme peak loads [8], and utility operators maintain costly short time generators to support peak load. Moreover fluctuations and uncertainty in timely load support is a phenomenon of solar and wind energy. By integrating proper sized energy storage (ES) with RE, this peak load demand can be minimized and eventually helps to reduce the cost of energy.

Different ES technologies coexist and different characteristics make them suitable for different applications. Recent developments and advances in ES and power electronics technology make ES applications a feasible solution for modern power applications. In an AC (Alternating current) system electrical energy cannot be stored electrically, however energy can be stored by converting and storing it electrochemically, electromagnetically, kinetically or as potential energy. ES technologies can be classified considering energy & power density, response time, cost, lifetime, efficiency or operating constraints. Among different forms of ES systems, pumped hydro storage (PHS), compressed air energy storage (CAES), thermal energy storage (TES), flywheel, hydrogen, different type of batteries, capacitors, superconducting magnetic energy storage (SMES) are suitable for different types of applications.

In large scale application, electrical ES can be divided into three main functional categories such as:

(i) Power Quality: Stored energy applied only for seconds or less to ensure continuity of power quality.

(ii) Bridging power: Stored energy applied for seconds to minutes to assure continuity of service when switching from one source of energy to another.

(iii) Energy Management: Stored energy used to decouple the timing of energy generation and consumption especially in the application of load levelling. Load levelling involves charging of storage in low demand time and use in peak time which enables consumers to minimize the total energy cost.

ES can bring change in electric power system with RE by supporting peak load demand, improving stability and power quality. Storage can be applied to generation, transmission or in various parts of the distribution system, at the customer site or with any particular appliances. The main advantage of the ESS is to maintain the grid power in constant level [9] by supporting grid voltage, grid frequency, load leveling, peak shaving, improving power quality, spinning reserve also by increasing RE penetration. ES reduces overall cost of energy by reducing installation of additional generation and transmission/distribution capacity and ES helps to reduce the GHG emission.

Therefore, ES will play a unique role in future smart grid development by combining different RE sources capabilities into the grid. Storage can buffer the power spikes and dips and fluctuations [10]. Energy storage technology can play a significant role in maintaining power quality and system reliability [11]. The principle application is to respond to sudden changes in load, support load during transmission or distribution interruptions, correct load voltage profiles with rapid reactive power control that allow generators to operate in balance with system load at their normal speed [11]. The technical advantages of different ESS are summarized in Table 1.

Prolific application of ESS depends on potential locations of RE to generate sufficient electricity, proper size of storage and maximizing the benefit of using ESS.

Table 1: Applications of different energy storage technologies [9, 12].

Energy storage applications	Pumped hydro	CAES	SMES	Lead-acid battery	Flow batteries	Flywheels	Super capacitors	Hydrogen/fuel cell	TES
Load levelling	√	√		√	√			√	√
Load flowing	√	√		√	√			√	√
Peak generation	√	√		√	√	√		√	√
Fast response spinning reserve	√	√		√	√	√	√	√	
Conventional spinning reserve	√	√		√	√	√		√	
Emergency backup	√	√		√	√			√	√
Uninterruptible power supply				√	√	√		√	
Transient and end use ride through			√	√	√	√	√	√	√
Transmission and distribution stabilization	√	√	√	√	√			√	
RE integration	√	√		√	√	√		√	√
RE backup	√	√		√	√				√

4. Potential Locations of Renewable Energy in Australia

Solar and wind are the two major sources of RE. Austria, France, Germany, Spain, Netherlands and United Kingdom are the six leading countries in Europe representing 98% of installed PV power in European Union [13]. Again several European countries especially Germany and Spain are leading in wind power generation [14]. Australia is one of the best location for both solar and wind energy. However the inherent characteristics of solar radiation and wind speed, diurnal condition and several intermittent causes restrict useful electricity generation. Based on the weather data different locations in Australia were identified suitable for solar and wind energy. By comparing the daily average solar radiation and wind speed data of 210 locations in Australia, the potential areas were identified. This data was collected from NASA's SSE resource website [15], which was formulated from 20 years period data. Potential locations are defined as where wind speed is ≥6.0 m/s and solar radiation is ≥6.0 kWh/m^2/d and the potential areas for both sources are defined where wind speed ≥5.0 m/s and solar radiation ≥5.0 kWh/m^2/d. Table 2 shows the number of potential areas for solar and wind energy in different states in Australia.

Among 210 observed locations in Australia it was found that, Macquarie island, Maatsuyker island, Wellington and Cape Grim in Tasmania (TAS) are best for wind power system. Alice Springs, Tennant Creek, Ngukurr in Northern Territory (NT) are the best place for solar power system. Queensland (QLD) and Western Australia (WA) are the two largest states and some north and north-central locations (Weipa, Cloncurry, Georgetown in QLD, Karratha, Roebourne, Learnmonth in WA) in both states are suitable for solar energy and southern locations (Cape Moreton, Finders Reef, Marion Reef in QLD, Cape Leeuwin, Rottnest island, Bunbury in WA) are suitable for wind energy. South Australia is suitable for both energy, some locations in Victoria (VIC) is suitable for wind energy. Compared to other states, RE prospect of New South Wales (NSW) is less, but 14 locations have daily average solar radiation above 5.0 kWh/m^2/d but less than 6.0 kWh/m^2/d and in 4 locations wind speed is above 5.0 m/s but less than 6 m/s, although Newcastle and Gabo island has strong wind speed. Some potential locations identified in Australia are shown in Figure 1.

Three best locations for wind energy in Australia are Macquarie Island in Tasmania, Wilsons Promontory in Victoria, Cape Leeuwin in Western Australia and three best location for solar energy are Weipa in Queensland, Alice springs in Northern Territory and Karratha in Western Australia was identified in [16]. Australian states were ranked in [16] by comparing maximum, average and minimum values of wind speed and solar radiation of 21 different locations to compare the potential areas of RE as shown in Table 3.

However, highly potential locations also not able to provide energy for 24 hours a day and energy storage is essential for solar and wind energy applications. 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. Estimation of the required storage for highest ranked locations are explained in next section. Table 4 shows daily average data of wind speed and solar radiation of few potential locations in Australia.

5. Estimation of Required Energy Storage

Prospect of solar and wind energy is enormous but the inherent characteristics of these sources allow extracting energy only for a part of the day. However load demand continues for the whole day although the level of load demand

Table 2: Number of potential locations in different states in Australia.

Australian states	Number of observed locations	Solar radiation location ≥ 6.0 kWh/m^2/d		Wind speed location ≥ 6.0 m/s		Both solar and wind locations ≥ 5.0 m/s and 5.0 kWh/m^2/d	
		Numbers	%	Numbers	%	Numbers	%
Northern Territory (NT)	18	8	44.4	1	05.5	3	16.7
Queensland (QLD)	50	10	20.0	5	10.0	13	26.0
New South Wales (NSW)	47	1	02.1	2	04.3	1	02.1
South Australia (SA)	15	0	00.0	2	13.3	6	40.0
Victoria (VIC)	31	1	03.2	5	16.1	1	03.2
Western Australia (WA)	35	8	22.8	10	28.6	12	34.3
Tasmania (TAS)	14	0	00.0	8	57.1	0	00.0

Table 3: Ranking of different Australian states for solar and wind energy generation potentials [16].

Australian states	Ranking	
	Solar energy	Wind energy
Northern Territory (NT)	1	7
Queensland (QLD)	2	5
New South Wales (NSW)	3	6
South Australia (SA)	4	2
Victoria (VIC)	5	3
Western Australia (WA)	6	4
Tasmania (TAS)	7	1

varies with time. Estimation of required storage depends on estimation of load, RE output and standard guideline.

IEEE Std-1013-2007 [17] 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 [18] 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 [19] provides guideline to connect Distributed Resources (DR), such as PV, wind and storage with the power grid at the distribution level. Grid connected PV system sizing for storage integration also explained in [20].

Considering the above sizing practice and guidelines, estimation of required storage for steady state residential load was accomplished by calculating the area under the daily load profile and energy output from solar and wind profile. Finally subtracting the load from total generation which is the common area under the load and generation profile and the remaining load is the load on required storage. Details are explained in the following sub sections considering different potential locations and results are summarized in Section 5. Calculation involves the following steps

Step 1. Determining the daily load (ex: a residential load).

Step 2. Determining the required PV or wind turbine rating for the load.

Step 3. Determining daily energy output from the PV array or wind turbine.

Step 4. Estimating the PV array size and wind turbine rotor diameter.

Step 5. Comparing daily electricity generation from RE (from PV or wind turbine) with daily load and get the load on storage.

Step 6. Estimating the required Battery (Storage) size in Ah for the load on storage.

5.1. Estimation of Daily Residential Load. The average Australian household electricity use is about 16 kWh/day [21]. In Queensland, Australia, peak demand generally occurs between 4:00 PM to 8:00 PM, when most householders return home and turn on energy intensive appliances [8]. Considering the common household equipment the daily electricity load profile was generated by multiplying the power rating of all the household appliances by the number of hours it is expected to operate on an average day. Residential load profile varies according to the residents work time pattern. It was found that maximum load demand was in the evening from 06:00 PM to 10:00 PM and in the morning 07:00 AM to 09:00 AM as shown in Figure 2.

Hourly load is a time series data and area under the curve is calculated by trapezoidal method. Therefore total daily load can be estimated by calculating the area under the load profile curve using (3)

$$\text{Daily Load} = P_{\text{Load}} = \int_{t_1}^{t_{24}} \frac{1}{2}\left(p_{t_1} + p_{t_2}\right) T_{12} dt \qquad (3)$$

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

Following (3), total daily load of a residential house in Rockhampton, Australia considered for this analysis is the area under the load curve which is 21.59 kWh and the equivalent DC load is 25.40 kWh as shown in Figure 2 considering efficiency of the converter as 85%.

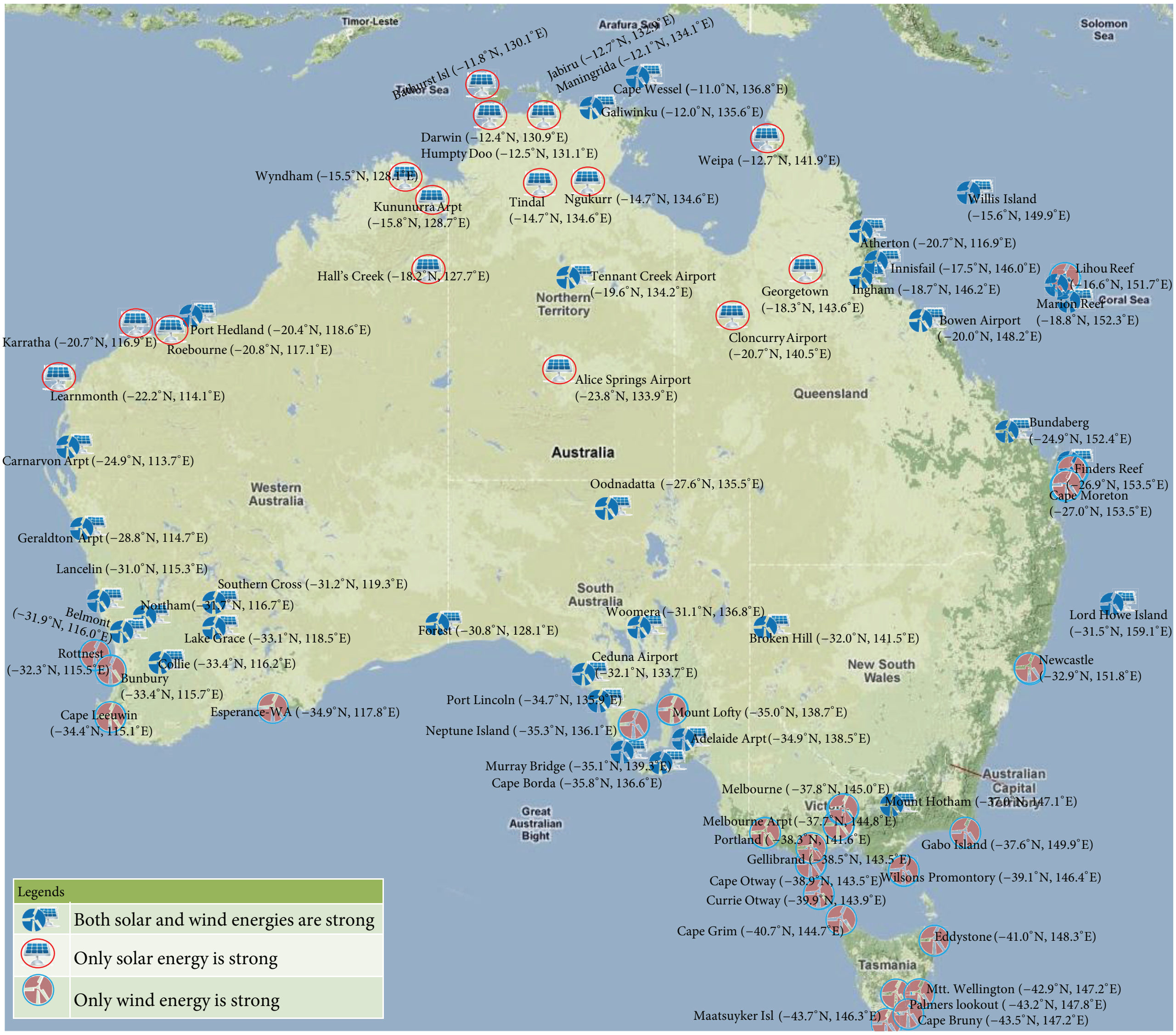

Figure 1: Potential Locations of Solar and Wind Energy in Australia.

5.2. Estimation of Required Storage. Improper sized solar PV or wind system is unable to meet the required load demand moreover local utility operators have limits in accepting RE into the grid. Ergon Energy (utility operator in Queensland, Australia) restricts each installation of PV capacity to 1.3 kW in rural areas for distribution transformer (DT) up to 50 kVA and in urban areas 4.0 kW for DT up to 100 kVA [22]. Therefore proper estimation of energy from solar and wind source is required.

Sometimes electrical energy generated from RE wasted which neither can be used by the load nor can be stored in storage battery. This event occurs when the battery State of Charge (SOC) exceeds its maximum allowable value and solar/wind generates more than the load demand. The amount of waste/loss of energy can be avoided or reduced by proper choice of battery and PV/wind generator size. Shrestha and Goel [23] 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. For estimation of solar and wind energy worst month solar radiation and wind speed was considered to ensure that the designed system can operate year-round. Estimation of storage with solar PV and wind turbine system are explained below considering that solar PV or wind system should support daily steady state load demand.

5.2.1. Estimation of Storage with Solar PV. In Australia yearly average sunlight hours varies from 5 to 10 hours/day and maximum area is over 8 hours/day [24]. In Alice Springs the monthly lowest solar radiation was in June and solar window is over 10 hours. Figure 3 shows solar radiation in three potential locations in Australia. The daily average solar energy in Alice Springs was estimated by calculating the area under the solar radiation curve (as shown in Figure 3) using (3) and total radiation becomes 3.54673 kWh/m^2/d.

Table 4: Selected location's solar and wind data [15].

Month	Solar radiation ($kWh/m^2/d$)			Wind speed (m/s)			
	Alice Springs (NT)	Weipa (QLD)	Karratha (WA)	Macquarie Island (TAS)	Newcastle (NSW)	Neptune Island (SA)	Melbourne (VIC)
Jan	7.64	5.86	8.14	9.8	7.9	7.8	5.7
Feb	7.17	5.12	7.37	10.3	7.8	7.5	8.2
Mar	6.58	5.68	6.96	10.3	7.6	7.0	6.2
Apr	5.67	6.07	5.88	10.8	6.9	6.9	6.2
May	4.42	5.65	4.82	10.3	6.8	7.3	6.2
Jun	4.08	5.39	4.32	10.8	7.4	8.4	6.7
Jul	4.47	5.63	4.86	10.3	7.0	9.0	7.2
Aug	5.31	6.33	5.88	10.3	7.5	9.1	7.2
Sep	6.31	7.20	7.10	10.3	7.8	8.7	7.2
Oct	7.06	7.62	8.07	10.3	8.0	8.1	7.2
Nov	7.47	7.45	8.52	9.8	8.0	8.0	5.7
Dec	7.72	6.50	8.45	9.3	7.9	7.8	5.7
Annual	**6.15**	**6.21**	**6.69**	**10.2**	**7.6**	**8.0**	**6.6**

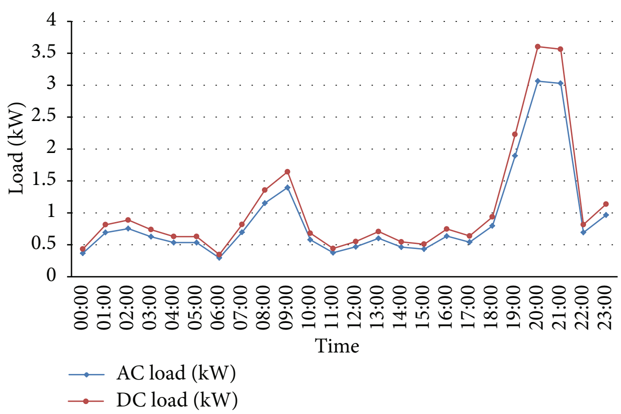

Figure 2: Residential Load Profile.

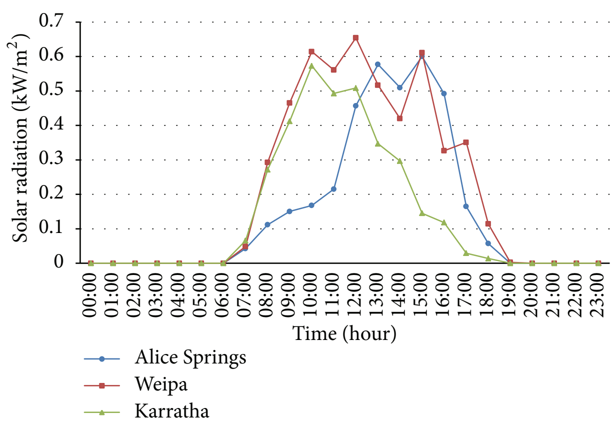

Figure 3: Solar radiation in different potential locations.

However, PV array should support 21.59 kWh (AC) of load every day. Following the guideline of [20], the required PV array capacity becomes:

$$P_{\text{ac}}\,(\text{kW}) = \frac{\text{Load}\,(\text{kWh/day})}{\text{Solar window}\,(\text{h/day})} = \frac{21.59}{10} = 2.159\,\text{kW}. \quad (4)$$

Equivalent DC capacity can be found by considering the efficiency of the PV system. Overall efficiency (η) of PV system considered 85% including efficiency of inverter, dirt and mismatch losses of PV modules

$$P_{\text{dc,STC}} = \frac{P_{\text{ac}}\,(\text{kW})}{\eta} = \frac{2.159}{0.85} = 2.54\,\text{kW}. \quad (5)$$

According to IEEE-1013 [17], size of the PV array should be more than 1.3 times the load to charge the battery while supporting the load. But in grid connected condition, it is good to consider 1.0 or 1.1 to avoid over design. So the adjusted PV array capacity for the equivalent DC load becomes:

$$P_{\text{dc,STC (Adjusted)}} = 1.1 \times P_{\text{dc,STC}} = 1.1 \times 2.54 = 2.79\,\text{kW} \quad (6)$$

Therefore, for this residential load 2.79 kW capacity of PV array with proper sized storage is required to support the load for 24 hours a day.

For known PV panel efficiency and for 1 kW/m^2 rated PV module, the required surface area of the PV array can be calculated. The efficiency of crystal silicon PV module is 12.5% [20], however LG Polycrystalline module efficiency is 13.7% [25], therefore surface area of PV array becomes:

$$P_{\text{dc,STC}} = \left(1\,\text{kW/m}^2\right)\text{insolation} * A * \eta$$
$$A = \frac{P_{\text{dc,STC}}}{(1\,\text{kW/m}^2) * \eta} = \frac{2.79}{1 \times 0.125} = 22.32\,\text{m}^2 \quad (7)$$

Thus 22.32 m^2 PV module with PV panel efficiency of 12.5% will support the load with sufficient storage size.

To estimate the required storage for the load, the total energy generated from this PV array is used. The capacity of the required battery bank can be calculated by multiplying the daily load on battery by autonomy day or number of days it should support the system to 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 (ex. 24 V or 48 V). Total electricity generated by 22.32 m^2 PV array at the solar radiation of Alice Springs is plotted in Figure 4 and calculated using (3) as 79.16 kWh which is the area under the curve. By superimposing the DC load with the PV output curve the common area that load and PV output shares is 9.57 kWh which is the amount of load that PV array supports while charging the batteries as well. The remaining (25.40 − 9.57) = 15.83 kWh/d load should be supported by the storage. This is the daily minimum load on storage to support the load.

However the design was based on PV array generated energy to support the total load, therefore the remaining energy from the PV array should be managed by the storage system which is (79.16 − 9.57) = 69.59 kWh/d. This is the maximum load on storage if total energy generated by solar PV needs to be managed by the storage.

Inverters are specified by their DC input voltage as well as by their AC output voltage. Inverters DC input voltage which is the same as the battery bank voltage is called the system voltage. The system voltage usually considered as 12 V, 24 V or 48 V. For this design, system voltage considered 24 V and the system was designed for one day. Considering inverter (with battery) efficiency of 95% [26], the required battery capacity can be calculated. Therefore load on battery is:

$$\begin{aligned}
&\text{Daily minimum load in Ah @ system voltage}\\
&\quad = \frac{\text{Load (Wh/day)}}{\text{System Voltage}}\\
&\quad = \frac{15.83 \times 10^3}{24} = 659.58\ \text{Ah/d}\\
&\text{Daily maximum load in Ah @ system voltage}\\
&\quad = \frac{\text{Load (Wh/day)}}{\text{System Voltage}}\\
&\quad = \frac{69.59 \times 10^3}{24} = 2899.58\ \text{Ah/d}.
\end{aligned} \tag{8}$$

Energy stored in a battery typically given in Ah, at system voltage and at some specified discharge rate. 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 battery (i.e., discharge for 20 hours) at 25°C is explained in [20]. The maximum depth of discharge (MDOD) for Lead-acid battery is 80% [20], thus for one day discharge the battery need to store:

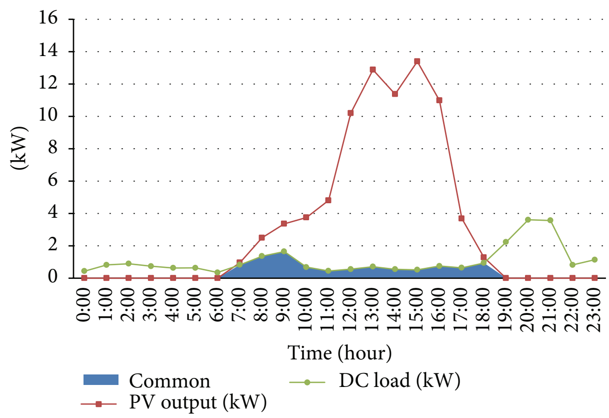

Figure 4: Storage estimation for solar system in Alice Springs.

$$\begin{aligned}
&\text{Battery storage (minimum)}\\
&\quad = \frac{\text{Load (Ah/day)} \times \text{No of days}}{\text{MDOD}}\\
&\quad = \frac{659.58 \times 1}{0.80} = 824.48\ \text{Ah}\\
&\text{Battery storage (maximum)}\\
&\quad = \frac{\text{Load (Ah/day)} \times \text{No of days}}{\text{MDOD}}\\
&\quad = \frac{2899.58 \times 1}{0.80} = 3624.47\ \text{Ah}.
\end{aligned} \tag{9}$$

The rated capacity of battery is specified at standard temperature. At 25°C, the discharge rate of C/20, becomes 96% [20], therefore finally required battery capacity becomes:

$$\begin{aligned}
&\text{Required minimum Battery storage (25°C, 20 hour-rate)}\\
&\quad = \frac{\text{Battery storage}}{\text{Rated capacity}} = \frac{824.48}{0.96} = 858.83\ \text{Ah}\\
&\text{Required maximum Battery storage (25°C, 20 hour-rate)}\\
&\quad = \frac{\text{Battery storage}}{\text{Rated capacity}} = \frac{3624.47}{0.96} = 3775.50\ \text{Ah}.
\end{aligned} \tag{10}$$

Thus for 21.59 kWh/d load minimum 858.83 Ah to maximum 3775.50 Ah of storage battery required at system voltage 24 V with 2.79 kW solar PV.

5.2.2. Estimation of Storage with Wind Turbine. Wind speed varies with different natural factors, time and season. Wind speed in Macquarie Island is very good, even in worst month (in December) wind blows at speed of above 6 m/s for daily average duration of 20 hours.

The collected wind speed data was measured at 10 m height. However wind speed increases with height and for

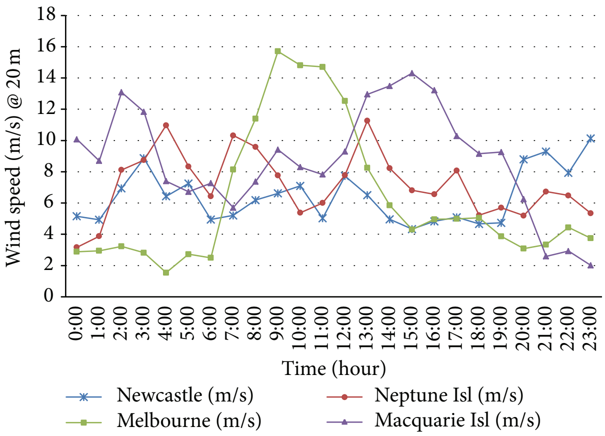

Figure 5: Wind speed at 20 m height in different locations.

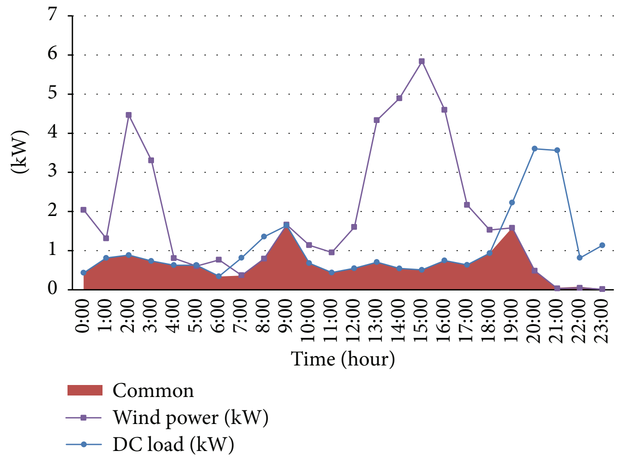

Figure 6: Storage estimation for wind system in Macquarie Island.

the analysis 20 m height was considered and corresponding energy output from wind speed was calculated using (2) for 1 m^2 of rotor area considering turbine efficiency 25%. Wind speed at 20 m height at four different locations is shown in Figure 5.

Energy generated by the wind turbine in Macquarie island is 0.871 kWh/m^2/d as calculated by the area under the curve using (3). The required wind turbine capacity for the same load can be calculated as:

$$P_{ac}\ (\text{kW}) = \frac{\text{Load (kWh/day)}}{\text{Wind window (h/day)}} = \frac{21.59}{20} = 1.08\ \text{kW}. \tag{11}$$

Estimation of required storage (a DC component) requires inverter to support the load. DC capacity of the wind turbine can be calculated considering inverter efficiency of 90%

$$P_{dc,STC} = \frac{P_{ac}\ (\text{kW})}{\eta} = \frac{1.08}{0.90} = 1.2\ \text{kW}. \tag{12}$$

Likewise PV assumption, the required wind turbine capacity was considered 1.1 times the load to charge the batteries while supporting the load. So the adjusted wind turbine capacity for the equivalent DC load becomes:

$$P_{dc,STC\,(\text{Adjusted})} = 1.1 \times P_{dc,STC} = 1.1 \times 1.2 = 1.32\ \text{kW}. \tag{13}$$

Energy generated by the wind turbine on that particular day was 0.871 kWh/m^2/d. To support total load, rotor swept area needs to be adjusted. Equation 2 shows that power output is not linear for increase in rotor diameter. It was found that at 20 m height wind speed varies from 2.0 m/s to 14.31 m/s; therefore average wind speed of 8.72 m/s was considered to calculate the rotor diameter for the rated wind turbine capacity of 1.32 kW. The rotor diameter was calculated as 4.07 m and calculated total energy from this turbine is 45.24 kWh which is the area under the wind power curve as shown in Figure 6.

Daily load curve was plotted with wind turbine output curve to get the common area (as shown the shaded area in Figure 6) or the load that directly supported by the wind turbine which is 15.11 kWh. The minimum (25.40 − 15.11) = 10.29 kWh of load needs to be supported by the storage each day. The design was considering to support the total load therefore maximum (45.24–15.11) = 30.13 kWh of load must be supported by the storage if total RE generation needs to be completely managed. Considering the DC system voltage as 24 V, load on battery in Ah can be calculated for one day as:

$$\begin{aligned}
&\text{Daily minimum load in Ah @ system voltage}\\
&\quad = \frac{\text{Load (Wh/day)}}{\text{System Voltage}}\\
&\quad = \frac{10.29 \times 10^3}{24} = 428.75\ \text{Ah/d}\\
&\text{Daily maximum load in Ah@ system voltage}\\
&\quad = \frac{\text{Load (Wh/day)}}{\text{System Voltage}}\\
&\quad = \frac{30.13 \times 10^3}{24} = 1255.42\ \text{Ah/d}.
\end{aligned} \tag{14}$$

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

$$\begin{aligned}
\text{Battery storage (minimum)} &= \frac{\text{Load (Ah/day)} \times \text{No of days}}{\text{MDOD}}\\
&= \frac{428.75 \times 1}{0.80} = 535.94\ \text{Ah}\\
\text{Battery storage (maximum)} &= \frac{\text{Load (Ah/day)} \times \text{No of days}}{\text{MDOD}}\\
&= \frac{1255.42 \times 1}{0.80} = 1569.27\ \text{Ah}.
\end{aligned} \tag{15}$$

Table 5: Required storage in different locations in Australia.

	Solar locations in Australian (solar radiation and solar window)	Solar PV rating	Required storage
NT	Alice Springs ($3.55\,kWh/m^2/d$) 10 hr	2.79 kW, 22.32 m^2 panel	Min 858.83 Ah Max 3755.50 Ah
QLD	Weipa ($4.98\,kWh/m^2/d$) 11 hr	2.54 kW, 20.32 m^2 panel	Min 839.84 Ah Max 4964.73 Ah
WA	Karratha ($3.27\,kWh/m^2/d$) 9 hr	3.10 kW, 24.83 m^2 panel	Min 890.84 Ah Max 3923.07 Ah
	Wind locations in Australian (wind speed and wind window)	Wind system rating	Required storage
NSW	Newcastle (6.40 m/s) 9 hr	2.93 kW, rotor diameter = 9.64 m	Min 46.11 Ah Max 3289.93 Ah
SA	Neptune Island (7.17 m/s) 16 hr	1.65 kW, rotor diameter = 6.1 m	Min 405.27 Ah Max 1692.71 Ah
VIC	Melbourne (6.16 m/s) 11 hr	2.40 kW, rotor diameter = 9.23 m	Min 630.97 Ah Max 7879.76 Ah
TAS	Macquarie Island (8.72 m/s) 20 hr	1.32 kW, rotor diameter = 4.07 m	Min 535.94 Ah Max 1634.66 Ah

At 25°C, the discharge rate of C/20 batteries is 96% [20], therefore finally required battery capacity becomes:

$$\begin{aligned}
&\text{Required minimum Battery storage } (25^\circ\text{C, 20 hour-rate}) \\
&= \frac{\text{Battery storage}}{\text{Rated capacity}} \\
&= \frac{535.94}{0.96} = 558.27\text{ Ah} \\
&\text{Required maximum Battery storage } (25^\circ\text{C, 20 hour-rate}) \\
&= \frac{\text{Battery storage}}{\text{Rated capacity}} \\
&= \frac{1569.27}{0.96} = 1634.66\text{ Ah.}
\end{aligned} \tag{16}$$

Finally, Table 5 shows the required storage for the same load (21.59 kWh/d) at system voltage 24 V DC in different locations in Australia. The annual average daily solar radiation in Alice Springs, Weipa and Karratha is 6.15, 6.21 and 6.69 $kWh/m^2/d$ respectively, however for the estimation the particular day average radiation was 3.55, 4.98, 3.27 $kWh/m^2/d$ respectively. The annual average daily wind speed in Newcastle, Neptune Island, Melbourne and Macquarie Island is 7.6, 8.0, 6.6 and 10.2 m/s but for the estimation the particular day average wind speed was 6.40, 7.17, 6.16 and 8.72 m/s, respectively.

6. Advantage of Energy Storage with Solar and Wind Energy

The advantage of storage is explained below by investigating it's influence in load support, fluctuation handling capability and also the advantage explained in environmental and economical context. A computer aided model was developed to identify the significance of storage with solar and wind power systems.

Table 6: Load allocation in three nodes.

Node	Phase-1		Phase-2		Phase-3	
	kVA	$\cos\varphi$	kVA	$\cos\varphi$	kVA	$\cos\varphi$
Node-1, -2, -3	9.55	0.9	9.55	0.9	9.55	0.9

6.1. Load Support by Storage. This study identifies the storage role on distribution transformer (DT) loading considering residential load and roof-top solar PV connected to the distribution network (DN) through DT.

To investigate the storage role, a model was developed in PSS SINCAL as shown in Figure 7. Model considered three groups of residential houses connected to the single phase line of DN through DT. In Australia residential peak load demand is 1.72 kW [27], that is, 1.91 kVA considering $\cos\varphi = 0.9$. Model considered 5 such houses connected in each phase in each node, also considered same load for each house. Therefore 15 houses are connected in each node and total 45 houses are connected in three nodes from the DT with a total load of 85.95 kVA. It was also considered that 5 such houses installed roof top solar PV in each node and connected to phase-1 in Node-1, phase-2 in Node-2 and phase-3 in Node-3 as shown in Figure 7. All 3 nodes are considered 500 m apart from each other.

As mentioned earlier, in Queensland, Australia, peak demand generally occurs between 4:00 PM to 8:00 PM when most householders return home and turn on energy intensive appliances [8]. Daily household load profile is based on the working nature of the residents and the daily average load pattern as shown in Figure 8.

Model considered urban area load with DT (11 kV/415 V) capacity of 100 kVA. Without PV and storage, DT was 87.22%

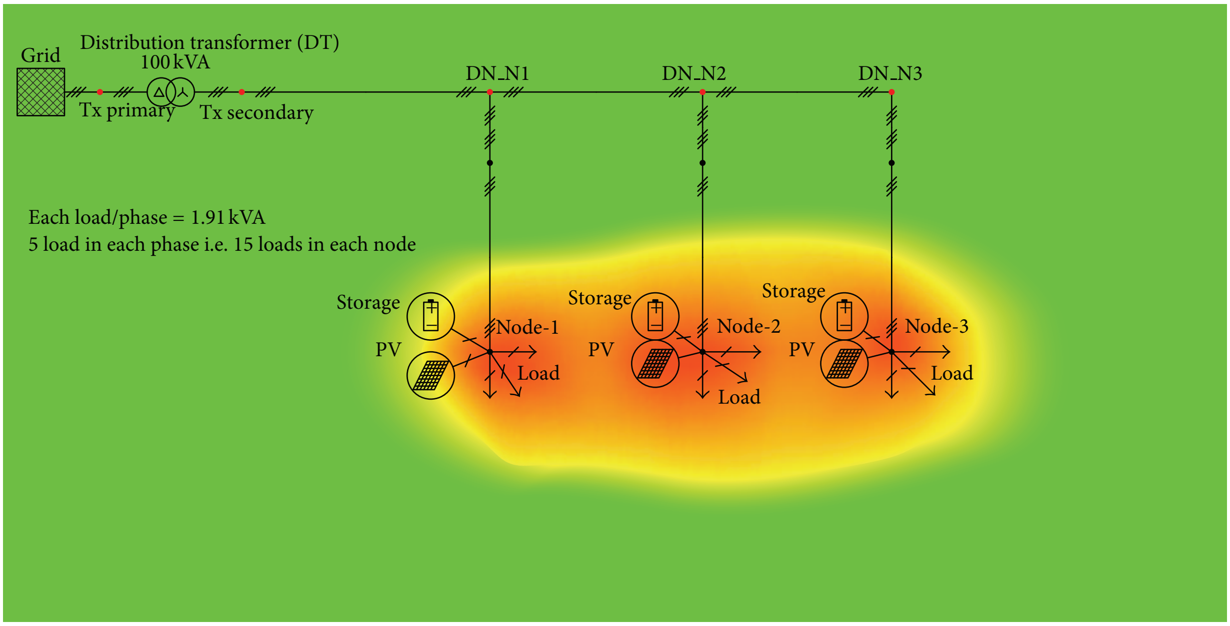

Figure 7: Model scenario: residential load, PV and storage.

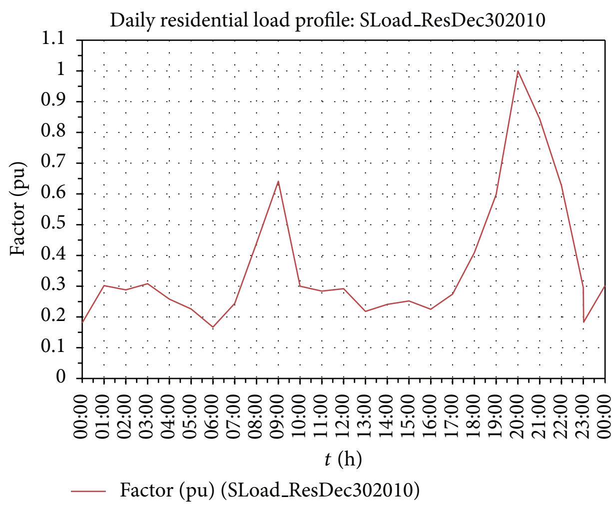

Figure 8: Daily residential Summer load profile in Rockhampton [28].

Table 7: Installed solar PV/house in different nodes.

Node	Phase-1 kW	Phase-1 Number of house	Phase-2 kW	Phase-2 Number of house	Phase-3 kW	Phase-3 Number of house
Node-1	5	5	—	—	—	—
Node-2	—	—	5	5	—	—
Node-3	—	—	—	—	5	5

Table 8: Installed Storage/house in different nodes.

Node	Phase-1 kW	Phase-1 Number of house	Phase-2 kW	Phase-2 Number of house	Phase-3 kW	Phase-3 Number of house
Node-1	1.72	5	—	—	—	—
Node-2	—	—	1.72	5	—	—
Node-3	—	—	—	—	1.72	5

loaded in peak demand time (at 20:00 PM) considering total load and line impedance. Load allocations as shown in Table 6.

Ergon Energy, local distribution network service provider (DNSP) in Rockhampton, Australia allows 4.0 kW capacity PV for each urban house [22]. The output from PV is not available for 24 hours period and residential load demand is lowest when PV generates highest energy and excess energy supplies to the grid eventually increases the voltage at the connected node. In this model, inverter efficiency was considered as 97% and line loss until inverter was considered 5%. For this investigation, it was considered that five houses in node-1 installed 5 kW PV/house in phase-1, similarly 5 houses in node-2 and 5 houses in node-3. It was considered that storage was installed with the same peak capacity of load which is 1.72 kW in each house where solar PV was installed. Tables 7 and 8 shows the installed PV and storage in different nodes.

Based on allocated load, the daily utilization of DT is shown in the Figure 9 and the peak utilization is 87.22% of DT capacity at the time of 20:00 PM.

Solar PV was added to phase-1 in node-1 and summer time solar radiation in Rockhampton was considered. Daily solar radiation data of Rockhampton was collected from [29] and daily profile is as shown in Figure 10. However due to cloud movement energy level received by the PV

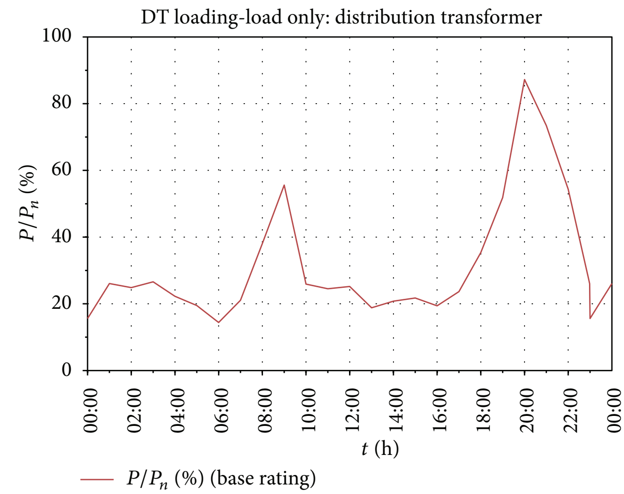

FIGURE 9: Distribution Transformer loading due to load only.

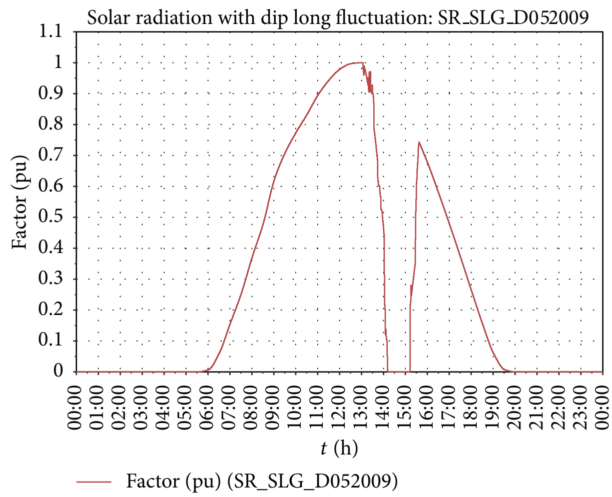

FIGURE 11: Solar radiations with long deep fluctuation.

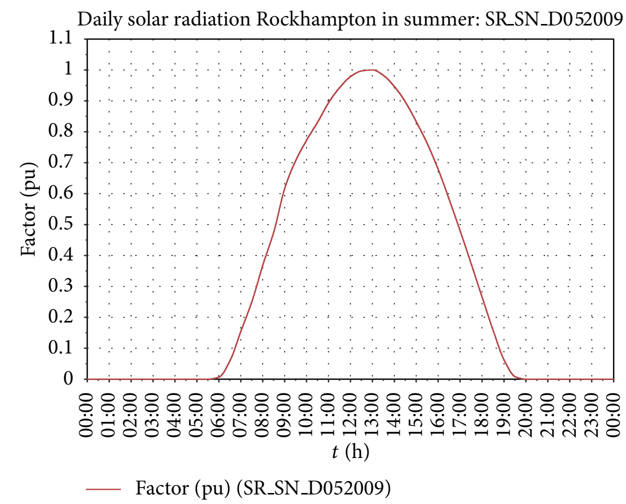

FIGURE 10: Daily solar radiation profile in Rockhampton, Australia.

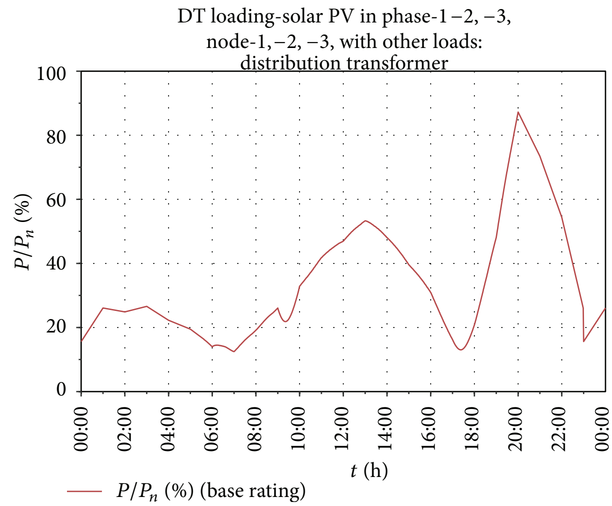

FIGURE 12: Distribution Transformer loading when PV installed in all 3 phases.

array fluctuates. Figure 11 shows the dip fluctuation in solar radiation for long period.

Model was simulated for load flow (LF) and load curve (LC) analysis. LF is an effective tool for calculating the operational behavior of electrical transmission and distribution network. LF calculates current and voltage distribution from generation to the consumer on rated power or voltage at the node elements. LC is a load flow calculations with load values varied over time.

It was found from LC simulation that PV output increases loading on DT during day time (especially at 13:00 PM) when load demand was low and when storage was not integrated with the system. However maximum loading was at 20:00 PM when residential load demand is highest and when PV was not able to support the load therefore maximum load on DT remains 87.22% as shown in Figure 12. After integrating PV in all 3 nodes, PV supports the load in the morning which lowers the DT loading in the morning at 08:00 AM and afternoon at 18:00 PM as shown in Figure 12. However PV increases DT loading during midday (52.06% at 13:00 PM) between 10:00 AM to 16:00PM also peak load on DT in the evening remains same as 87.22%.

After adding storage only in Node-1 and connected to phase-1, storage supports the phase-1 load, although which was not enough compared to the total load on phase-1, therefore it was not reflected on overall DT loading. By adding storage in Node-2 and connecting to phase-2, it was found that maximum/peak loading on DT now reduced to 80.51% moreover midday loading also reduced to ~42% at 13:00 PM. Gradually storage was added in phase-3 in node-3 and found that loading on DT reduced not only during midday but also in peak demand time in the evening. Figure 13 shows the charging and discharging period of storage connected in phase-3 in node-3.

After adding storage in all three phases it was found that maximum or peak time loading reduced to 66.76% as

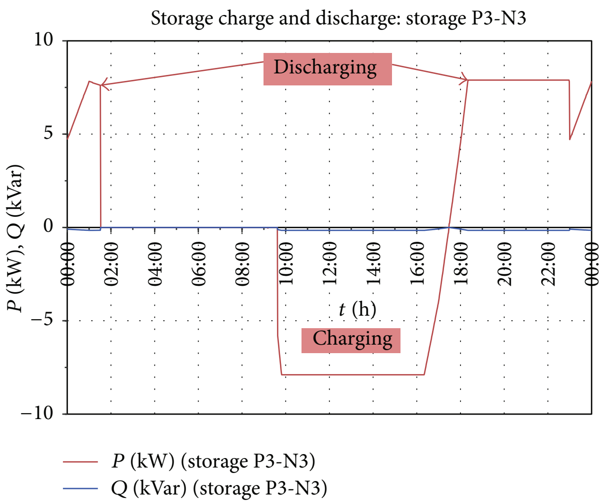

Figure 13: Charging/discharging of storage in node-3.

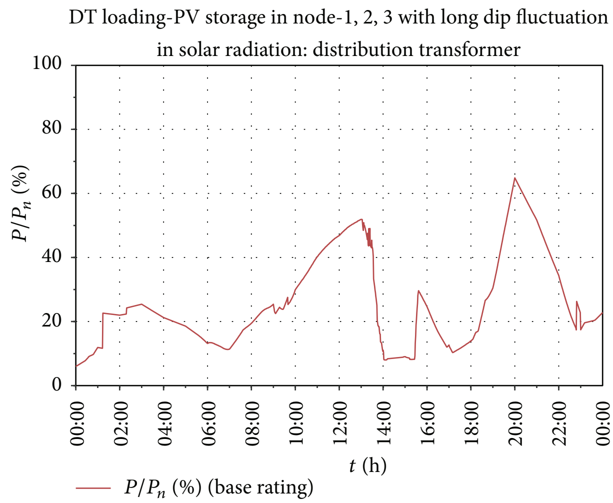

Figure 15: DT loading when PV and storage connected and solar radiation with long deep fluctuation.

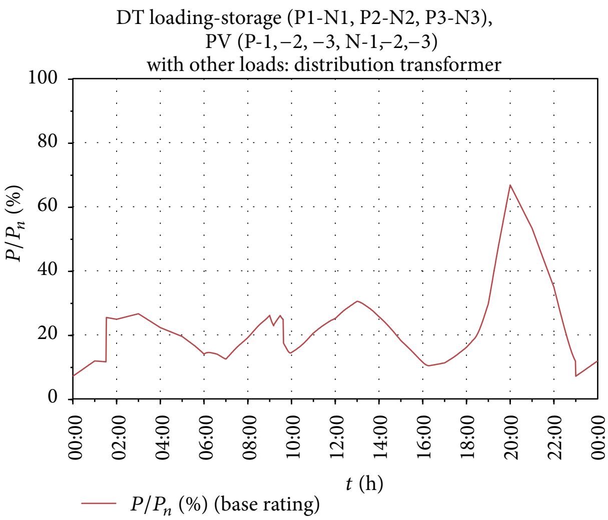

Figure 14: Distribution Transformer loading after adding storage in all 3 phases.

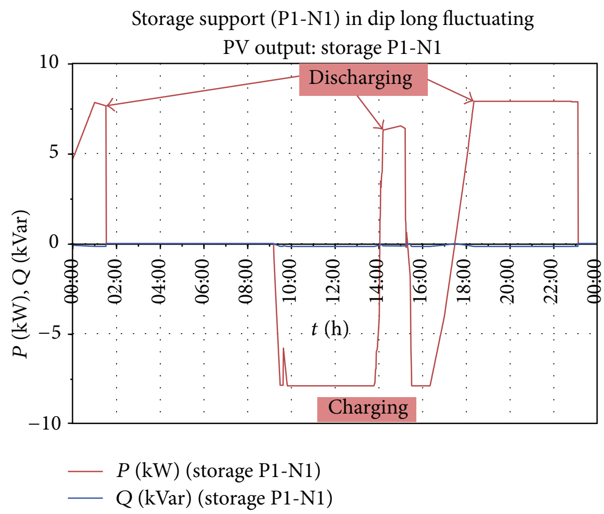

Figure 16: Storage supports load when solar PV output has long deep fluctuation.

shown in Figure 14 which is a great improvement in RE utilization and also reduces the risk of changing/upgrading the existing DT capacity. Moreover storage also reduces the load on DT during day time when residential load demand is low particularly during 10:00 AM to 16:00 PM and during this time maximum loading reduced to ~30% of DT capacity at 13:00 PM.

Cloud movement or various natural conditions could change the solar radiation profile from ideal type to solar radiation with long dip fluctuation as considered for this analysis. PV output also fluctuates due to long dip fluctuations in solar radiation. Due to the fluctuation DT loading also impacted which was supported by storage at 14:00 PM as shown in Figure 15. While the PV output interrupts for long time storage connected in 3 nodes in 3 phases also supports the load (at 14:00 PM) by discharging stored electricity as shown in Figure 16.

Therefore it is evident from this investigation that, storage effectively reduces the load on DT and supports the load when RE generation fluctuates and reaches lower than the load demand.

6.2. Economical and Environmental Benefit of Storage. The adoption of storage with the RE system certainly incurs additional cost to the system however the benefit of adding storage is much greater. The advantage of storage is explained by investigating it's influence in reduction of GHG emission and cost of energy (COE). For this analysis, Alice Springs and Macquarie island were considered the location for solar and wind energy source respectively. A model was developed

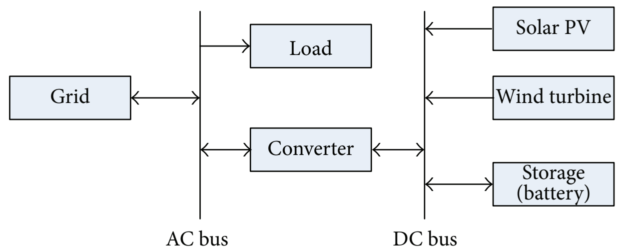

Figure 17: Model Configuration (Grid and Solar/Wind and/or Storage).

Table 9: Technical data and study assumptions.

Description	Cost/information
PV array [31]	
Capital cost	$3100.00/kW
Replacement cost	$3000.00/kW
Operation and maintenance costs	$50.00/year
Life time	25 years
Wind turbine [32]	
Capital cost	$4000.00/kW
Replacement cost	$3000.00/kW
Operation and maintenance costs	$120.00/year
Life time	25 years
Grid electricity [33]	
Off-peak rate (09:00AM–06:00PM, 10:00PM–07:00AM)	$0.30/kWh
Peak rate (07:00AM–09:00AM, 08:00PM–10:00PM)	$0.35/kWh
Super peak rate (06:00PM–08:00PM)	$0.45/kWh
Inverter [34]	
Capital cost	$400.00/kW
Replacement cost	$325.00/kW
Operation and maintenance costs	$25.00/year
Life time	15 years
Storage (battery) [35]	
Capital cost	$170.00/6 V 360 Ah
Replacement cost	$130.00/6 V 360 Ah
System voltage	24 V

using HOMER version 2.68 [30]. Model configuration is as shown in Figure 17. HOMER is the micropower optimization tool and simulates the operation of a system by making energy balance calculation for each of the 8760 hours of a year. Cost considerations are shown in Table 9.

The model was configured in the following five configurations to investigate the overall influence of storage considering the project life time of 25 years.

(i) Configuration 1: Grid only

(ii) Configuration 2: Solar PV with Grid

(iii) Configuration 3: Solar PV and Storage with Grid

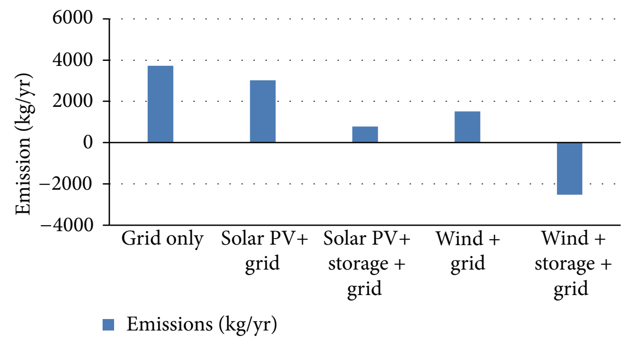

Figure 18: Greenhouse gas (GHG) emission in different configurations.

(iv) Configuration 4: Wind turbine with Grid

(v) Configuration 5: Wind turbine and Storage with Grid.

In all configurations the residential load was considered which is 16 kWh/day or 5840 kWh/year. The costing was considered according to the available market value for each unit. Grid electricity price for Tariff-11 in Queensland is $0.3145/kWh (including GST and service) [36]. The influence of storage was analyzed from the optimized model to evaluate environmental and economical benefits.

The influence of storage in overall performance of the solar PV or wind turbine system was analyzed by evaluating GHG emission from the system and the COE after integrating storage with the system. Optimization result shows that for the residential load of 16 kWh/d in Alice Springs, solar PV generates electricity that reduces GHG emission by 18.69% compared to grid only configuration however after adding battery as storage with the system GHG emission reduces 79.05% compared to grid only configuration as shown in Figure 18. Similarly, Wind turbine in Macquarie Island reduces 59.19% GHG emission for the same load, however after adding storage much more electricity was consumed from wind source and enough electricity was sold back to the grid that GHG emission reduced up to 167.78% compared to grid only configuration as shown in Figure 18.

To support 5840 kWh/yr of residential load in Alice Springs, 1.0 kW PV with 1.0 kW inverter was used in optimized model without battery and only 26% of this load was supported while remaining load was supported by grid therefore overall COE becomes $0.376/kWh. However in storage integrated system for the same load in the same place 3.0 kW PV was used with 2.0 kW inverter and 16 Batteries. This optimized model supports 75.51% of load and storage helps the load for extended period that reduces use of grid electricity and overall COE becomes $0.343/kWh as shown in Figure 19. At system voltage of 24 V this configuration needs 1440 Ah of battery support. In Macquarie Island 1.0 kW wind turbine with 1.0 kW inverter supported 30.21% of load. Although this configuration is without storage and generates much more electricity than required as a result 31.39% generated electricity wasted and overall electricity cost becomes $0.321/kWh. When battery was added to support the same load, optimized model used 2.0 kW wind turbine,

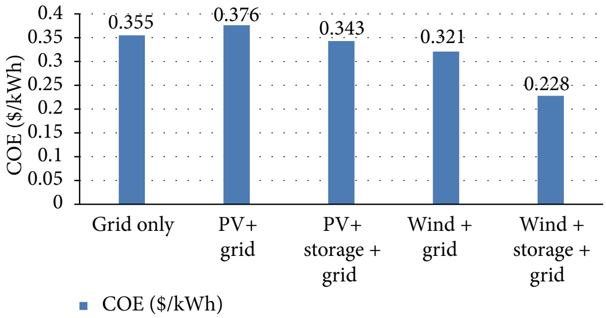

Figure 19: Cost of Energy (COE) in different configurations.

5.0 kW inverter and 12 batteries. This configuration supports 96.42% of load demand and increases grid sales and overall COE becomes $0.228/kWh. To support 96.42% of load this configuration used 1080 Ah battery at 24 V system voltage. Therefore storage has great influence in reducing GHG emission and cost of energy.

7. Conclusions

Australia is one of the best places for solar and wind energy. To meet the target of 2020 to supply 20% electricity to the grid from RE it is essential to identify the potential locations and also to address the required capacity of these systems for a particular type of load profile. As the nature of these RE sources restricts load support for some particular time and this study showed that storage can improve this situation, however proper estimation of these resources is essential. Therefore how much storage is required that assessment is done in this study for different locations in Australia.

By analyzing the solar radiation and wind speed data of 210 locations in Australia it was found that 57.1% of observed locations in Tasmania are very good for wind energy and 44.4% of observed locations in Northern Territory are very good for solar energy. However, 20% & 10% of observed locations in Queensland and 22.8% & 28.6% of observed locations in Western Australia are found very well for solar and wind energy respectively. Estimation was done considering worst month solar and wind data to assess the required PV, wind turbine capacity and storage size. It was found that daily solar window or daily wind window greatly influences in determining the required size of storage or solar and wind turbine capacity. It was found that in Macquarie Island and Weipa where wind and solar window is greater, the required wind turbine and solar PV capacity is small to support the same load compared to the other locations. Similarly, required storage size is small to support the load 24 hours a day. However, to support daily load demand or to manage total energy generated by the renewable sources, storage is essential even where wind speed, solar radiation is strong and duration is also greater. Table 5 provides the details of required storage in various potential locations in Australia.

Advantages of storage were analyzed in two different simulation scenarios. The simulation result showed that storage greatly influences the performances of solar PV or wind system application. Storage reduces load on distribution transformer and support load during fluctuations. Storage improves RE production, increase load support, reduces GHG emission and reduces cost of energy. Therefore to increase the RE participation, properly estimated storage is required in every potential location in Australia.

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