Chapter 4
Energy Storage: Applications and Advantages

Mohammad Taufiqul Arif, Amanullah M. T. Oo and A. B. M. Shawkat Ali

Abstract Energy storage (ES) is a form of media that store some form of energy to be used at a later time. In traditional power system, ES play a relatively minor role, but as the intermittent renewable energy (RE) resources or distributed generators and advanced technologies integrate into the power grid, storage becomes the key enabler of low-carbon, smart power systems for the future. Most RE sources cannot provide steady energy supply and introduce a potential unbalance in energy supply and load demand. ES can buffer sizable portion of energy generated by different intermittent RE sources during low demand time and export it back into the network as required. ES can be utilized in load shifting, energy management and network voltage regulations. It can play a large role in supplementing peaking generation to meet short-period peak load demand. ES technologies are classified considering energy and power density, response time, cost, lifetime and efficiency. Different application requires different types of ES system (ESS). IEEE 1547 and AS 4777 provide guideline to connect RE and storage into the distribution network. Based on the standards, utility operators plan in gradual integration of RE into the grid. Storage can play significant role in reduction in greenhouse gas (GHG) emission by maximizing RE utilization. As the utility operator needs to support costly peak load demand which could be supported by storage and as a consequence, storage can help in energy cost reduction. Although, the present cost of storage considered a barrier for extensive use, however, research is going on for low-cost, high-performance storage system. Therefore, in the low-carbon future power system, ES will play a significant role in increasing

M. T. Arif (✉) · A. M. T. Oo · A. B. M. S. Ali
School of Engineering and Technology, Central Queensland University, Bruce Highway, Rockhampton, QLD 4702, Australia
e-mail: m.arif@cqu.edu.au

A. M. T. Oo
e-mail: a.maungthanoo@cqu.edu.au

A. B. M. S. Ali
e-mail: S.Ali@cqu.edu.au

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grid reliability and enabling smart grid capabilities for sustainable future by balancing RE output.

This chapter explained various energy storage (ES) technologies, their applications, advantages, cost comparison and described integration of storage into the grid. Two case studies are explained in this chapter to illustrate the advantages of ES. First one explained storage advantage in distribution transformer (DT) utilization and fluctuation minimization. Other one explained economical and environmental benefit of ES. Lastly, future direction of ES system (ESS) also explained.

4.1 Introduction

Demand of ESS increased due to the technological development to use with intermittent RE and to support the growing use in electric vehicle (EV). ES can augment generation from renewable distributed energy generators (DEG) such as solar and wind in three ways. Firstly, it can be used for stabilizing purposes by enabling DEGs to run in the acceptable limit and minimizes energy fluctuations. Secondly, proper-sized ES can ride through periods by load shifting when DEGs are unable to generate energy. Thirdly, ES can permit non-dispatchable DEG to operate as a dispatchable unit by supporting timely load demand in network. Large storage lets RE producers to store surplus energy and supply to the grid when load demand goes high and also balances the demand and supply.

In Australia, approximately 10 % of Queensland's electricity network has been built to support only the extreme peak loads [1], similarly other utility operators maintain costly short time generators to support peak load. By integrating proper-sized ES with RE, this peak load demand can be minimized and eventually helps to reduce the cost of energy (COE).

In Queensland, Australia, peak demand generally occurs between 4:00 PM and 8:00 PM, when most householders return home and turn on energy-intensive appliances [1]. Queensland's electricity demand will continue to grow more than 3.5 % per year [1]. Utility operators need to maintain additional facility to support the peak demand. Also during peak demand, RE such as solar and partly wind is not able to generate energy. Therefore, storage is the key enabler to support future load demand especially in peak demand period and to extend the use of RE. There are different ES technologies available and suitable for different applications.

4.2 Different Energy Storage Technologies

Different ES technologies coexist and different characteristics make them suitable for different applications. ES is now seen more as a tool to improve power quality in power systems, assist in power transfer and to enhance system stability. 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. Each ES technology contains a power conversion unit. Two factors characterize the application of ES technology. One is the amount of energy that can be stored and other is the rate of energy transfer to/from the storage devices.

ES technologies can be classified considering energy and power density, response time, cost, lifetime, efficiency or operating constraints. Among different forms of ESS, pumped hydroelectric storage, compressed air energy storage, thermal energy storage, flywheel, hydrogen, different types of batteries, capacitors, superconducting magnetic energy storage are suitable for different types of applications. Different ESSs are explained below.

4.2.1 Battery Energy Storage System (BESS)

Battery is one of the most cost-effective ES technologies available today where energy stored electrochemically [2]. BESS is a modular technology and one of the promising storage technologies for power applications such as regulations, protection, spinning reserve and power factor correction [3]. Batteries are charged/stored energy by internal chemical reaction when potential is applied to the terminal and discharge energy by reverse chemical reaction. Battery stores DC charge, and therefore, converter is required to interface with the AC system.

There are a number of battery technologies under consideration for large-scale application. Lead-acid batteries is an established and mature technology that can be designed for bulk ES or for rapid charge or discharge application. Other battery technologies are nickel-metal hydride (Ni-MH), nickel–cadmium (Ni–Cd), lithium-ion (Li-ion), sodium–sulphur (NaS) and flow battery (FBs). There are three types of FBs: vanadium redox battery (VRB), polysulphide bromide battery (PSB) and zinc bromide battery (ZnBr). Figure 4.1 shows different battery systems.

Lead-acid Lithium-ion Vanadium-Redox

Fig. 4.1 Different battery technology. *Source* http://electrical-engineering-portal.com/wp-content/uploads/lead-acid-battery-construction.jpg, http://www.okta.net/_okta/okta_board_view.asp?idx=1612&flag=world_talk, http://peswiki.com/images/thumb/7/75/VanadiumRedoxBattery.png/333px-VanadiumRedoxBattery.png

BESS can response very fast and cost is comparatively low. Lead-acid battery is suitable for backup power application. Ni–Cd is suitable for peak shaving application and to support during voltage sag. NaS battery has more energy density therefore has longer life and higher round-trip energy efficiency. NaS battery is suitable for energy management and power quality. VRB has fast response and it can be used for load levelling, peak shaving and integrating RE resources. PSB can be used in load levelling, peak shaving and integrating RE resources. PSB batteries particularly useful for frequency response and voltage control. ZnBr batteries are suitable for smoothing out fluctuations, and load management.

Lead-acid battery is sensitive in operating temperature, and best operating temperature is about 27 °C, has depth of discharge (DoD) limit and charge/discharge cycle limit. NaS needs to keep in elevated temperature between 300–350 °C [4]. VRB has lower power density.

The largest lead-acid battery installed in California has a capacity of 10 MW/40 MWh [5]. Largest NaS battery has a rating of 9.6 MW/64 MWh, and largest VRB has a rating of 1.5 MW/1.5 MWh [5].

4.2.2 Superconducting Magnetic Energy Storage (SMES)

It is a device that stores energy in the magnetic field generated by the DC (Direct current) current flowing through a superconducting coil. The inductively stored energy (E in joules) and the rated power (P in watts) are the common specifications of SMES and can be expressed by Eq. (4.1) [2]:

$$E = \frac{1}{2}LI^2 \quad P = \frac{dE}{dt} = \quad LI\frac{dI}{dt} = VI \tag{4.1}$$

where L is the inductance of the coil, I is the DC current flowing through the coil and V is the voltage across the coil. Energy can be drawn from SMES almost as an instantaneous response and can be stored or delivered over periods ranging from a fraction of a second to several hours.

SMES attracted attention due to their fast response and high efficiency (a charge–discharge efficiency over 95 %). Possible applications of SMES include load levelling, voltage stability, dynamic stability, transient stability, frequency regulation, transmission capacity enhancement and power quality improvement [2]. SMES system still costly compared to other ES technologies. It is sensitive to temperature and can become unstable in temperature change.

4.2.3 Super Capacitors Energy Storage (SCES)

Capacitors store accumulated positive or negative electric charges on parallel plates separated by dielectric materials. Capacitance (C) represented by the relationship between stored charge (q) and voltage between plates (V). Capacitance depends on the area of the plates (A), distance between plates (d) and permittivity of the dielectric (ε) as shown in Eq. (4.2) [2].

$$q = CV \quad C = \frac{\varepsilon A}{d} \quad E = \frac{1}{2}CV^2 \tag{4.2}$$

The amount of energy can be increased by increasing capacitance or voltage between the plates. However, voltage depends on the withstand strength of the dielectric, also impacted by the distance between plates. The total voltage change when charging or discharging capacitors is shown in Eq. (4.3) [2] where C_{tot} and R_{tot} are the total capacitance and resistance from a combined series/parallel configuration of capacitor cells to increase total capacitance and total voltage level.

$$\mathrm{d}V = i * \frac{\mathrm{d}t}{C_{\mathrm{tot}}} + i * R_{\mathrm{tot}} \tag{4.3}$$

Capacitors are used in many AC or DC applications. Capacitors are often used as very short-term storage with power converters. Capacitance can be added to the DC bus of motor drives or consumer electronics to provide additional capability to operate during voltage sags and momentary interruptions. DC capacitors are used as large-scale ES on distribution dynamic voltage restorer (DVR) that compensates for temporary voltage sags on the power distribution systems [6]. The disadvantage of capacitor is its low energy density.

Ceramic hyper-capacitors have both fairly high voltage withstand capacity (about 1 kV) and high dielectric strength. Ultra-capacitors are double-layer capacitors that have increased storage capacity and suitable for high peak power, low energy applications. Electrochemical double-layer capacitors (EDLCs) work similar as conventional capacitors but have very high capacitance ratings, long life cycle and better efficiency.

4.2.4 Flywheel Energy Storage (FES)

FES stores energy in a rotatory mass. Flywheel can be used to store energy for power systems when it coupled to an electric machine such as synchronous generator. Stored energy (E) depends on the moment of inertia (J) of the rotor and the square of the rotational velocity (ω) of the flywheel. Moment of inertia depends on the radius (r), mass (m) and length/height (h) of the rotor as shown in Eqs. (4.4) and (4.5) [2]. Figure 4.2 shows a FES application scheme.

$$E = \frac{1}{2}J\omega^2 \tag{4.4}$$

$$J = \frac{r^2 \mathrm{mh}}{2} \tag{4.5}$$

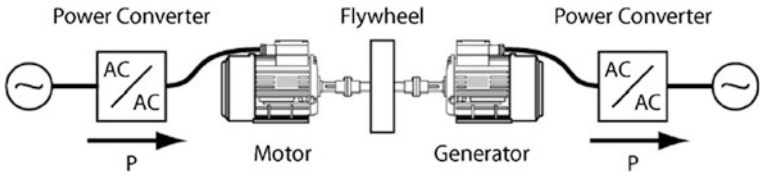


Fig. 4.2 General scheme of flywheel with two machines [7]

FES systems are able to provide very high peak power, high power and energy density and virtually have infinite number of charge–discharge cycles [7]. Flywheel has been considered for numerous power system applications, including power quality, peak shaving and stability enhancement applications and also for transportation applications. It requires cooling and there is power loss during ideal time.

4.2.5 Thermal Energy Storage (TES)

It involves storing energy in a thermal reservoir to use at a later time. TES system suitable for solar thermal power plants consists of synthetic oil or molten salt as heat ES. Heat collected from concentrated solar power plant (CSP) as shown in Fig. 4.3. CSP with TES can store thermal energy for period up to 15 h, thus improve flexibility of the grid and facilitate towards greater penetration of solar energy into the grid. TES can be used to increase reliability of intermittent RE sources.

Other types of TES utilize electricity during off-peak periods and stores energy as hot or cold storage in underground aquifers, in water or ice tanks or to other storage materials and uses this stored energy to reduce peak-time electricity consumption for building heating or air conditioning system.

Fig. 4.3 Concentrated solar power with molten salt as heat storage [8]

4.2.6 Pumped Hydroelectric Storage (PHS)

It is a large-scale ESS that uses potential energy of water developed by the gravitational force by pumping water from a lower reservoir to an upper reservoir during low demand time as shown in Fig. 4.4. During high demand time, water is released back into the lower reservoir through turbine to produce electricity. Low energy density of PHS requires either large water body or greater height variation. PHS provides critical backup during peak demand on the national grid.

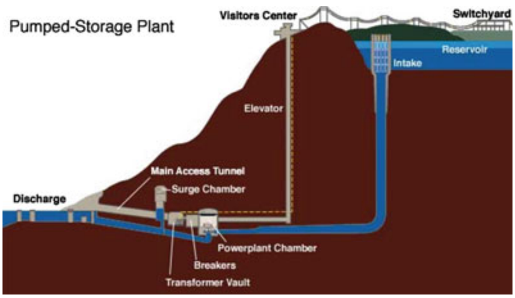
Power capacity (W) of PHS is a function of the water flow rate and the hydraulic head, while the energy stored (Wh) is a function of the reservoir volume and hydraulic head. Power output of a PHS facility can be calculated by Eq. (4.6) [9] and storage capacity of PHS can be calculated by Eq. (4.7) [10]:

$$P_c = \rho g Q H \eta \tag{4.6}$$

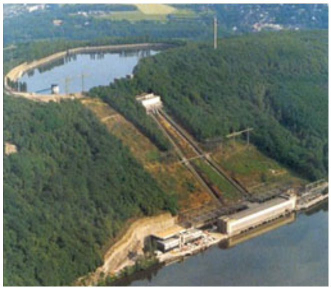
$$S_c = \frac{\rho g H V \eta}{3.6x10^9} \tag{4.7}$$

where P_c is the power capacity in Watts (W), ρ is mass density of water (kg/m^3), g is the gravitational constant (m/s^2), Q is the discharge through the turbines (m^3/s), H is the effective head height (m) and η is the generating efficiency, S_c is the storage capacity in megawatt-hour (MWh), V is the volume of water that is drained and filled each day (m^3).

PHS is the cost-effective large storage system currently available although installation requires specific geographical site. An example of PHS is operated by First Hydro Company in UK [11] and the Dinorwig Power Station is capable of moving from 0- to 1,320-MW power injection in 12 s. This station can inject 1,728 MW for 5 h [12]. PHS has comparatively longer life span and can respond quickly to support demand. It is ideal for load levelling applications. It is also suitable for peak load support and frequency regulation.



Pumped hydroelectric energy storage layout [13]



PHS facility at Alaska [14]

Fig. 4.4 Pumped hydroelectric storage layout and example

4.2.7 Compressed Air Energy Storage (CAES)

CAES stores energy as compressed air for later use. It consists of a power train motor that drives the compressor, a high-pressure turbine (HTP), a low-pressure turbine (LPT) and a generator as shown in Fig. 4.5. Most commercially implemented CAES systems use diabatic storage system to manage heat exchange. CAES uses off-peak electricity to compress air to store and release compressed air to operate gas turbine. Gas turbine uses compressed air with natural gas therefore efficiency improves using CAES compared to the conventional gas turbine system. Commercial systems use natural caverns as air reservoirs and installed commercial system capacity ranges from 35 to 300 MW.

CAES are considered for applications such as electric grid support for load levelling [7], frequency regulation, load following and voltage control. It is dependent on the specific geographical location for underground reservoir therefore installation cost is high.

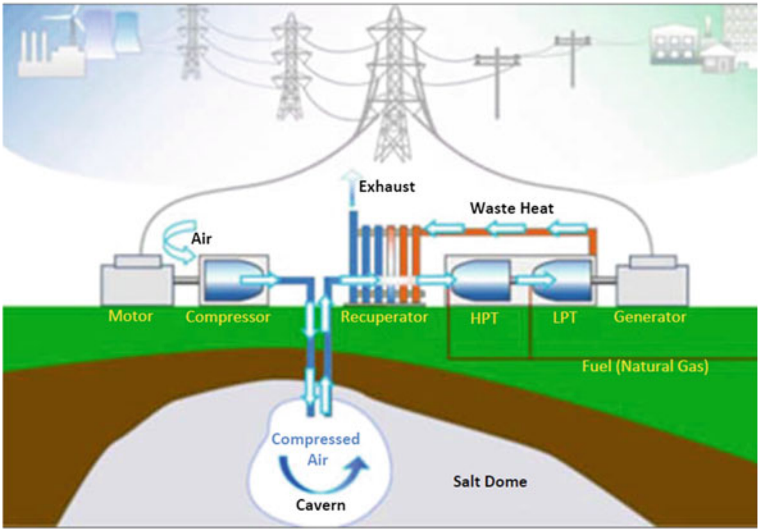


Fig. 4.5 Compressed air energy storage facilities [15]

4.2.8 Hydrogen Energy Storage (HES)

HES differs from the conventional idea of ES, because it uses separate processes for hydrogen production, storage and use. An electrolyzer produces hydrogen and oxygen from water by introducing electric current. A hydrogen fuel cell converts hydrogen and oxygen back into water and release energy. Main drawback of HES is hydrogen is extremely flammable and difficult to store as gas under pressure.

Different strategies of integrating HES with wind and solar energy were proposed in [16].

Fuel cell used stored hydrogen and passed it over the anode (negative) and oxygen over the cathode (positive), causing ions and electrons to form at the anode. The electrons flow through an external circuit that produces electricity while the hydrogen ion passes from the anode to cathode and combines with oxygen to produce water. Figure 4.6 shows the structure of a hydrogen fuel cell.

The characteristics of different ESS described above are summarized in Table 4.1.

In order to support the applications that require combination of high power (for devices with quick response) and high energy (for devices with slow response), hybrid ESS was proposed in different studies [7]. The following section illustrates the applications and benefits of ESS.

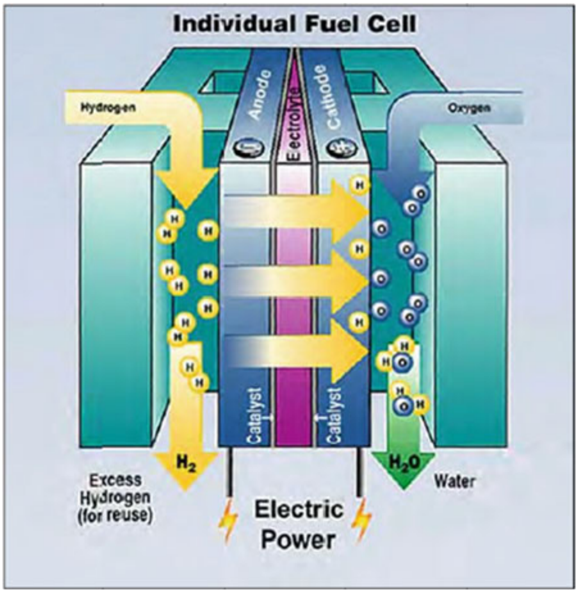


Fig. 4.6 Structure of fuel cell

4.3 Applications of Energy Storage System

ES could bring the revolution in electric power system with RE by supporting peak load problem, improving stability and power quality. Storage can be applied with the generation, transmission, in various point of the distribution system, at the customer site or with any particular appliances. ESS in combination of advanced power electronics applies with the intermittent RE sources provides technical benefit, financial benefit and environmental benefit which are explained below.

Table 4.1 Energy storage system [4, 7, 12, 13, 17, 18]

Type	Energy efficiency (%)	Energy density (Wh/kg)	Power density (W/kg)	Life (cycles or years)	Discharge at rated capacity (h)	Response time (s)	Self-discharge
Pumped hydroelectric	70–80	0.3	–	20–60 years	1–24+	10	Negligible
CAES	40–50	10–30	–	20–40 years	1–24+	360	Low
TES	75	–	–	30 years	–	>10 s of minutes	–
SMES	90	10–75	–	>100,000	2.7×10^{-7}–0.0022	0.01	10–15 %
Flywheel (steel)	85–95	5–30	1,000	>20,000	2.7×10^{-7}–0.25	0.1	Very high
Super capacitor	80–95	2–5	800–2,000	10 years	2.7×10^{-7}–1	0.01	5–20 %
Lead-acid	65–80	20–35	25	200–2,000	0.0027–2+	<1/4 cycle	Low
Ni–Cd	60–90	40–60	140–180	500–2,500	0.0027–2+	<1/4 cycle	0.2–0.3 %
Li-MH	50–80	60–80	220	<3,000			High
Li-ion	70–85	100–200	360	500–10,000	0.017–2+	<1/4 cycle	1–5 %
Li-polymer	70	200	250–1,000	>1,200			Medium
NaS	70–89	120	120	2,000–3,000	0.0027–2+	<1/4 cycle	–
VRB	80–85	25	80–150	>16,000	0.0027–10	<1/4 cycle	Negligible
EDLC	95	<50	4,000	>50,000			Very high
Hydrogen	50	100–150	–	–	–	360	Low
Fuel cell	–	–	–	>1,000	0.0027–24+	<1/4 cycle	–

4.3.1 Technical Benefit of ESS

ESS can improve performance of the application suitable for eclectic utility and transport system such as EV. The main advantage of the ESS is to maintain the grid power in constant level [17] by contributing in the following ways.

- *Grid voltage support*:

It means power provided by the ESS to the grid to maintain acceptable grid voltage range especially when RE is integrated.

- *Grid frequency support*:

It means real power provided by the ESS to the grid to reduce any sudden large generation imbalance and to keep the grid frequency within allowable limit. Storage plays significant role in minimizing high-frequency power fluctuations [18].

- *Transient stability*:

ESS reduces power oscillation by injecting or absorbing real power.

- *Load levelling or peak shaving*:

Storing electricity during low demand time and supply it during peak demand time are termed as load levelling as shown in Fig. 4.7. ESS provides freedom in load levelling. Peak shaving moves peak demand into off-peak period.

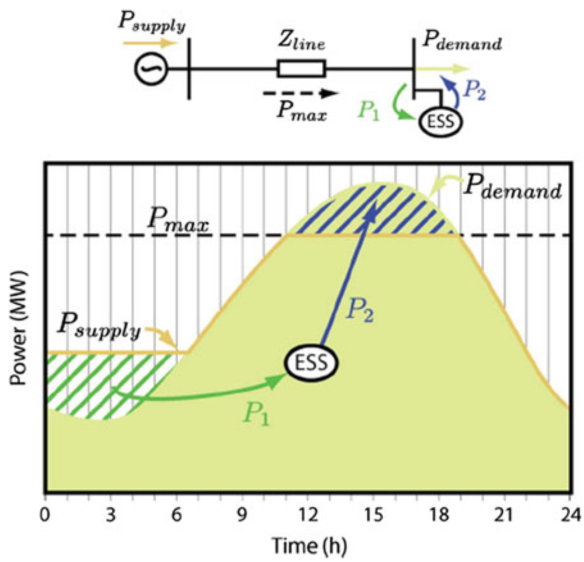


Fig. 4.7 Basic concept of load levelling using ESS [7]

- *Spinning reserve*:

It is defined as the amount of generation capacity that can be used to produce active power over a given period of time.

- *Power quality improvement*:

It is basically the change in magnitude or shape in voltage or current which includes harmonics, power factor, transients, flicker, sag, swell and ESS can mitigate these problems.

- *Reliability*:

It is the percentage or ratio of interruption in electric power delivery to the consumer during total uptime. ESS can reduce the interruption and improve reliability.

- *Ride through support*:

It means electric load stays connected during system disturbance such as voltage sag or momentary blackout. ESS provides support by providing necessary energy to ride through.

- *Unbalanced load compensation*:

ESS can inject or absorb power to/from individual single-phase unbalanced loads. ESS needs to be connected with 4-wire inverter to support in this situation.

- *Increasing penetration of RE sources*:

The intermittent characteristics of solar and wind energy causes fluctuation in voltage and frequency which poses a great barrier in large-scale integration of this fastest-growing RE sources. Moreover, unbalance is demand and supply becomes eminent due to the nature of solar and wind energy generation. Investigation showed that for every 10 % of wind energy penetration into the grid, a 2–4 % of installed wind capacity of balancing power is required from other source for stable operation [7], this is also critical for solar PV integration. ES acts as a buffer that isolates the grid from the frequent and rapid power fluctuations by high penetration of renewable resources [19]. Storage improves the grid penetration of PV energy [20]. A large ESS allows high penetration of wind and solar PV into the grid [12, 21–24].

4.3.2 Financial Benefit of ESS

Although integration of ESS incurs additional cost, however, there are various financial benefits as explained below:

- *Cost reduction*:

Electricity can be purchased during low demand time to store and use it during high demand time, so the overall total consumption cost is reduced. Moreover, stored electricity can be sold during high demand time. Electricity from RE can be used in similar fashion to reduce total consumed energy cost.

- *Avoiding additional cost in generation*:

ESS can help in avoiding installation or renting cost of additional generation to support peak load demand.

- *Avoiding additional cost in transmission/distribution*:

ESS can improve the transmission and distribution performance by operating utilities with its capacity and avoids additional cost of installation to support peak load. Moreover, transmission access/congestion cost can be avoided by the use of ESS.

- *Reduce reliability and power quality–related financial loss*:

ESS helps to improve power quality by supporting loads during outage, sag, and flickering that improves the reliability and that reduces penalty cost of the utility operators.

- *Increases revenue from RE generation*:

ESS helps in time shift in load demand by storing electricity from RE generators and supplying when needed. This ensures maximum utilization of RE.

4.3.3 Environmental Benefit of ESS

- *Reduction in GHG emission*:

ESS helps in best utilization of RE which also reduces the use of conventional energy source and therefore reduces GHG emission [24].

Therefore, ES technology can play a significant role in maintaining power quality and system reliability [2]. 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 [2]. The technical advantages of different ESS are summarized in Table 4.2.

Proper utilization of ESS depends on various cost involvement with different applications. Cost is one of the key indexes in proper choice of ESS.

Table 4.2 Applications of different energy storage technologies [17, 25]

Energy storage applications	Pumped hydroelectric	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	√	√		√	√				√

4.4 Cost of Energy Storage System

Selection of suitable ESS is determined by the criteria includes lifetime, life cycle, power and energy, self-discharge rate, environmental impact, efficiency, capital cost, storage duration and technical maturity of the storage system. Present cost of storage is considered the major barrier for large-scale utilization. The operational cost (maintenance, loss during operation and ageing) and capital investment cost are the most important factors to select the suitable ESS. Efficiency and lifetime also affect on the overall cost of the ESS. Table 4.3 summarizes the power- or energy-related cost of various ESS.

Per cycle cost of ESS is 5–80 c/kWh for VRB, 8–20 c/kWh for NaS, 20–100 c/kWh for NiCd and 20–100 c/kWh for lead-acid battery [26].

Table 4.3 Cost of various ESS

Storage technology	Power-related cost ($/kW) [25]	Energy-related cost ($/kWh) [25]	Power capacity cost ($/kW) [4]	Storage cost rank
Pumped hydroelectric	600–2,000	0–20	5–100	Low [13, 26]
CAES	425–480	3–10	2–50	Low [26]
Lead-acid battery	200–580	175–250	50–400	Low [13, 26]]
Ni–Cd battery	600–1,500	500–1,500	400–2,400	High [13, 26]]
NaS battery	259–810	245	300–500	Medium
Li-ion battery	–	900–1,300[13]	600–2,500	High [26]
Vanadium redox	1,250–1,800	175–1,000	150–1,000	Medium
ZnBr	640–1,500	200–400	150–1,000	Medium
High-speed flywheel	350	500–25,000	300–25,000	High [13]
Super capacitors	300	20,000–82,000	300–2,000	High [13, 23]
Fuel cell (hydrogen)	1,100–2,600	2–15	425–725	Low
SMES	300	2,000	1,000–10,000	High [12, 26]

4.5 Classification of Energy Storage

ES will play unique role in future smart grid development by combining different RE sources capability into the grid. Storage can buffer the power spikes and dips and fluctuations [18]. Highest-valued applications of storage identified by EPRI [27] are to maintain commercial and industrial power quality and reliability, to enable stationary and transportable system for grid support.

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

- *Power Quality*: Stored energy applied only for seconds or less to ensure continuity of power quality.
- *Bridging power*: Stored energy applied for seconds to minutes to assure continuity of service when switching from one source of energy to another.

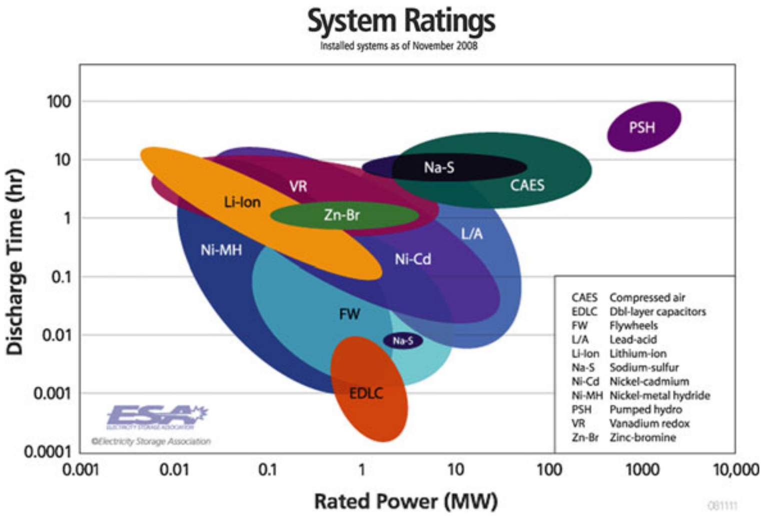


Fig. 4.8 Ratings of different storage systems [28]

- *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 uses in peak time which enables consumers to minimize the total energy cost.

ESS has a number of applications in electrical power systems, especially integrating intermittent RE into the grid. Integration of ESS into the grid is briefly explained in Sect. 4.6. ESS can be classified according to capacity, discharge time,

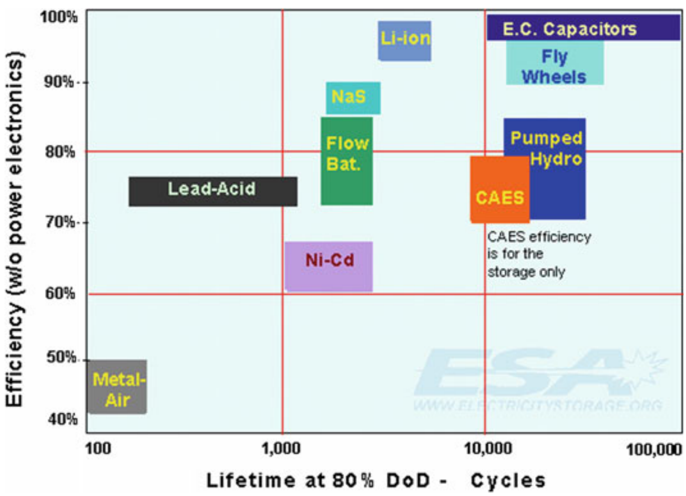


Fig. 4.9 Efficiency and lifetime of each storage technology (at 80 % DoD) [28]

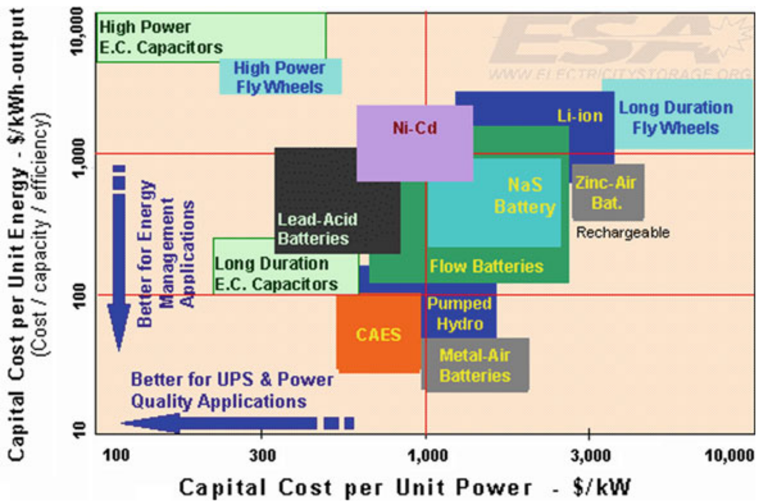


Fig. 4.10 Capital COE storage technology [28]

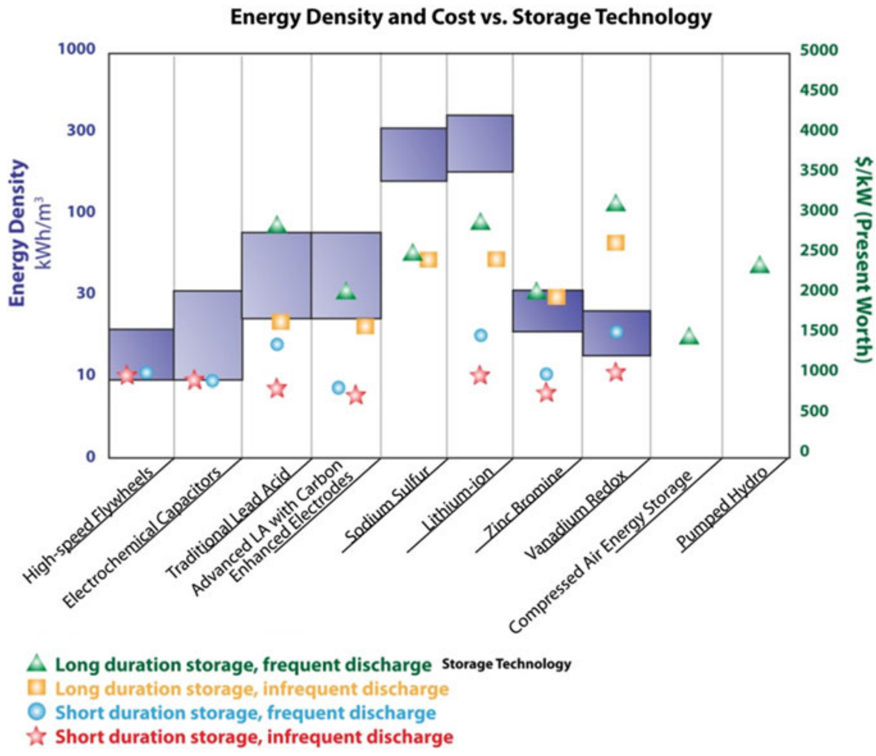


Fig. 4.11 Storage technology and cost comparison [28]

efficiency and capital cost as shown in Figs. 4.8, 4.9 and 4.10. The cost of storage technologies is decreasing as they mature. Figure 4.10 shows the COE based on 2002 value. Figure 4.11 shows the comparison of storage technology to the cost as a function of application.

4.6 Integration of Energy Storage into the Power Network

The main objectives of introducing ESS to the power utility are to improve system load factor, peak shaving, to provide system reserve, achieve reliability and effectively minimize energy production cost. Some ESSs like BESS, EDLC, SMES, FESS and FC require power converter to connect between two different DC voltage level buses, a DC voltage bus and an AC voltage bus or even connect a current source to a voltage bus [7]. Power converter with ESS should have the following features:

- To manage the energy flow in bidirectional way and controlling the charging and discharging process of ESS
- To have high efficiency
- To provide fast response (frequency regulation applications)
- To stand with high peak power (peak shaving application)
- To manage high-rated power (load levelling application)

ESS with flexible AC transmission systems (FACTS) devices adds flexibility to achieve improved transmission system by improving system reliability, dynamic stability, power quality, transmission capacity and also by supporting active and reactive power[2, 29].

There is no concrete standard developed yet for integrating bulk and large storage integration into the grid. However, IEEE 1547-2003 [30] provides guideline to connect distributed resources (DR) such as solar PV, wind and ES to the power grid at the distribution level. AS 4777 [31] provides guideline to connect RE and storage to the distribution network (DN) via inverters up to 10 kVA for single-phase unit and 30 kVA for three-phase unit.

While integrating ESS into the grid, role of ESS is explained in Sect. 4.7.

4.7 Role of Energy Storage: Case Studies

Energy fluctuation collapses the smooth operation of load demand, and storage supports the load by minimizing the fluctuation level. Integration of fluctuating RE into the large flexible grid may not have significant impact; however, if the penetration of fluctuating RE continues to grow, at some point, flexibility of present grid may be fully tapped [32]. Again during best weather condition when RE provides maximum output and during peak time when demand reaches very high, that could potentially breaches the limit of DT capacity and may need to upgrade the costly network capacity. Storage can support the peak load demand and can reduce the load on DT which helps in reducing the overall cost of consumed energy. Storage helps in maximizing the use of RE which eventually helps in reducing greenhouse gas (GHG) emission. Two case studies below show how storage can play role in these regards.

4.7.1 Case Study 1: Storage Role on DT Loading and Minimizing Fluctuations

The case study describes the storage role on DT loading considering residential load. It was also considered that roof-top solar PV was connected to the DN and total load appears on the secondary side of DT.

In order to investigate the storage role, a model was developed in PSS SINCAL as shown in Fig. 4.12. In this model, it was considered that 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 [33] or 1.91 kVA considering power factor of 0.9. It was also considered that 5 such houses connected in each phase in each node with same load for each case. Therefore, 15 houses are connected in

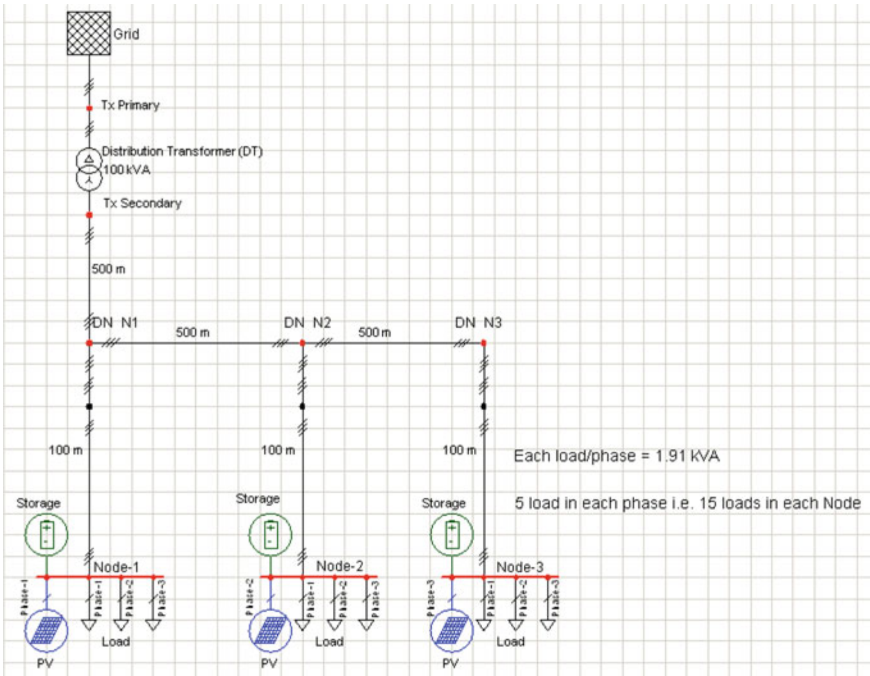


Fig. 4.12 Model scenario

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 rooftop 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 Fig. 4.12. All 3 nodes are considered 500 m apart from each other.

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 [1]. Daily household load profile is based on the working nature of the residents and the average load pattern as shown in Fig. 4.13.

Urban area load with DT (11 kV/415 V) capacity of 100 kVA was considered in this model. Due to total load and line impedance, DT was 87.22 % loaded in peak demand time (at 20:00 PM) in load-only configuration of the model. Load allocations are shown in Table 4.4.

Daily average residential load and solar radiation in Rockhampton was considered in selecting required PV capacity. Ergon Energy, local distribution network service provider (DNSP) in Rockhampton, Australia, allows 4-kW-capacity PV for each urban area house [34]. The output from PV is not available for 24-h 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 Australia, yearly average sunlight hours vary from 5 to 10 h/day and maximum area is over 8 h/day [35]. In this model, inverter efficiency was considered as 97 % and loss until inverter was considered 5 %. For this

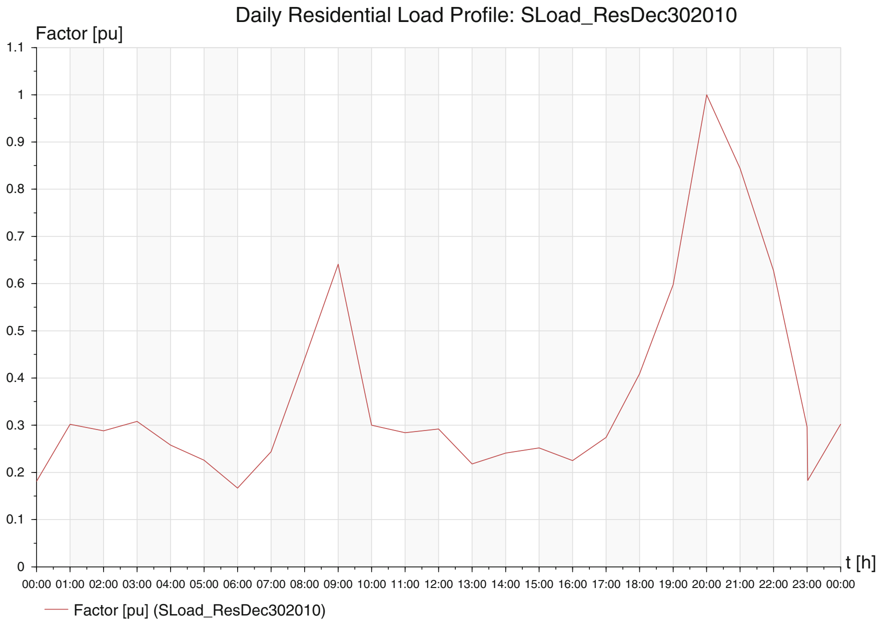


Fig. 4.13 Daily residential summer load profile in Rockhampton [24]

Table 4.4 Load allocation in three nodes

Node	Phase 1		Phase 2		Phase 3	
	kVA	cos φ	kVA	cos φ	kVA	cos φ
Node 1, 2, 3	9.55	0.9	9.55	0.9	9.55	0.9

Table 4.5 Installed solar PV in different nodes

Node	Phase 1		Phase 2		Phase 3	
	kW	No of house	kW	No of house	kW	No of house
Node 1	5	5	–	–	–	–
Node 2	–	–	5	5	–	–
Node 3	–	–	–	–	5	5

Table 4.6 Installed storage in different nodes

Node	Phase 1		Phase 2		Phase 3	
	kW	No of house	kW	No of house	kW	No of house
Node 1	1.72	5	–	–	–	–
Node 2	–	–	1.72	5	–	–
Node 3	–	–	–	–	1.72	5

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 also 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 4.5 and 4.6 show the installed PV and storage in different nodes.

Daily utilization of DT in supporting the allocated load is shown in the Fig. 4.14, and the peak utilization was found 87.22 % of DT capacity at the time of 20:00 PM.

It was explained earlier that solar PV was added to phase-1 in node-1 and summertime solar radiation in Rockhampton was considered for the analysis. Daily solar radiation data of Rockhampton was collected from [35] and daily profile is as shown in Fig. 4.15. However, due to cloud movement, energy level received by the PV array fluctuates and fluctuation varies with the variation of cloud movement. Figure 4.16 shows the dip fluctuation in solar radiation for a long period.

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

It was found from LC simulation that PV increases the DT loading during peak generation 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

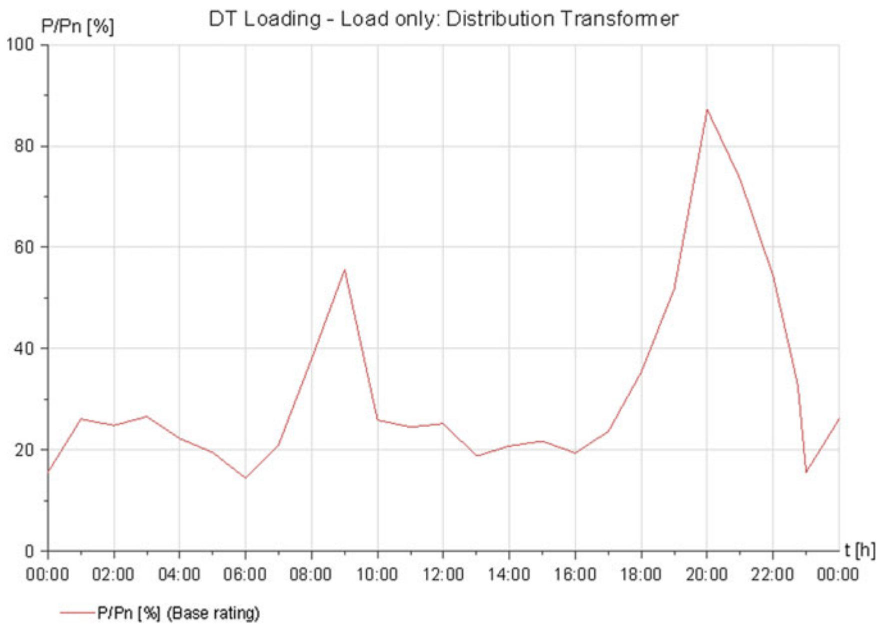


Fig. 4.14 DT loading due to load only

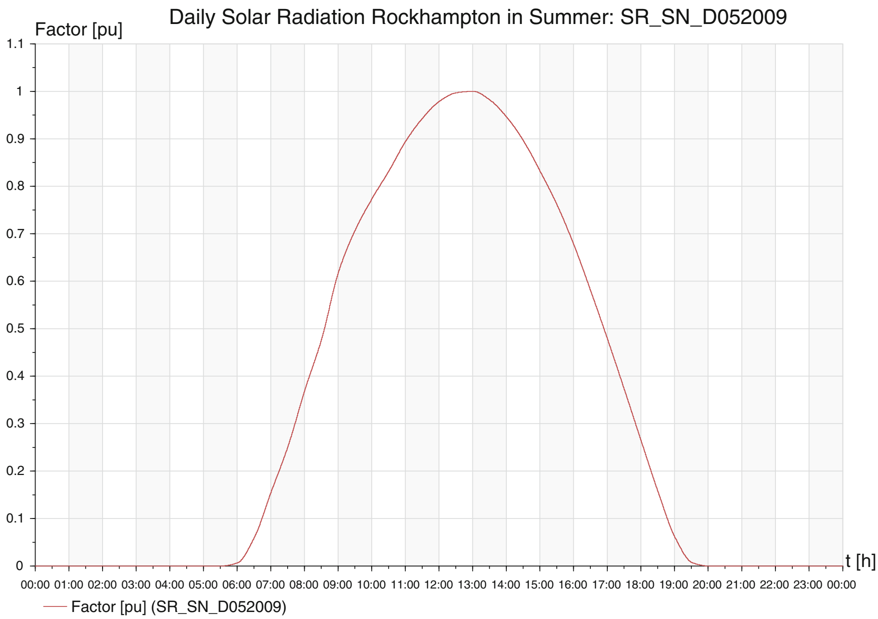


Fig. 4.15 Daily solar radiation profile of Rockhampton, Australia

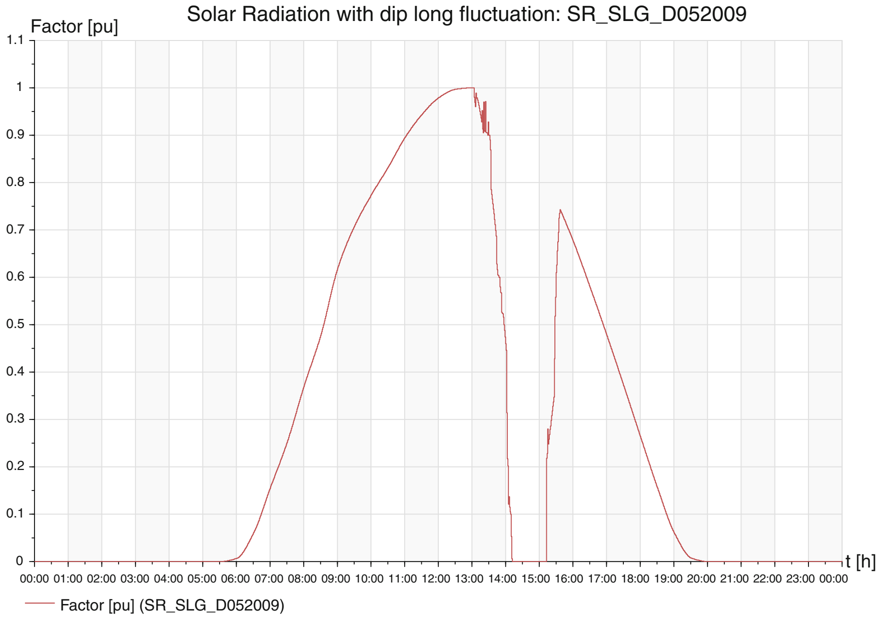


Fig. 4.16 Solar radiations with long dip fluctuation

support the load, therefore maximum load on DT remains 87.22 % as shown in Fig. 4.17. After integrating PV in all 3 nodes, three phases in 3 nodes become balanced in loading and support 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 Fig. 4.17. However, PV increases DT loading during midday (52.06 % at 13:00 PM) from 10:00 AM to 16:00 PM and also peak load in the evening remains same as 87.22 %.

When storage was integrated only in node-1 and connected to phase-1, storage supported 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 4.18 shows the charging and discharging period of storage connected in phase-3 in node-3.

After integrating storage in all three phases, it was found that peak-time loading reduced to 66.76 % as depicted in Fig. 4.19 which is a great improvement in RE utilization and also reduced the risk of upgrading the DT capacity. Moreover, storage also reduced the load on DT during day time when residential load demand was 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.

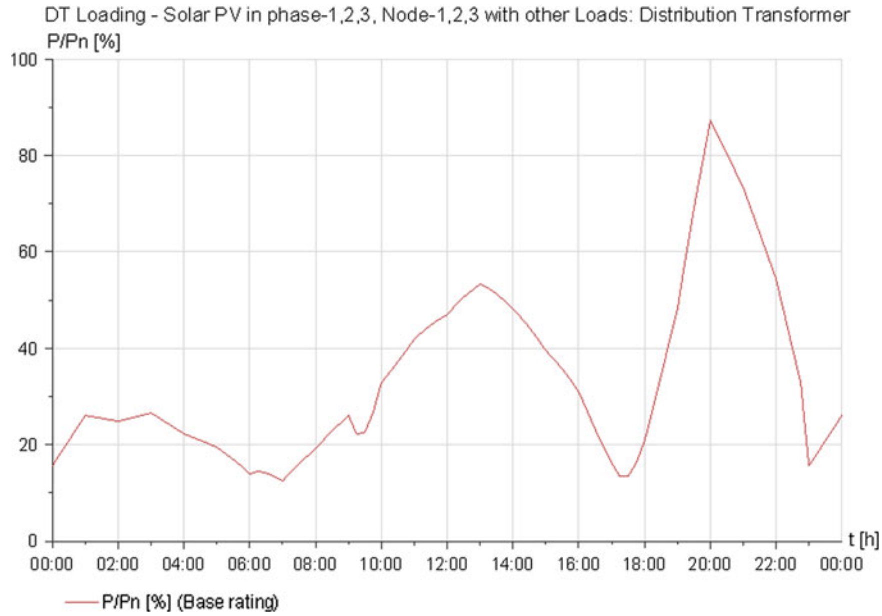


Fig. 4.17 DT loading when PV installed in all 3 phases

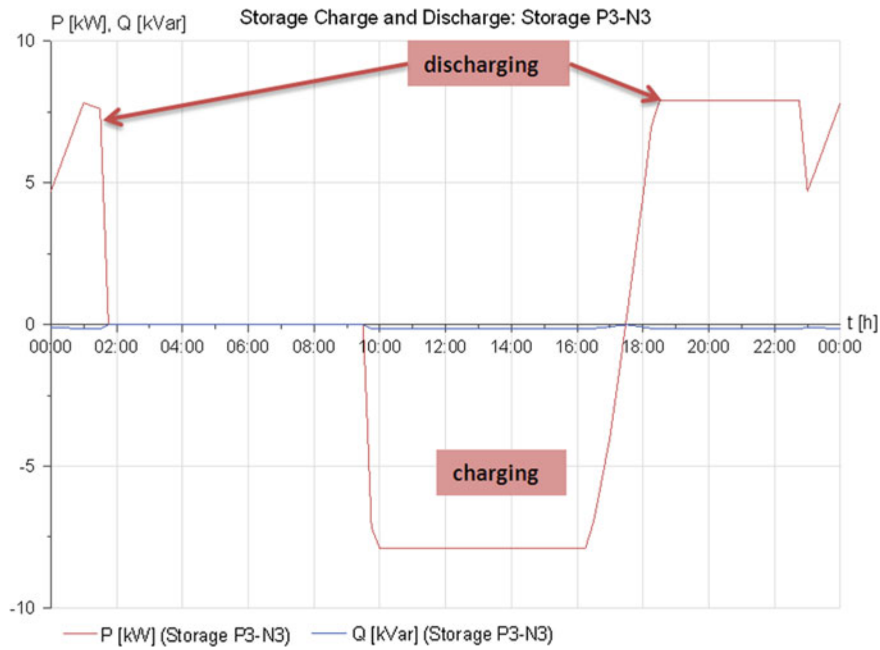


Fig. 4.18 Charging/discharging of storage in node-3

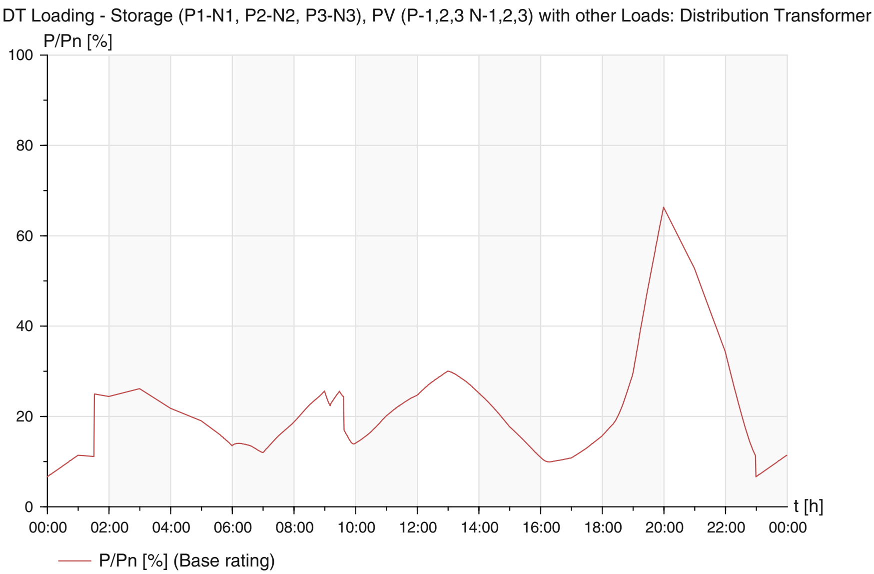


Fig. 4.19 DT loading after adding storage in all 3 phases

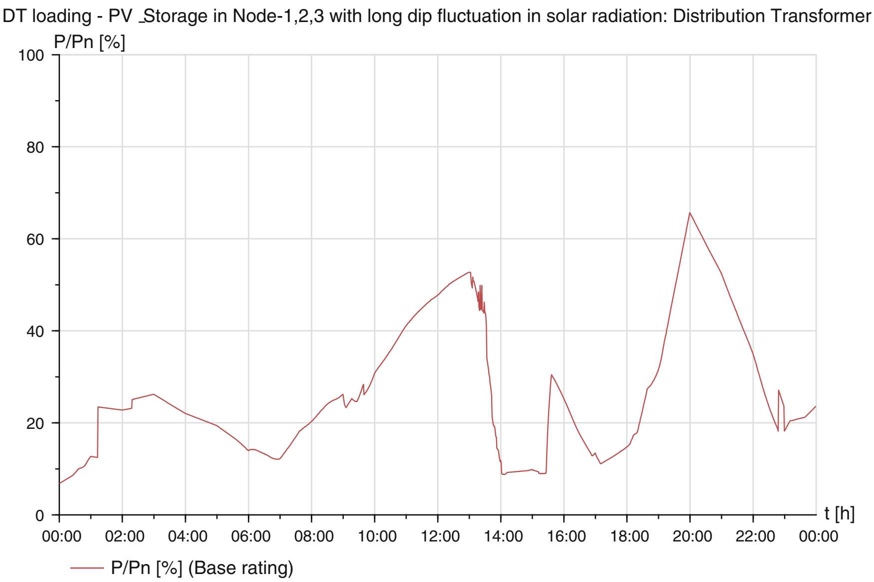


Fig. 4.20 DT loading when PV and storage connected and solar radiation with long dip fluctuation

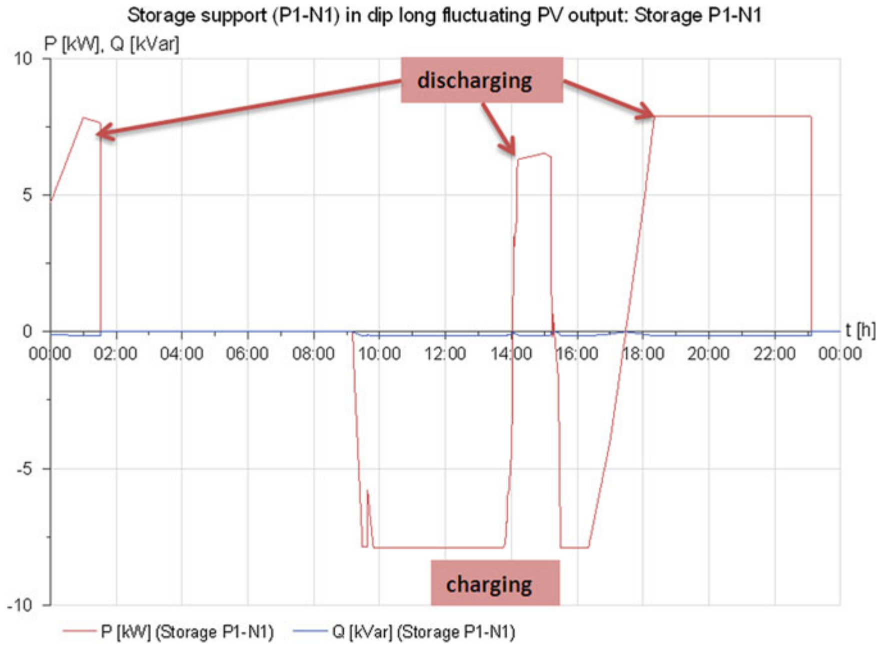


Fig. 4.21 Storage supports load when solar PV output has long dip fluctuation

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, and load demand was supported by storage at 14:00 PM as shown in Fig. 4.20. While the PV output interrupts for a 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 Fig. 4.21.

Therefore, this investigation clearly illustrated that storage effectively reduced the load on DT and supported the load when RE generation fluctuates and reaches lower than the load demand.

4.7.2 Case Study 2: Economical and Environmental Benefit of Using Energy Storage

This study identified the storage role on overall COE and greenhouse gas (GHG) emission reduction considering residential load in Australia.

In order to investigate the economic and environmental role of storage, a model was developed in HOMER version 2.68 [36] considering solar and wind data of two potential locations in Australia. Integration of ES certainly incurs additional cost to the system; however, study showed that storage increases RE utilization,

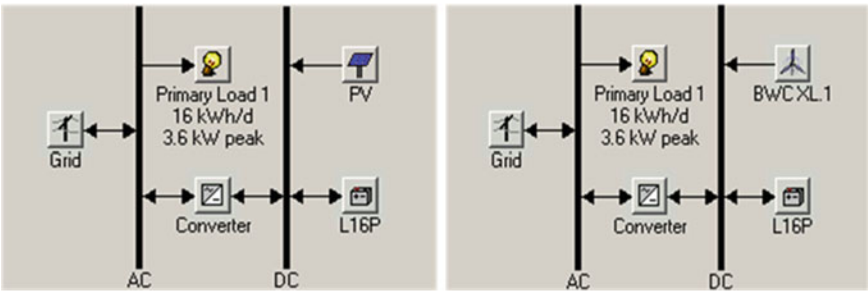


Fig. 4.22 Model configurations (Grid-Solar-Storage and Grid-Wind-Storage)

reduces COE and reduces GHG emission [37]. Residential load was considered for this analysis, and daily load profile is shown in Fig. 4.13. Model configuration is shown in Fig. 4.22. The costing of all required components was considered according to the available market price of each unit. Grid electricity price for Tariff-11 in Queensland is $0.3145/kWh (including GST and service) [38]. According to the load demand, grid electricity cost was considered for off-peak, peak and super-peak period. Element cost and supporting considerations of the required components are shown in Table 4.7.

Table 4.7 Technical data and study assumptions

Description	Cost/information
PV array [39]	
Capital cost	$3,100.00/kW
Replacement cost	$3,000.00/kW
Operation and maintenance cost	$50.00/year
Lifetime	25 years
Wind turbine [40]	
Capital cost	$4,000.00/kW
Replacement cost	$3,000.00/kW
Operation and maintenance cost	$120.00/year
Lifetime	25 years
Grid electricity [41]	
Off-peak rate (09:00 AM–06:00 PM, 10:00 PM–07:00 AM)	$0.30/kWh
Peak rate (07:00 AM–09:00 AM, 08:00 PM–10:00 PM)	$0.35/kWh
Super-peak rate (06:00 PM–08:00 PM)	$0.45/kWh
Inverter [42]	
Capital cost	$400.00/kW
Replacement cost	$325.00/kW
Operation and maintenance cost	$25.00/year
Lifetime	15 years
Storage (battery) [43]	
Capital cost	$170.00/6 V 360 Ah
Replacement cost	$130.00/6 V 360 Ah
System voltage	24 V

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

- Case 1: Grid only
- Case 2: Solar PV with Grid
- Case 3: Solar PV and Storage with Grid
- Case 4: Wind turbine with Grid
- Case 5: Wind turbine and Storage with Grid

For all five cases, the residential load was considered 16 kWh/day or 5,840 kWh/year. The influence of ES in overall performance of the solar PV or wind turbine system was analysed by evaluating GHG emission and the COE of the present system (Case-1) and after integrating storage with the solar PV or wind turbine integrated system. Australia is one of the best places in the world for solar and wind energy, and Alice Springs is one potential location in Queensland for solar energy where as Macquarie island in Tasmania has great potential for wind energy [24]. Optimization result showed that for a residential load of 16 kWh/d in Alice Springs solar PV generates electricity that reduces GHG emission by 18.69 % (Case-2). However, after adding battery as storage with the system, GHG emission reduces 79.05 % (Case-3). This significant reduction in GHG emission achieved as storage increased the use of RE, and without storage, this energy was wasted and load demand was supported by conventional sources. Similarly Wind turbine in Macquarie Island reduces 59.19 % GHG emission (Case-4) 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 % in Case-5. Figure 4.23 shows the total GHG emission to support the residential load in five case configurations.

Optimization results showed that to support 5,840 kWh/year of residential load in Alice Springs, 1-kW PV with 1-kW inverter was used (Case-2) without battery and only 26 % of this load was supported by PV while remaining load was supported by the grid; therefore, overall COE becomes $0.376/kWh. However, in storage-integrated system (case-3) for the same load at the same place, 3-kW PV was used with 2-kW inverter and 16 batteries. This optimized model supports

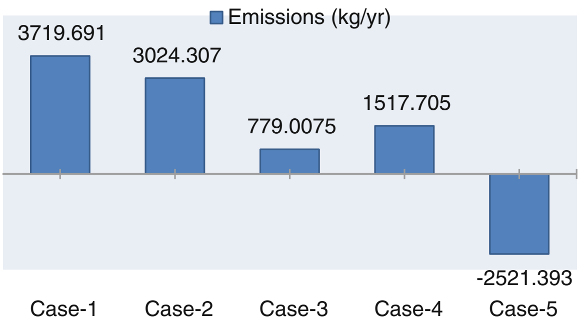


Fig. 4.23 Greenhouse gas (GHG) emission in different configurations

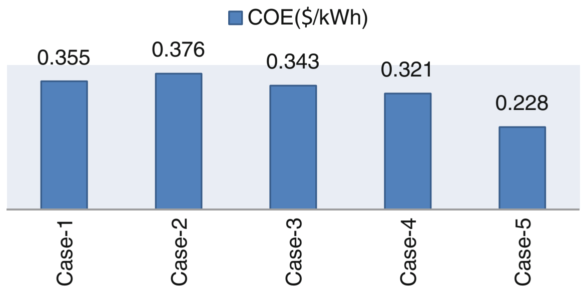


Fig. 4.24 COE in different configurations

75.51 % of load and storage supports the load for extended period that reduces use of grid electricity and overall COE becomes $0.343/kWh as shown in Fig. 4.24. At DC system voltage of 24 V, this configuration needs 1440 Ah of battery support. In Macquarie Island, 1-kW wind turbine with 1-kW inverter supports 30.21 % of load (Case-4) without storage and generates much more electricity than required; as a result, 31.39 % generated electricity was wasted and overall electricity cost becomes $0.321/kWh. When battery was added to support, optimized model used 2-kW wind turbine, 5-kW inverter and 12 batteries. This configuration supports 96.42 % of load demand and increased electricity export to grid and overall COE becomes $0.228/kWh. To support 96.42 % of load, this configuration used 1,080-Ah battery at 24-V system voltage.

Therefore, storage has strong influence in greater utilization of RE and that reduces GHG emission and COE.

4.8 Future of Energy Storage and Conclusions

Although there are currently few installations of large-scale ES exists, the potential of ESS and advantages with various applications have been noted in different research findings. Future use of ES is concentrating mostly with stationary energy and transport sector. Research forecasted utility ES market will grow from $329 million in 2008 to approximately $4.1 billion in 10 years [44]. Cost of ES is considered the main barrier for wider use [32]. Research is going on for efficient, cost-effective storage for grid integration [45]. The importance of ES has been evaluated by forming working group to develop standard IEEE P2030.2 for the interoperability of ESS integration with the electric power infrastructure [46]. Advantages of ES already proved its potential in utility and transport sectors.

This chapter described various storage systems and their characteristics that show their potential to be used in various power quality application, load levelling, load shifting, transmission/distribution system stabilization and RE integration application. This chapter also showed the cost comparison among different storage systems. Case studies showed that storage significantly improves the capability of DT by reducing loading on it which eventually reduces the risk of upgrading DT and transmission/distribution capacity. Storage reduces fluctuations generated by RE and support the load during fluctuation. Other case study showed that storage plays key role in more RE utilization which eventually reduces overall COE. Storage helps in RE utilization that reduces consumption of grid electricity from conventional sources (e.g., coal) which ensures reduction in GHG emission. Research is going on for cost-effective large storage, and investment is increasing in storage market. Therefore, it is likely that storage will play the key role in future power network applications.

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