University Of Southern Queensland

Faculty of Health, Engineering and Sciences

Improving Electricity Network Utilisation with Distributed Energy Storage Systems

A dissertation submitted by

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Abstract

Network capacity utilisation is the ratio of the average energy demand to the installed capacity required to meet peak demand. Network capacity utilisation is one of the biggest problems faced by network operators in Australia and around the world. As a response to high peak demands, network operators expand the generation and network capacity. This results in large investments in infrastructure that only operates a couple of hours annually. Investment and operation costs of the underutilised infrastructure are passed on to customers through increased energy prices. Accordingly, there is a need to control peak demand, and distributed energy storage systems hold promise for this application.

The immediate objective of this research project is to improve utilisation of network assets in an urban area with distributed energy storage systems. The NSW network was analysed under both winter and summer conditions to determine the size of the peak demand and the unused network capacity during the off peak period that could be used for charging energy storage systems without creating a peak. The minimum number of households required to be programmed to use energy storage systems during peak periods in order to avoid the network peak demand and the maximum number of households that the network could charge in the off peak period without creating a peak demand were determined. A model was developed to evaluate the effectiveness of distributed energy storage systems on the NSW network. A power flow analysis was conducted to analyse the voltage regulation capabilities of distributed energy storage systems at demand nodes on the network.

Analysis and simulation results showed that distributed energy storage systems are a viable solution to improving network capacity utilisation.

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Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Tony Bonaventure Sunzu

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Signature

Date

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Nomenclature

AGM : Absorbed Glass Mat
BSS : Battery Storage System
CAES: Compressed Air Energy Storage
DLC : Double-Layer Capacitors
DNSPs: Distribution Network Service Providers
DoD : Depth Of Discharge
DR : Demand Response
DSM : Demand Side Management
ESS : Energy Storage System
FES : Flywheel Energy Storage
HFB : Hybrid Flow Battery
H_2 : Hydrogen Storage
LA : Lead Acid Battery
Li-Ion : Lithium Ion Batterries
MEPS: Minimum Energy Performance Standards
NaNiCl: Sodium Nickel Chloride Battery
NaS : Sodium Sulfur Battery
NiCd : Nickel Cadmium Battery
NiFe : Nickel Ion Battery

NiMH : Nickel Metal Hydride

NPC : Net Present Cost

PHS : Pumped Hydroelectric Storage

PV : Photovoltaic

RFB : Redox Flow Battery

SMES : Superconducting Magnetic Energy Storage

UPS : Uninterruptible Power Supply

VRFB : Vanadium Redox Flow Battery

VRLA : Valve Regulated Lead Acid

Zn-Br: Zinc-Bromine flow battery

Zn-Ce : Zinc-Cerium flow batter

Chapter 1: Introduction

1.1 Electricity Network Capacity Utilisation

Balancing electricity supply and demand is one of the biggest issues faced by power companies in Australia and around the world. The fact that electrical energy is consumed at the same time as it is generated means that supply and demand must be balanced in real time. With an ever increasing peak demand, power electricity suppliers must ensure the grid has the required capacity to meet the demand at all times.

Electricity suppliers use different strategies to ensure energy demand does not exceed supply capacity. This requires installing backup power stations known as peaking power plants, expanding transmission and distribution infrastructure, using demand management strategies etc. This approach solves the problem but leaves power providers with billions of dollars invested in underutilised infrastructure that only operate for a few days a year and energy consumers with increased price of electricity to cover investments and running costs of the underutilised infrastructure .

Energy demand varies from time to time and the price of electricity varies accordingly. When energy demand exceeds the average demand, power suppliers are forced to operate peaking power plants or buy more expensive power from other companies to supplement their supply, thus higher price of electricity. During off-peak periods the energy demand is less and the need for costly types of generation is not needed, thus reduced price of electricity.

Energy storage systems can be used to store energy during off-peak periods for use during peak periods. For energy providers, stored energy can be reinjected back into the power grid during peak periods and reduce generation costs. For consumers, energy storage systems can be used to store low cost electricity during off-peak periods for use during peak periods when the price of electricity is high.

By reducing the energy demand during peak periods using distributed energy storage systems, the required generation capacity to meet peak demand can be reduced, unnecessary infrastructure expansion can be avoided and the existing network capacity utilisation can be improved.

1.2 Project Aim

The aim of this project is to improve utilisation of network assets in an urban area with distributed energy storage systems.

1.3 Project Objectives

For completion, this project was divided into a number of deliverable outcomes:

- Research electricity network utilisation issues
- Research energy storage technologies
- Design an energy Storage System to meet energy requirements
- Analyse electricity network
- Model effectiveness of distributed ESS on the network
- Assess cost effectiveness of ESS using HOMER ENERGY software

1.4 Overview of the Dissertation

This dissertation is organised as follow:

Chapter 2 discusses electricity network capacity utilisation issues and the existing strategies to improve network capacity utilisation. Investigations on existing approaches to peak demand management are to evaluate the effectiveness of these approaches and to recommend a basis to consider a new approach. Types of energy storage technologies are discussed.

Chapter 3 details the methodology used for analysis and simulation required to achieve the goal of this research project.

Chapter 4 discusses, interprets and evaluates the results of this research project.

Chapter 5 details the analysis and simulation results of this research project

Chapter6 summarises the work achieved, conclusions, limitations, recommendations and identifies further research and development.

Chapter 2: Literature Review

2.1 Introduction

In Australia and around the world, maximising electricity network capacity utilisation is still a big challenge to energy providers. According to Ergon Energy (2013), network utilisation is an important driver of network performance and investment efficiency.

Underutilisation of electricity network capacity is the result of network capacity expansion as response to the increasing peak energy demand. According to DEEDI (2011), the rising network and generation costs affect consumers through higher electricity prices. Despite billions of dollars spent on network capacity expansion, it is still argued not to be the most efficient approach to solve the peak demand problem. According to Productivity commission (2013, p.227), "while much of the recent increase in network capacity appears to be related to peak demand, it is not clear that increased investment was an efficient response".

According to DEEDI (2011), due to population growth in Queensland, the peak demand capacity is expected to increase from approximately 8,300 MW in 2008/2009 to more than 12,800 MW by 2020 and more than $15 billion in capital infrastructure will be required to be able to keep up with the increase in peak demand.

Different energy management strategies have been used alongside network capacity expansion as response to peak energy demand, however, peak energy demand is still a big threat to energy providers and a financial problem to energy consumers.

The overall goals of this chapter are firstly to establish the significance of the general field of study, and then identify a place where a new contribution could be made. The bulk of the chapter is on critically evaluating the causes of electricity network capacity utilisation and the existing strategies used as response to this problem. Energy storage technologies were evaluated.

2.2 Network Capacity Utilisation Issues

2.2.1 Network Capacity Utilisation

Network capacity utilisation is defined as the ratio of the average demand to the installed capacity required to meet peak demand. Different measures are used to determine network capacity. According to Productivity Commission (2013), network capacity is measured by the product of total installed transformer capacity (in MWA) and the aggregate length of network lines (in circuit km). When comparing network performances, the ratio of network capacity to peak load is used as an indicative measure.

According to Ergon Energy (2013), network capacity utilisation is an important driver of network performance and investment efficiency.

2.2.2 Causes of Peak Demand

The need for energy is not the same throughout the day. There are times of the day when people's need for energy is higher than other times. According to Energy Action (2014), "peak demand refers to the highest amount of electricity being consumed at any one point in time across the entire network". Peak demand results from many users using a lot of electricity at the same time. The peak demand varies from hour-to-hour, season to season and year to year.

Daily Peak Demand

Normally, daily peak demand occurs during the times when most people arrive home and simultaneously switch on televisions, air conditioners, washing machines, dryers, cookers, lights, computers and other household appliances. Daily peak demand usually occurs between 4 pm and 8pm (Energex, 2014).

Network Peak Demand

Network peak demand occurs only a few times a year. Major spikes in energy demand result from extreme weather conditions when a much higher number of households and offices use high-energy appliances such as air-conditioners to cool down or warm up homes and workplaces at the same time as other daily appliances (Energex, 2014).

2.2.3 Effects of Extreme Weather Conditions

When extreme weather conditions occur, energy demand becomes very high and major spikes are observed due excessive use of air conditioners at work places and in households. As indicated on Figure 2.1, the difference between the average demand of three hottest days and the average demand of a full year is very significant.

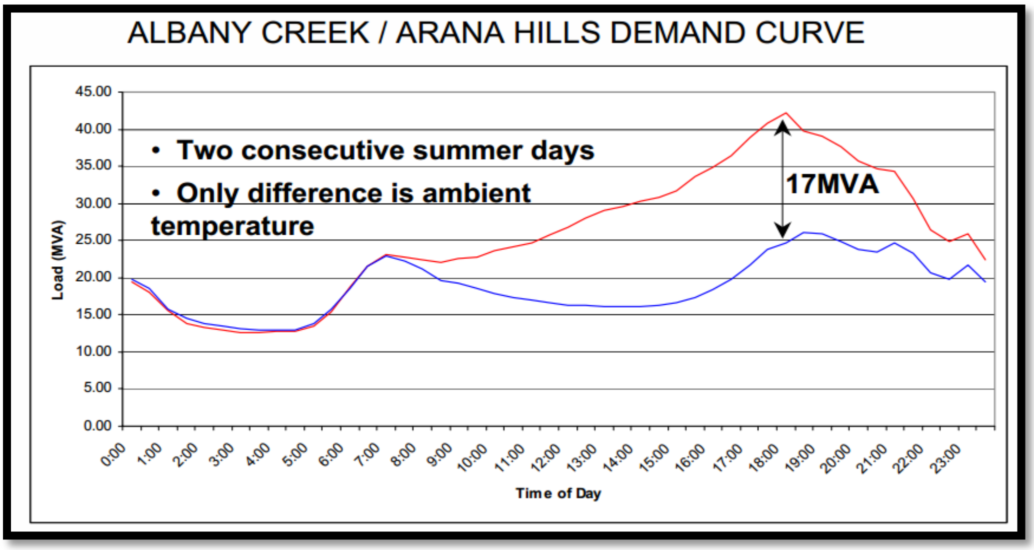


Figure 2.1: Comparison between two consecutive summer days at different ambient temperatures (Energex, 2014).

2.2.4 Load Curves for Typical Electricity Grid

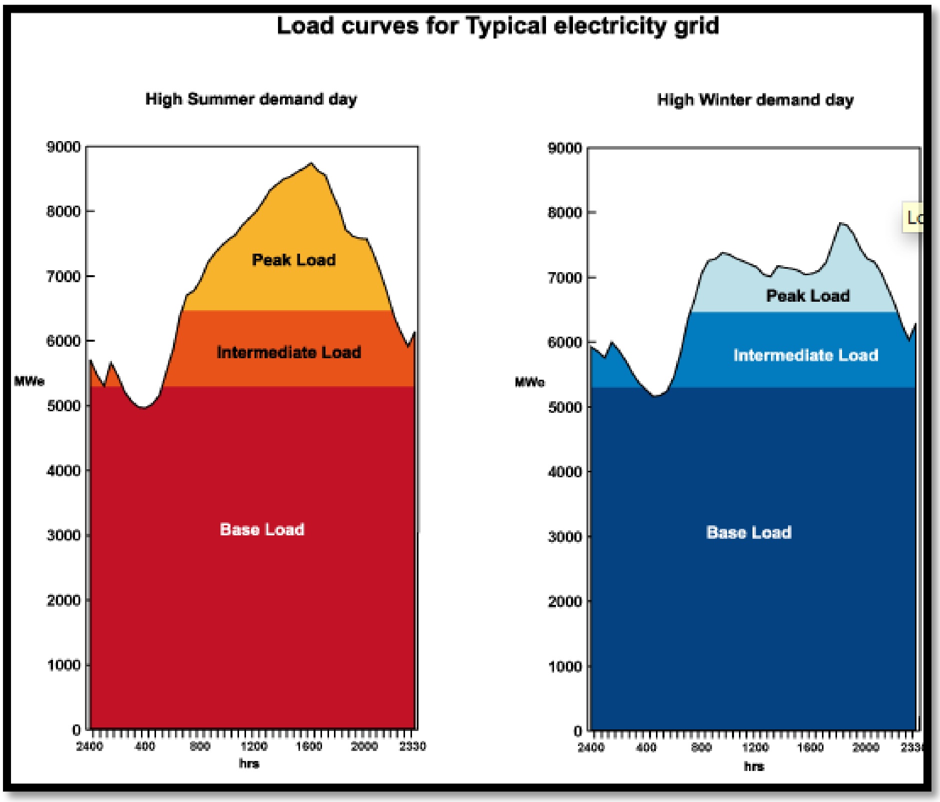


Figure 2.2: Load curves for typical electricity grid (World Nuclear Association, 2014).

Base Load

Base load is the amount of electricity that is demanded and produced at any time. It relates to the minimum level of electricity demand on an electrical supply system over 24 hours. Even though the electricity demand drops during the late evening and early morning, it never goes a certain base level. Grid operators must ensure the grid is able to supply the base load throughout the year, even during the lowest demand periods. Normally base load plants operate continuously and only stop for repair or when maintenance is needed (New York AREA, 2008).

In most cases, base load is produced using nuclear, hydroelectric power or brown coal plants, and depending on regional availability, hydro and geothermal plants can also be used. These types of plants take a long time to start up and produce energy at a constant rate and at low cost compared with other energy production plants (Global Energy Network Institute, 2012).

When electricity demand goes beyond the base load level, intermediate or peak power plants are used to supply the additional demand. For most power systems, base load power is usually 35-40 percent of the maximum load during the year (New York AREA, 2008).

Intermediate Load

Intermediate load is the middle load. Intermediate load plants, also known as load following plants, adjust their power outputs as demand for electricity fluctuates throughout the day. These types of plant are easier and faster to regulate. They are in-between base load and peaking plants in efficiency, speed of start-up and shutdown, construction cost, cost of electricity and capacity factor (Global Energy Network Institute, 2012).

Intermediate load plants generally operate 30 to 60 percent. Wind and solar can be considered intermediate power sources. Due to their nature, both sources are intermittent due to their dependency on weather conditions. Even though wind and solar are not always available when needed, they can still play a big role as intermediate sources and help reduce the need for fossil fuel intermediate load plants during high demand days (New York AREA, 2008).

Peak Load

Peak load related to high electricity demand that results from unexpected extreme weather conditions such as very hot days during winter or very cold days during winter. These events lead to excessive use of air conditioners on top of normal appliances. When the system demand is high, peak load power plants are used. These types of plants have faster response times, normally within seconds to a few minutes. They are used as response to changes in electrical demand as they can vary the quantity of electrical output fairy quickly.

Peak load power plants are generally natural gas combustion turbines but sometimes do run on light oil. Generally, peak load power plants only operate for between 10 to

15 percent of the time and use more expensive fuel, resulting in a very expensive operational cost (New York AREA, 2008).

2.2.5 Consequences of Peak Demand

According to Government of South Australia (2014), historically, infrastructure expansion such as building additional power stations or upgrading network capacity has been used as the primary response to increasing peak demand.
Productivity Commission (2013) argues that peak demand is the key driver of investment in generation and network capacity.

To avoid damages that may result from energy demand exceeding network capacity such as damage to equipment and loss of network performance, which can result in partial or full system failure, utilities must ensure the network capacity is able to handle the energy demand at all times (Productivity Commission, 2013).

The additional generation and network capacity requires large investments but only operates on maximum peak demand days, which add up to a couple of days annually. According to Productivity Commission (2013), in New South Wales the infrastructure used to support the grid during high peak demand periods only operate for less than 40 hours a year, which is less than 1% of time, but accounts for about 25 percent of retail electricity bills. To cover investment and running costs of these assets, costs are passed on to consumers through increased electricity prices.

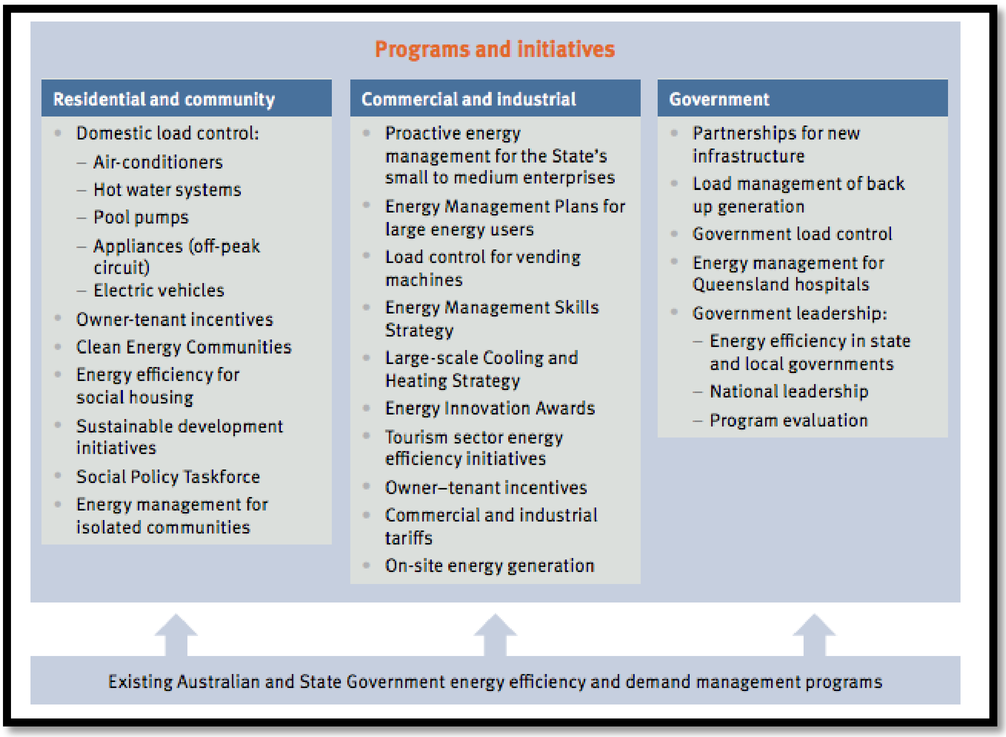
Peak demand affects both utilities and consumers. Consumers end up paying higher electricity prices to cover the cost of additional infrastructure they barely use while utilities end up with un-necessary infrastructure and underutilised electricity network capacity (Productivity Commission, 2013).

2.3 Energy Demand Management

Demand management involves administration of when and how electricity is used to ensure a reliable supply. The purpose of demand management is to offer potential solutions to the problem of peak demand. This is achieved by encouraging energy consumers to reduce their energy usage during peak hours and, where possible, shift some energy consuming activities to off –peak hours such as night times and weekends (Productivity Commission, 2013).

When peak energy demand is lowered, the need to invest in infrastructure expansion for additional generation and network capacity in order to cope with a higher peak demand is also reduced or avoided. Keeping the peak energy demand levels low is important to efficiently expand the network and keep electricity prices reasonable (Western power, 2014).

Figure 2.3 shows the existing Australian and Stage Government energy efficiency and demand management programs.



Programs and initiatives

Residential and community

- Domestic load control:
  - Air-conditioners
  - Hot water systems
  - Pool pumps
  - Appliances (off-peak circuit)
  - Electric vehicles
- Owner-tenant incentives
- Clean Energy Communities
- Energy efficiency for social housing
- Sustainable development initiatives
- Social Policy Taskforce
- Energy management for isolated communities

Commercial and industrial

- Proactive energy management for the State's small to medium enterprises
- Energy Management Plans for large energy users
- Load control for vending machines
- Energy Management Skills Strategy
- Large-scale Cooling and Heating Strategy
- Energy Innovation Awards
- Tourism sector energy efficiency initiatives
- Owner–tenant incentives
- Commercial and industrial tariffs
- On-site energy generation

Government

- Partnerships for new infrastructure
- Load management of back up generation
- Government load control
- Energy management for Queensland hospitals
- Government leadership:
  - Energy efficiency in state and local governments
  - National leadership
  - Program evaluation

Existing Australian and State Government energy efficiency and demand management programs

Figure 2.3: Existing Australian and State Government energy efficiency and demand management programs (DEEDI, 2011).

2.4 Types and Features of Energy Storage Technologies

In this section the types of energy storage technologies and their features are discussed. Energy storage technologies are classified according to the form of energy used and an overview of each storage technology is given.

2.4.1 Energy Storage

According to Akhil et al. (2013), energy storage mediates between variable sources and variable loads. If energy is not stored, energy generation must equal energy consumption. Energy storage enables energy generated at one time to be used at another time.

2.5 Energy Storage Systems (ESS)

Energy Storage Systems are devices that store energy when energy production exceeds energy demand and used when energy demand is high. Energy generation and consumption happen in real time. To avoid wastage of the excess energy produced, a storage system is required. Moreover, renewable energy sources such as wind and solar depend on weather conditions and time of the day.

To be able to take full advantage of renewable energy sources, energy produced by renewable sources needs to be stored whenever it is available so that it can be used when it is needed (Carnegie et al., 2013).

2.6 Classification of Energy Storage Systems

Classification of energy storage systems is based on the form of energy used. According to (UBS, 2012), there are five main energy storage methods: chemical, electrochemical, electrical, mechanical, and thermal. Figure 2.4 indicates the classification of electrical storage system.

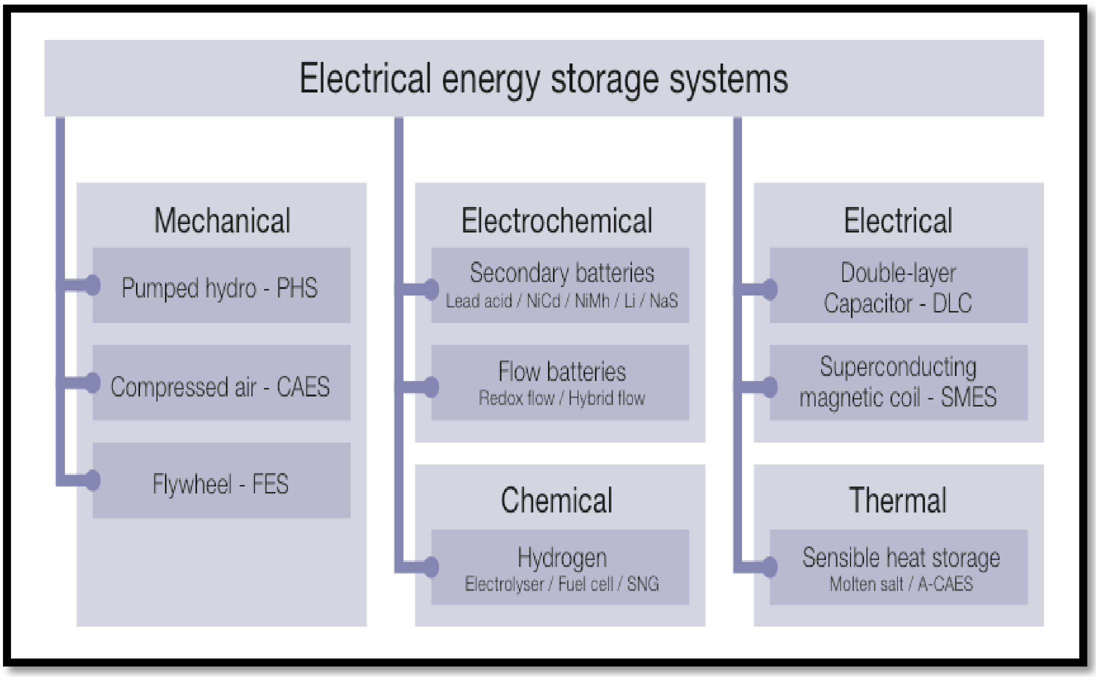


Figure 2.4: Classification of electrical energy storage systems according to energy form (IEC, 2011).

2.6.1 Mechanical Energy Storage Systems

In mechanical energy storage, different methods are used to store energy. According to (IEC, 2011), the most common mechanical storage systems are Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage (CAES) and Flywheel Energy Storage (FES).

2.6.1.1 Pumped Hydro Storage (PHS)

- Lifetime and Efficiency

Pumped Hydro Storage plants have an efficiency range of 76% to 85% depending on the design. Pumped hydro plants have very long lifetimes, ranging between 50-60 years (Akhil et al., 2013).

- Advantages

The advantages of pumped hydro storage systems include: very long lifetime, practically unlimited cycle stability of the installation, fast response time, lower emissions than fossil fuel-fired generators, they are considered as renewable energy sources (Carnegie et al. 2013).

- Disadvantages

Disadvantages of pumped hydro storage systems include: dependence on topographical condition and large land use, water availability, environmental impact such as forest removal for large systems, disturbance of the surrounding watersheds and ecosystem (Carnegie et al. 2013).

- Applications

Pumped hydro storage systems are used for energy management via time shift, control of electrical network frequency; provide reserve generation, and level fluctuating output of intermittent energy sources (Carnegie et al. 2013).

2.6.1.2 Compressed Air Energy Storage (CAES)

Concept

Compressed Air Energy Storage (CAES) is a system used to store energy during peak period for use during-off peak period. The simple version of the system uses a compressor to store energy as compressed air in an air-tight vessel. To covert the stored energy back to electricity, the cool and pressurized air is reheated and mixed with fuel, passed through an expansion turbine where it is combusted to drive an electric generator. Typical underground options for storage include: -caverns and abandoned mines. Compressed Air Energy Storage Systems exist in two different types - bulk and small.

Bulk CAES is suitable for energy need greater than 5 hours or from one hundred to thousands of megawatts. Its capacity ranges from 300 MW to 400 MW over the course of 10 to 30 hours. This size of CAES is suitable for regulation control and combination of load shifting, regulation control and spinning reserve.

Smaller CAES are installed above the ground and have capacities in the order of 10 to 20MW with shorter discharge time, which is typically less than 5 hours. This size of CAES is suitable for both short and long duration time shift applications. Depending on different factors such as sitting, construction, and system design, both types of CAES systems' capacities and discharge time will vary.

Three different major technologies are used in compressed air energy storage systems. This includes –*diabatic*, the most developed of the three and uses heat added during the expansion period in order to increase the system power capacity, *adiabatic*, which retains the heat produced by compression then returns it to the air when the fair is expanded for power generation, *near-isothermal*, which keeps the air temperature nearly constant by compressing and expanding slowly (Carnegie et al. 2013).

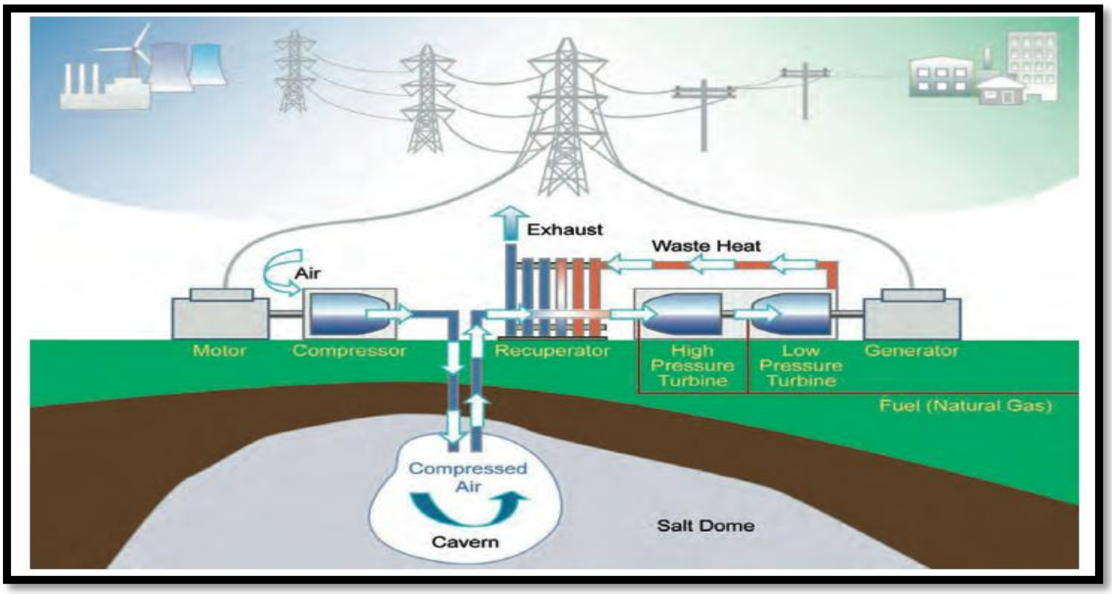


Figure 2.6: Schematic of an underground CAES (IEC, 2011).

- Lifetime and efficiency

The efficiency of Compressed Air Energy Storage system varies from one technology to another and geological features. For traditional large compressed air energy storage systems, the efficiency is estimated between 73 and 89 percent. For diabatic system, the efficiency drops as the result of using energy in the compression and heating process. Efficiency can also be affected if air escapes into surrounding formations and pressure is lost (Carnegie et al. 2013).

- Applications

Compressed Air Storage Systems are mainly used for the following applications: load shifting, regulation control and spinning reserve.

- Advantages

Advantages of CAES include: high reliability and large capacity (IEC, 2011).

- Disadvantages

Disadvantages of CAES include: geographic limitation for large subterranean CAES, low round-trip efficiency and safety concerns due to high pressures necessary for bulk CAES, the combination of leftover, flammable hydrocarbons, heat from the compression process, and oxygen creates a potential for explosion (Carnegie et al. 2013).

2.6.1.3 Flywheel Energy Storage (FES)

Concept

Flywheel energy storage system converts electricity to rotational kinetic energy. A rotating mass known as a rotor is used to capture energy. The charging is achieved by using an electric motor to accelerate the rotor to a very high speed and energy is maintained in the system as rotational energy. The system is able to maintain energy by keeping the rotational speed constant .Increasing the speed of the rotor increases the amount of energy stored in the system. Discharging is achieved by allowing the momentum to power the motor-generator and the rotational energy is converted back to electricity (IEC, 2011). The inside of a flywheel is shown in figure 2.7.

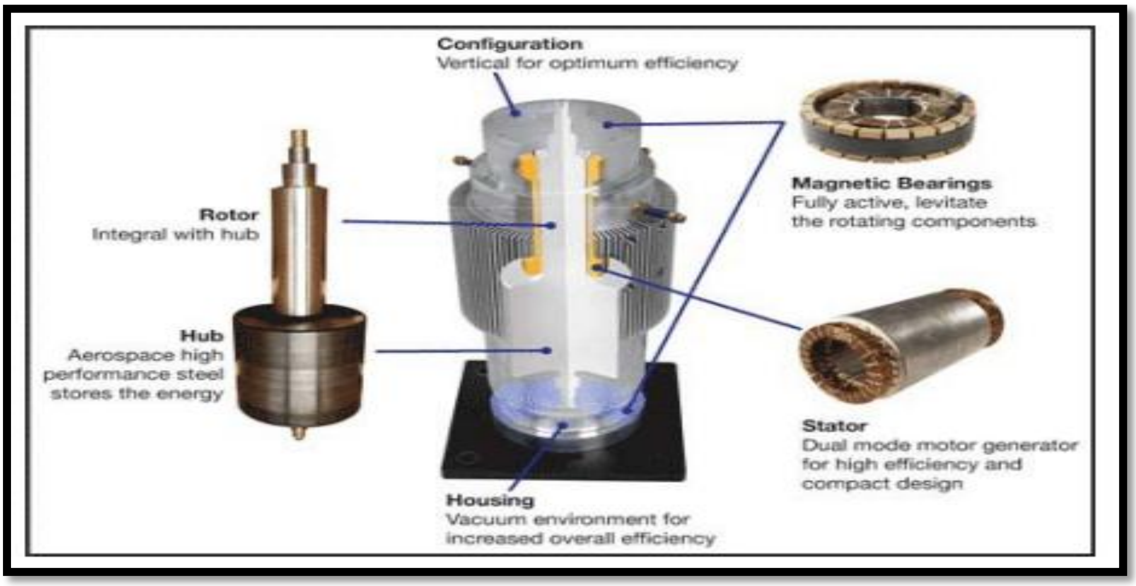


Figure 2.7: Inside of a flywheel (Global Energy Network Institution, 2012).

A modern single flywheel can achieve a spinning speed of up to 16,000 rpm and supply a capacity up to 25kWh, which can be absorbed and injected almost instantly (Global Energy Network Institution, 2012).

Despite the capability to provide energy for up to one hour, flywheel storage systems are commonly considered short discharge duration technologies and suitable for uninterruptible power supply and quality applications (Carnegie et al. 2013).

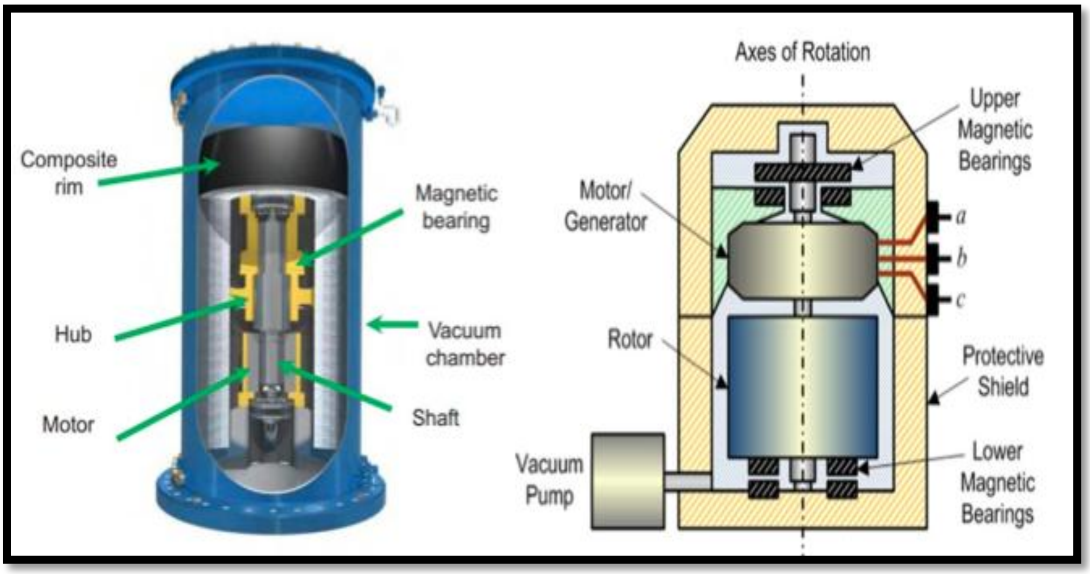


Figure 2.8: Flywheel energy storage components (Carnegie et al. 2013).

- Lifetime and efficiency

One of the advantages of flywheels is their longer lifetime compared with other energy storage systems. Flywheels can last decades with little or no maintenance. Commercial flywheel energy storage units have a lifecycle of up to 100,000 charge-discharge cycles. On top their long life times, flywheels also have high energy densities (100-130Wh/kg) and large maximum power output. Flywheels have a round trip efficiency ranging between 70 and 80 percent and have standby losses of 1 to 2 percent of the rated power output (Carnegie et al.2013).

- Advantages

The advantages of flywheels energy storage systems include excellent cycle stability, long life, little maintenance, high power density, temperature change resistance, environmentally friendly, instantaneous response time, small area requirement and easy energy content identification (IEC, 2011).

- Disadvantages

Despite all the advantages, flywheels have a high level of self-discharge and suffer from low current efficiency (IEC, 2011). According to Carnegie et al. (2013), operating noise may also be a problem on sitting of a flywheel storage system.

- Application

Flywheel energy storage systems were first used to smooth steam engine generation in large power electric power stations. The technology has been used in power supply for power quality maintenance and reliability. The storage system regulates frequency and provides protection against transient interruptions. Flywheels were first considered for energy storage in 1960s.

The flywheel storage system with a capacity of providing 340MW for 30 seconds is the largest and used for f in Japan. Flywheel systems with capacities ranging between 100kW to 2MW with discharge times of between 5 to 10 seconds are used for power applications.

Flywheel systems with the capacity to store between 0.5 to 1kWh of energy are used for energy applications. This technology is a common choice for uninterruptible power supply and power quality applications due to its instantaneous response time (Carnegie et al.2013).

2.6.2 Chemical Energy Storage

Chemical energy storage involves the storage of energy in the bonds of chemical compounds such as atoms and molecules. Chemical energy storage is the sole technology that allows storage of large amounts of energy. The technology can store up to the TWh range and this energy can be held for longer periods (IEC, 2011). The type of chemical energy storage considered in this project is hydrogen.

2.6.2.1 Hydrogen (H_2)

Concept

This technology uses hydrogen as the energy carrier. The production of hydrogen is achieved by using excess electricity to produce hydrogen via water electrolytes. This storage system is made up of a tank, an electrolyser and a fuel cell. The tank is used for hydrogen storage; the electrolyser is an electrochemical converter and is used to split water into hydrogen and oxygen with the help of electricity.

Hydrogen can be stored using different approaches. This can be in the form of a gas under high pressure, a liquid at very low temperature, chemically boded in complex hybrids, or absorbed on metal hybrids. When electricity is needed, hydrogen and oxygen are joined together into the fuel cell for an electrochemical reaction to take place. This reaction produces water and releases heat and electricity is generated (IEC, 2011).

- Lifetime and Efficiency

The overall efficiency of AC-AC is about 40 percent (IEC, 2011).

- Advantages

Large scale storage, volumetric storage density, scope for expansion (Hydrogen and electricity storage, n.d).

- Disadvantages

Expensive, weight and volume, less efficient, inadequate durability, long refuelling times (Fuel from the water, 2014). Other disadvantages include: energy balance, $C0_2$ reduction and technology availability (Hydrogen and electricity storage, n.d).

- Applications

For peaking plants (for gas and steam turbines with power of up hundreds of MW), could be used as peaking plants, stationary application and industrial applications (IEC, 2011). Other applications include: transportation (Fuel from the water, 2014).

2.6.2.2 Electrochemical energy storage

When charging, electrochemical energy storage systems convert electrical energy into chemical energy. This technology consists of two different technologies-electrochemical batteries and electrochemical capacitors (Carnegie et al. 2013).

2.6.2.3 Electrochemical batteries

According to Carnegie et al. (2013), electrochemical batteries exist in three different extensive categories. This includes: conventional, high temperature, and flow batteries. This section discusses the different categories of electrochemical batteries.

Conventional batteries

Conventional batteries are made of cells with two electrodes and electrolyte which are sealed in a container. This technology includes: Lead acid, Nickel-Cadmium, and Lithium-Ion (Carnegie et al. 2013).

I. Lead-Acid battery (LA)

Concept

Lead acid batteries are the most mature of the electromechanical energy storage systems and are the most used battery type in the world (IEC, 2011). Lead acid batteries exist in two broad categories – vented (flooded) and (VRLA) valve-regulated (sealed).Each of these categories has its subcategories. The subcategories of vented lead acid batteries are: starting, lighting, and ignition (SLI); deep-cycle and stationary. The subcategories of valve-regulated lead acid batteries are: absorbed glass mat (AGM) valve-regulated lead acid batteries and gelled electrolyte valve-regulated lead acid batteries. Lead acid batteries have a nominal voltage of 2V and a round trip efficiency ranging between 75 and 85 percent (Carnegie et al. 2013).

The inside of a Lead-Acid is shown in Figure 2.9.

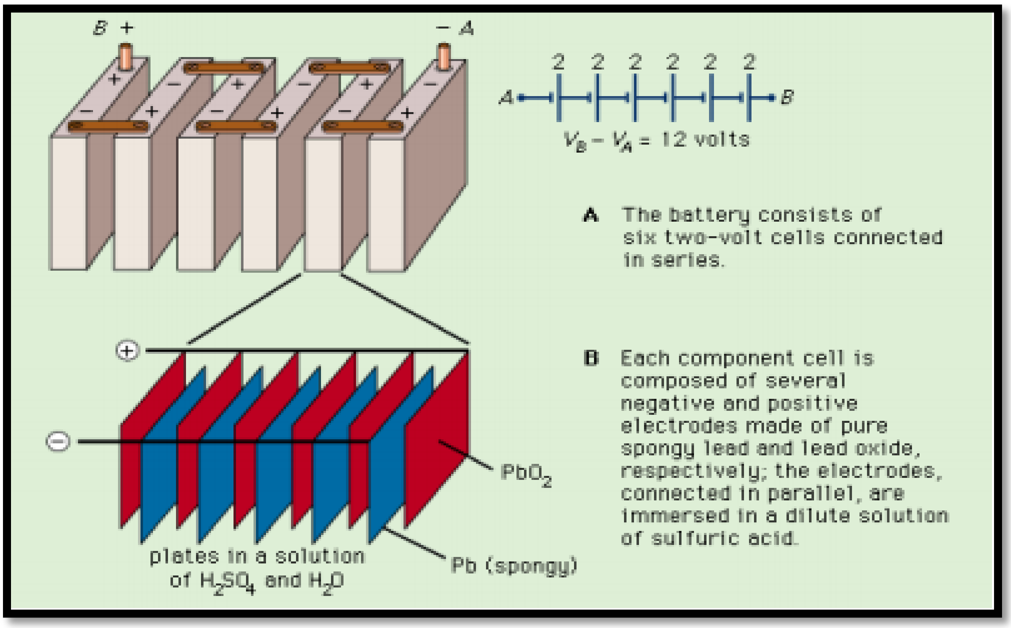


Figure 2.9: The inside of a Lead-Acid battery (Global Energy Network Institution, 2012).

- Lifetime and efficiency

The typical lifetime of lead acid batteries varies between 6 to 15 years with a lifecycle of 1500 cycles at 80 percent depth discharge. The cycle efficiency of lead-acid batteries is between 80 percent and 90 percent .The SLI flooded lead acid batteries are not relatively durable and last between 5 and 7 years (IEC, 2011).

At 100 percent depth of discharge, SLI flood batteries have a lifecycle ranging between 30 to 100 cycles. Deep-cycle flooded lead acid batteries have life expectancy ranging between 3 and 5 years. At 100 percent depth of discharge, deep-cycle flooded lead acid batteries have a life cycle of up to 1,000 cycles. Stationary flooded lead acid batteries are the strongest in this subcategory with a life expectancy ranging between 15 and 30 years. Absorbed glass mat valve-regulated lead acid batteries and gelled electrolyte valve-regulated lead acid batteries have lifetime ranging between 5 and 10 years (Carnegie et al. 2013).

- Advantages

The advantages of lead acid batteries include: low cost, simple to manufacture, reliable and well-understood technology, low self-discharge (among the lowest in rechargeable batteries), low maintenance requirements (no memory, no electrolyte to fill), can provide high discharge rates (Battery University, 2014).

- Disadvantages

Lead-acid batteries have low specific energy and power, short lifecycle, high toxicity, self-discharge, sensitivity to temperature, sulfation, hydration, and degradation. Valve-regulated lead acid batteries are sensitive to temperature, overcharge and discharge, corrosion and water loss .Other disadvantages of lead acid batteries include: cannot be stored when discharged, only suitable for standby use where only occasional deep discharge is needed, transportation limitations due to environmental concerns for flooded lead acid batteries regarding spillage in case of an accident (Carnegie et al. 2013).

- Application

Lead acid batteries were first used in 1870s in central electric plants for load levelling and peaking (Carnegie et al. 2013).

From 1910 to 1945, in the electrification age, this technology was used for grid energy. The current applications of Lead-acid batteries include: emergency power supply systems, stand-alone systems with PV, starter battery in vehicles, and battery systems for mitigation of output variations from wind power (IEC, 2011).

The SLI subcategory of flooded lead acid batteries is best suited for short term power quality applications, grid angular stability and grid voltage stability. Deep-cycle flooded lead acid batteries are best suited for deep discharge applications. Stationary flooded lead acid batteries are best suitable for power supply for controls and switching operations, for storing standby emergency power in utility substations, for use in power generation plants, for telecommunication systems, for grid frequency stability and for combined applications. Valve-regulated lead acid batteries are best suitable for uninterruptible power supplies (Carnegie et al. 2013).

II. Nickel cadmium (NiCd) and other Nickel electrode batteries

Concept

Nickel cadmium is a type of rechargeable battery that uses nickel oxide hydroxide and metallic cadmium as electrodes. This type of batteries is known as dry cell batteries. Nickel based batteries perform better than lead acid batteries. They have a higher power delivery capabilities, higher energy density, higher lifecycle, more reliable and perform better even at low temperatures (IEC, 2011).

When charging, Nickel cadmium batteries allow conversion of electrical energy to chemical energy. When discharging, the stored chemical energy is converted back to electrical energy (Bellis, 2014).

Nickel cadmium batteries provide a large battery systems version that use vented NiCd batteries and are currently only used for stationary purposes in Europe and are not available for customer use (IEC, 2011).

In the Nickel based batteries, only two have utility scale energy storage demonstrations or commercial installations: Nickel- cadmium and Nickel-iron. Nickel cadmium is still the most preferred for utility energy storage applications (Carnegie et al. 2013).

Nickel ion (NiFe) batteries are robust and tolerant of conditions such as overcharge, over discharge, and short-circuit. Nickel ion batteries have a long lifecycle and are preferred for use as backup power supply where continuous charging is not a problem (The Nickel Ion Battery Association, 2014).

Nickel metal hydride batteries (NiMH) were developed with the intention to replace Nickel cadmium batteries. They come with all the positive features of Nickel cadmium batteries except a much lower maximum nominal capacity compared to other battery types such as lead acid and nickel cadmium batteries (IEC,2011).

- Lifetime and efficiency

Nickel cadmium batteries have a lifecycle of up to 1000 charge/discharge cycles (Battery University, 2014). Nickel ion batteries have a lifetime of 30-100 years and charge/discharge efficiency ranging between 65 percent and 85 percent (The Nickel Ion Battery Association, 2014). According to Carnegie et al.(2013), pocket plate industrial nickel cadmium batteries have lifecycle ranging between 800 and 1,000 cycles, sintered-plate nickel cadmium batteries can stand up to3,500 both at 80 percent depth of discharge.

- Advantage

The advantages of Nickel cadmium batteries include: higher energy density, and high power delivery capabilities, hardness, reliable, longer lifecycle, fast and simple charge can be recharged even at low temperatures, easy to store and transport and exist in different sizes and performance options (Battery University, 2014). Nickel ion batteries are robust, can be overcharged for decades without damage, can be left discharged for years and ready for reuse whenever needed, ability to withstand vibrations, high temperatures and physical stress.

- Disadvantage

The disadvantages on Nickel cadmium batteries include: more expensive than lead acid batteries, toxic, environmentally unfriendly, low energy density compared with newer systems, memory effect and high self-discharge rate (Battery University, 2014).

- Applications

Nickel cadmium batteries are more suitable where long lifetime, high discharge rate, and economical price are important. The main applications are for: two-way radios, biomedical equipment, professional video cameras and power tools (Battery University, 2014).

Nickel ion batteries have been used in European mining operations and are being reviewed for possible use in modern electric vehicle applications; wind and solar power systems .They are also being used in Australia for solar homes (The Nickel Ion Battery Association, 2014).

III. Lithium ion batteries (Li-Ion)

Concept

Lithium-ion batteries store energy by allowing lithium ion to flow from the positive oxide electrode to the negative graphite electrode. Energy is released by reversing the flow of lithium ions (Carnegie et al. 2013).

The construction of Lithium-ion batteries is a bit similar to a capacitor, using three different layers curled up as a way to minimize space. The first layer, which is made of a lithium compound, is used as the anode; the second layer, which is usually made of graphite, is used as the cathode. Between the two layers (anode and cathode), there is a separator layer, which can be made of various compounds allowing different characteristics, different benefits and flaws. The separator layer separates the other two layers for lithium-ions to pass through. The movement of the lithium ions between the anode and cathode is achieved by submerging the three layers in an organic solvent-the electrolyte.

During the charging process, the lithium ions pass through the micro-porous separator into spaces between the graphite, which allows them to gain an electron from the external power source. During the discharging process, a current is produced as the lithium atoms situated between graphite release their electrons again, which moves over the external circuit to the anode (Global Energy Network Institution, 2012).

The charging and discharging processes of a lithium battery is shown in figure 2-10.

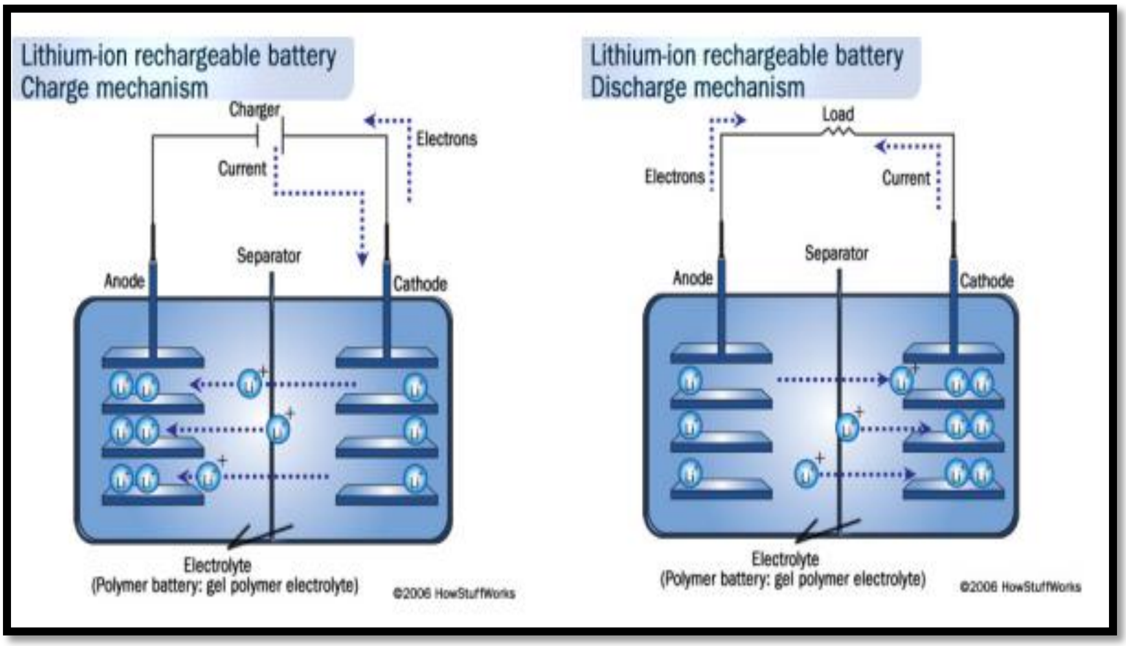
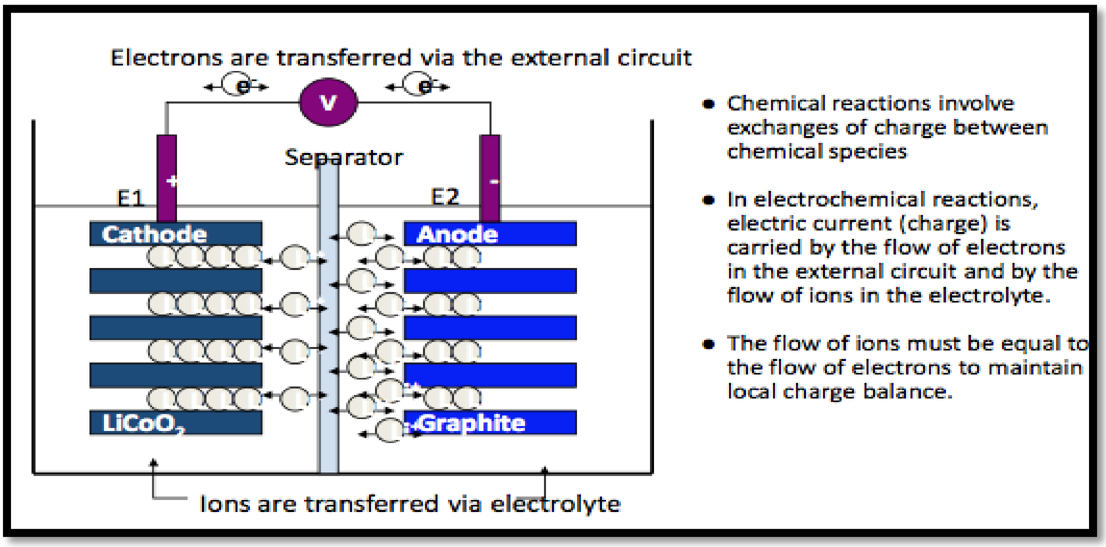


Figure 2.10: Charging and discharging of a lithium-ion battery (Global Energy Network Institution, 2012).

Although this technology began in 1912, with the first commercially available non-rechargeable lithium ion battery released in early 1970s, it was not until around 2000 that lithium ion batteries made big changes. Despite being a much less mature technology compared to lead acid batteries, it has become the most important when it comes to portable and mobile applications due to considerable advantages over competing technologies.

Li-ion batteries have twice the energy density of standard NiCd and with improvements in its chemistry; it is expected to increase its energy density up to three times that of the NiCd. Lithium ion battery technology is the fastest growing and the most promising battery chemistry (Battery University, 2014).

Li-ion battery cells have a nominal voltage of 3.7V.This means less cells are needed to produce the same power output as many other batteries. Multiple demonstrations are being carried out for utility functions (Carnegie et al. 2013).



- Chemical reactions involve exchanges of charge between chemical species
- In electrochemical reactions, electric current (charge) is carried by the flow of electrons in the external circuit and by the flow of ions in the electrolyte.
- The flow of ions must be equal to the flow of electrons to maintain local charge balance.

Figure 2.11: Principles of a Li-ion Battery (Akhil et al., 2013).

Lifetime and Efficiency

Li-Ion batteries have a round trip efficiency ranging between 85 and 95 percent. The lifetime of Li-Ion is expected to range between 2,000 and 3,000 cycles or 10 to 15 years (Carnegie et al. 2013).

According to IEC (2011), commercial Li-Ion batteries with a lifecycle of up to 5,000 full cycles are available, and depending on the type of material used for the electrodes, higher lifecycles can be achieved.

- Advantages

Advantages of Li-Ion batteries include: high energy density, higher voltages per cell (3.7 V compared with 2V for Lead-Acid), low energy loss (about 5% per month), lithium and graphite are available in large amounts, cycling tolerance, low weight, and low maintenance requirements (Global Energy Network Institution, 2012).

- Disadvantages

Advantages of Lithium batteries include: fragile, requires a protection circuit to maintain safe operation, subject to ageing even if it is not in use, transportation restrictions for large quantities, expensive to manufacture, not fully mature, very sensitive to high temperatures (Battery University, 2014).

Other disadvantages include: very expensive, full discharge affects the lifetime (Global Energy Network Institution, 2012).

- Applications

Lithium ion batteries are mostly used in consumer electronics such as laptops, mobile phones, electric cars and electric bicycles (IEC, 2011).

IV. Sodium Sulfur Batteries (NaS)

Concept

Sodium Sulfur Batteries were developed in the 1960s. The technology uses molten sulphur as the positive electrode and molten sodium as the negative electrode (Energy Storage Association, 2014).

Despite NaS batteries being classified as commercialised, in fact they are still in the early stages. Only-small scale NaS battery technology is fully developed, while the grid-scale version is still in early commercialisation stage and demonstrations have been carried out. According to NGK (2014), the prospect of commercial utilisation has now been finalised.

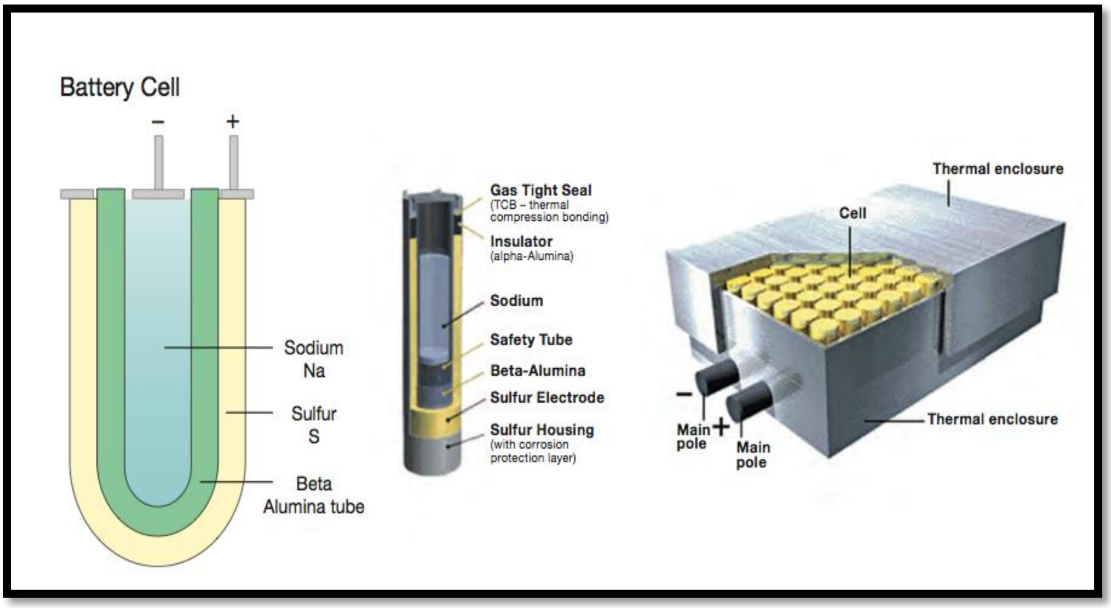


Figure 2.12: NaS battery cell design and 50 kW module (Akhil et al., 2013).

- Lifetime and Efficiency

NaS batteries normally have lifecycle of about 4,500 cycles and a round trip efficiency of about 75 percent. NaS batteries have discharge time ranging between 6 to7.2 hours (IEC, 2011). According to NGK (2014), the life expectancy of NaS batteries is 15 years. NaS batteries have power out ranging from 360kW to tens of MWh. The nominal discharge power of NaS batteries ranges from 50 kW to 100MW.

- Advantages

Advantages of NaS batteries include: quick response time, relatively high density (up to 240Wh/kg) , a long life span (10-15 years), high efficiency (75-90 percent) (Global Energy Network Institution, 2012).

- Disadvantages

According to IEC (2014), heat source is required to maintain operation temperatures. Carnegie et al. (2013), argue that NaS batteries must operate at extremely high temperatures and this makes them a safety hazard because they can explode when in contact with water, and they are toxic and relatively expensive for grid-scale batteries.

- Applications

NaS batteries are used in: combined power quality and time shift applications with high energy density, peak shaving, grid stabilisation (IEC, 2011). According to Carnegie et al.(2013), NaS batteries can be used for long duration energy storage, load levelling, arbitrage, emergency power supply, and renewable output smoothing. According to NGK (2014), grid-scale NaS batteries are expected to function as a power station to charge electric power in the base power source at low demand and discharge it at peak demand.

V. Sodium Nickel Chloride Batteries (NaNiCl)

Concept

Sodium Nickel Batteries are also known as the ZEBRA (Zero Emission Battery Research). The technology used in NaNiCl batteries is quite similar to NaS batteries. Both technologies are molten sodium based. The positive electrode is nickel chloride and the negative electrode is molten sodium (Carnegie et al. 2013).

According to Eurobat (2014), this technology has been commercially available since mid 1990s and only the mobile application version is currently in use while the stationary version is still in its starting phase and demonstrations are being carried out .The operating temperature of NaNiCl batteries is between 270 degrees Celsius and 350 degree Celsius.

- Lifetime and Efficiency

According to Eurobat (2013), NaNiCl batteries have a lifecycle of up to 2,000 cycles at a depth of discharge of 80 percent and have a lifetime of 15 years. The round trip efficiency of ZEBRA batteries ranges between 85 and 90 percent.

- Advantages

Advances of NaNiCl batteries include: no needs of air conditioning, high energy density, long lifecycle, long calendar life, no need for maintenance, remote monitoring of the systems, zero emission, not toxic, easily recyclable (Eurobat, 2014). Other advantages include: quick response time, tolerance of overcharge/discharge and high tolerance of short circuit (Carnegie et al. 2013).

- Disadvantages

Disadvantages of ZEBRA batteries include: expensive, suitable for large capacity batteries only (>20kWh), limited size and capacity choices, only produced by one company in the world, high operating temperature, and needs preheating to raise the temperature up to 270 degrees Celsius for operation, which takes up to 24 hours if the battery is cold, uses up to 14 percent of its own capacity daily to keep the temperature at a good level when not in use (Electropaedia, 2014).

- Applications

Sodium Nickel Chloride batteries are used in: EV (Electric Vehicles), HEV (hybrid electric vehicle) buses, trucks and vans and fleet applications (Eurobat, 2014). The advanced versions of ZEBRA with higher energy densities under development will be used for storing renewable energy for load-levelling and for industrial applications (IEC, 2011).

VI. Flow Batteries

Concept

A flow battery is an electrochemical storage device that can be recharged by putting in fresh electrolyte to replace the used electrolyte if no power source is available. According to Carnegie et al. (2013), flow batteries consist of two external electrolyte tanks that are used to store electrolyte material. Flow batteries have the ability to separate power and energy, which is a special function that separates flow batteries from other electrochemical storage systems (Energy Storage Association, 2014).

According to IEC (2011), the capacity of flow batteries depends on the size of the storage tanks. Flow batteries exist in different classes: redox, hybrid and membraneless (Energy without Carbon, 2014). Redox flow batteries (RFB) hold the ability to separate special function of separating power and energy.

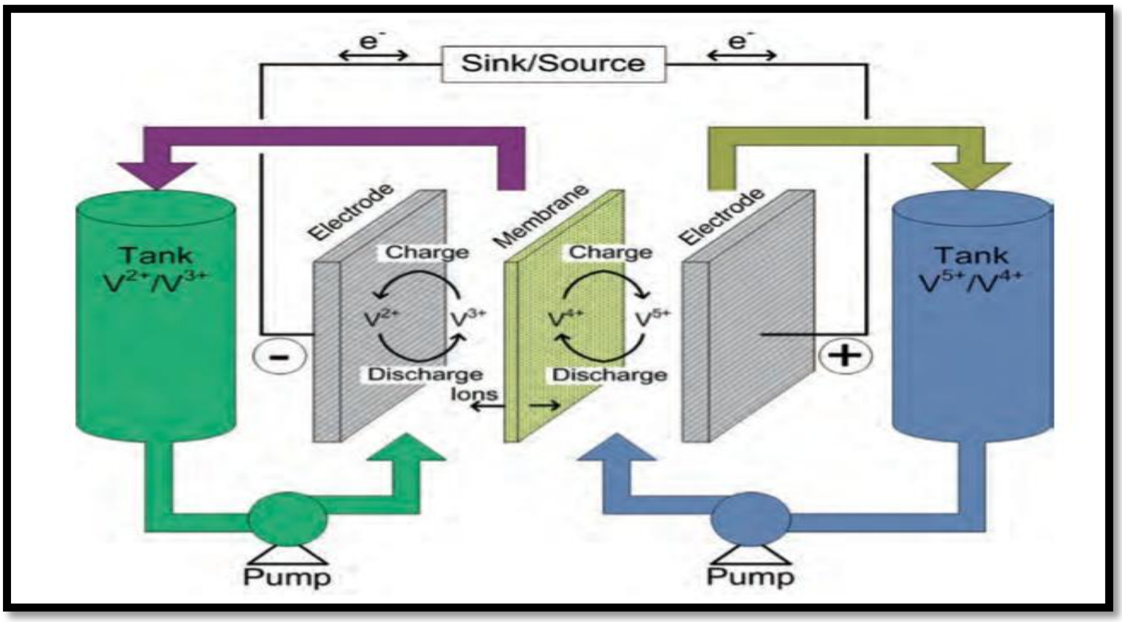


Figure 2.13: Schematic of a Vanadium Redox Flow Battery (IEC, 2011).

According to Energy Storage Association (2014), the name Redox refers to chemical reduction and oxidation reactions that are used to store energy in liquid electrolyte solutions. Recharging can be easily achieved by pumping out the discharged electrolyte and replacing it with charged electrolyte. The easy charging of a redox battery has allowed it to put under consideration for mobile applications (IEC, 2011).

Vanadium redox flow battery differs from other redox flow batteries as it uses vanadium in both tanks, preventing it from cross-contamination degradation, which is a big problem with other redox flow batteries (Wang, 2012).

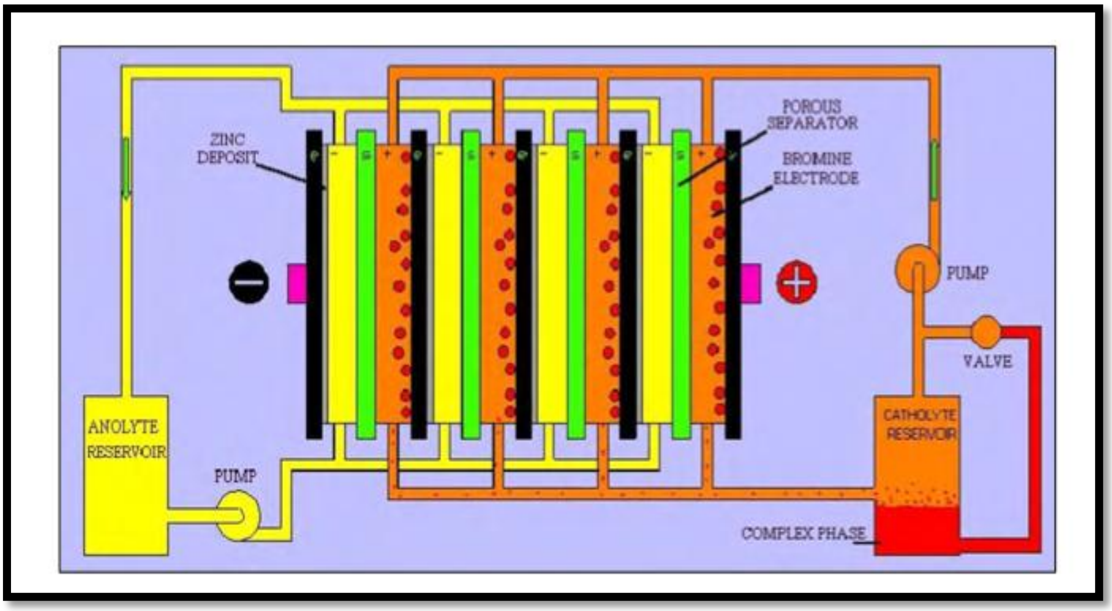


Figure 2.14: Zinc-Bromine cell configuration (Akhil et al., 2013).

Hybrid flow batteries (HFB) contain a single or a number of electro-active components placed as a solid layer. The battery cell of hybrid flow batteries encloses one battery electrode and one fuel cell electrode (Carnegie et al. 2013). Examples of hybrid flow batteries include: Zinc-Bromine (Zn-Br) flow battery and Zinc-Cerium (Zn-Ce) flow battery (IEC, 2011).

Zinc-Bromine flow battery uses two separate bromine electrolytes that react with Zinc on the electrodes. The lifetime of a Zinc-Bromine flow battery is calculated in terms of hours of operation. The cell of this type of provides a nominal voltage of 1.8

volts and operates at room temperature, ranging between 25 and 50 degrees Celsius (Carnegie et al. 2013).

- Lifetime and Efficiency

At 1,000 cycles a year, a vanadium redox battery is expected to last between 10 to 15 years and can be extended up over 20 years through pump and stack replacement. The round efficiency of a vanadium redox battery ranges between 70 and 90 percent. Depending on the system design, Zinc Bromine flow batteries energy efficiency can be between 70 and 80 percent with a lifetime of around 6,000 hours, which is about 2,000 cycles when the system is continuously operated at 100 percent depth of discharge (Carnegie et al. 2013).

- Advantages

The advantages of a Redox battery includes its very high power output (tens of kilowatts), fast recharge by replacing spent electrolyte, long life due to replacement of electrolyte, can be fully discharged , uses non toxic materials, very quick response time (Carnegie et al.2013). Other advantages include: the capacity can be easily increased by adding more solution, cost per kWh decreases as storage capacity increases, underground electrolyte tanks can be used to reduce space requirement (NewSouth Innovations, 2014).

- Disadvantages

Disadvantages of flow batteries include: expensive (VRFB), construction complexity, electrolyte leakage, relatively low power, low energy density, efficiency losses, toxic, large space requirement, corrosive elemental bromine in the electrolyte (Zn-Br) (Carnegie et al. 2013).

- Applications

Flow batteries are a good choice for applications that require energy for more than 5 hours due to cost efficiencies with large amounts of fairly inexpensive electrolyte material. Vanadium redox batteries are suitable for utility applications where long discharge durations with rated power ranging from 100 kW to 10MW is required. This includes: load shifting, renewable time shifting, fluctuation suppression, forecast hedging, spinning reserve and power quality. Zn-Br flow batteries are suitable for both energy and power applications such as peak shaving, load following and renewable time shifting (Carnegie et al. 2013).

Table2- 9 indicates capital and operating costs of a Vanadium redox battery.

2.6.3 Electrical and Magnetic Field Energy Storage

In Electrical energy storage, energy is stored using electric field. This technology uses capacitors, super capacitors and superconducting magnetic energy storage to store energy (Wu, 2012). Unlike battery storage systems, electrical and magnetic field energy storage systems store energy by generating an electrical field between two parallel conductor plates. According to Carnegie et al. (2013), the surface area of the conductor plates and gap between them are the determining factors of how much energy can be stored in a capacitor.

2.6.3.1 Double-layer capacitors (DLC)

Concept

Double- layer capacitor is also known as super capacitor due to its ability to charge and store energy at an exponentially higher density than standard capacitors (Thomas Publishing Company, 2014).

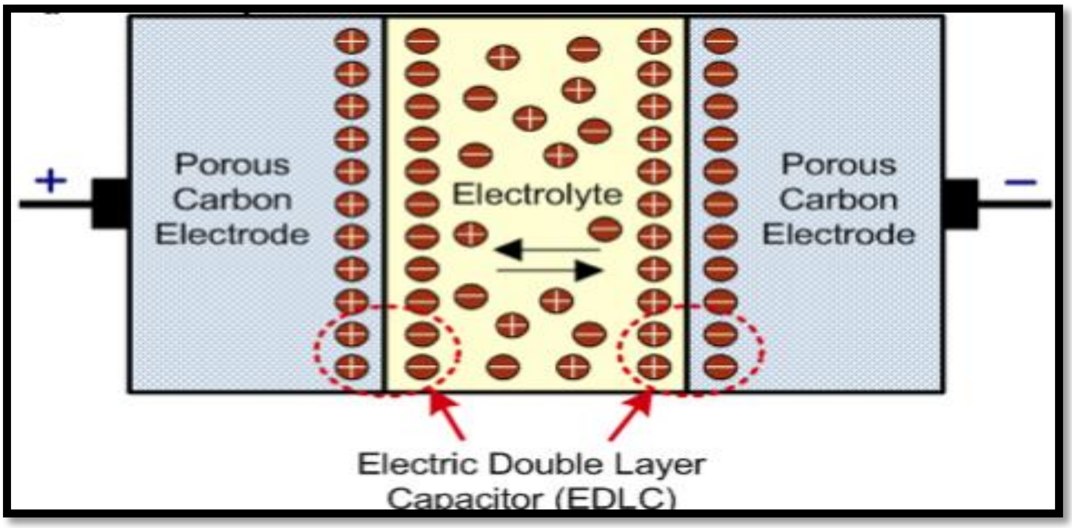


Figure 2.15: Capacitor conduction (Carnegie et al. 2013).

- Lifetime and Efficiency

Double-layer capacitors have a lifetime of up to 1,000,000 cycles or 10 years of operation. The efficiency of double-layer capacitors is typically around 90 percent.

- Advantages

Advantages of double-layer capacitors include: nearly unlimited cycle stability, extremely high power capability, higher energy storage capability, very fast charging and discharging rates, durable, no maintenance required, long lifetime, can operate over a range of temperatures, resilient to climate changes (IEC,2011).

- Disadvantages

Disadvantages of capacitors include: deterioration of solvent used and low energy density (IEC, 2011). Other disadvantages of double-layer capacitors include: interdependence of the cells, sensitivity to voltage imbalances between cells and maximum voltage thresholds, safety issues, cells lifetimes are directly dependent on strict maximum voltages, lethal voltages, environmental implications (Carnegie et al. 2013).

- Application

Double-layer capacitor is suitable for applications with a large number of fast charge and discharge cycles. They are not suitable for long-term storage due to high self-discharge rate, low energy density and high investment costs. They have been used in consumer electronics, power electronics, uninterruptible power supply to bridge short voltage failures, as a buffer system for acceleration and process and regression braking in electric vehicle (potential) (IEC,2011). Other applications include: power quality, intermittent renewable fluctuation suppression (Carnegie et al. 2013).

2.6.4 Superconducting Magnetic Energy Storage (SMES)

Concept

Superconducting Magnetic Energy Storage uses a superconducting coil to store energy in the form of a magnetic field surrounding the coil, which is made of a superconductor. This type of storage system consists of three main components: a coil, a power conditioning system (PCS) and a cooling system. Generally, some materials lose their electric resistance at very low temperatures and become superconducting. This is the principle used in superconducting magnetic energy storage systems. In this case, energy can be stored with very minimum loss (practically 90-95 percent efficiency).

Materials that can be used as superconductors are known to work at temperatures below -253 degree Celsius, thus the need for a cooling system. This level of cooling can be achieved by liquefying helium; which is very expensive and the process affects the system efficiency. A lower level of cooling requirement has already been reduced thanks to new high-temperature superconductors, which are able to work as superconductors at only -163 degree Celsius. This allows the use of liquid nitrogen, which is comparatively cheaper (Global Energy Network Institute, 2012). Figure 2-16 shows a Superconducting Magnetic Energy Storage.

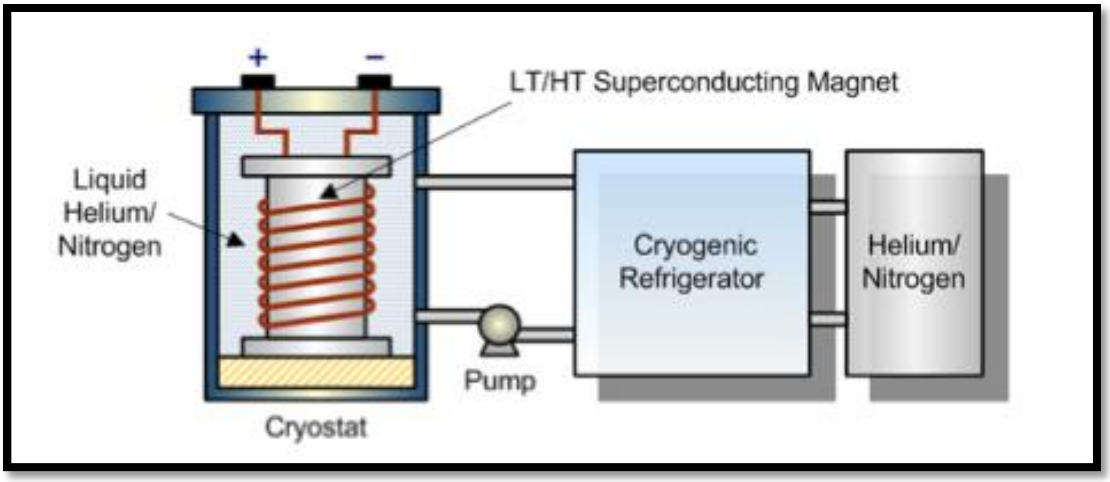


Figure 2-16: Superconducting magnetic energy storage (Carnegie et al. 2013).

For energy storage, the superconducting coil temperature is kept at a temperature below its superconducting critical temperature. In principal, a superconducting magnetic energy storage system can be able to stored energy independently as long as the cooling system is operational, but longer storage times are limited by the energy demand of the refrigeration system (IEC, 2011). Figure 2.17 shows the conceptual design of a superconducting coil.

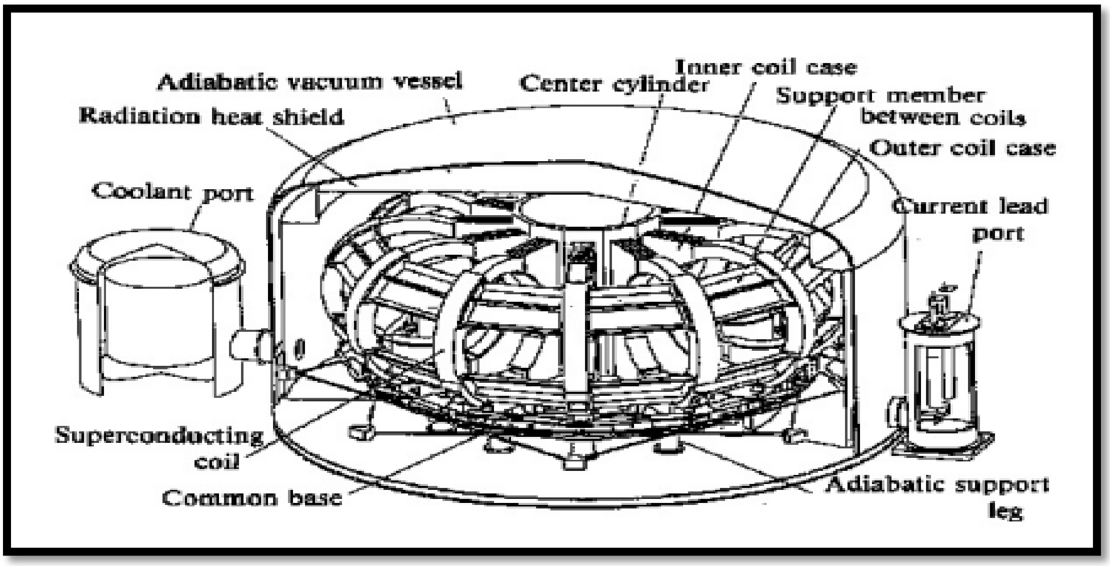


Figure 2.17: conceptual design of a superconducting coil (Global Energy Network Institute, 2012).

- Lifetime and Efficiency

The round-trip efficiency of superconducting magnetic energy storage is above 95 percent. The life expectancy does not depend on the number of cycles (Carnegie et al. 2013).

- Advantages

The advantages of super magnetic energy storage include: very quick response time (power is available almost instantaneously), high overall round-trip efficiency (85%-90%), very high power output (IEC, 2011). According to Carnegie et al. (2013), other advantages include: life expectancy is independent of duty cycle, high reliability, permanent storage (no standby loss), lifetime is not affected by depth of discharge.

- Disadvantages

Disadvantages of superconducting magnetic storage include: refrigeration energy requirements, requires large magnetic field (Carnegie et al. 2013). According to Global Energy Network Institute (2012), SMES) have high energy losses (~12% per day), very expensive in production and maintenance, reduced efficiency due to the required cooling process.

- Applications

Large superconducting magnetic energy storage systems with over 10MW are used for particle detectors. Smaller versions are used for power quality control in manufacturing plants (IEC, 2011). Other applications include: uninterruptible power supply (Carnegie et al. 2013).

2.6.5 Thermal Energy Storage

Concept

Thermal energy storage involves different technologies. Thermal energy storage technologies allow temporary storage or removal of heat for use at a different time (Energy Storage Association, 2014).

Technologies used in thermal energy storage include: storage of sensible heat, storage of latent heat, and thermo-chemical and absorption storage. Liquid or solid materials can be used as storage medium. This includes: water, thermal oil, concrete or ground, which are the determining factors of the capacity of the storage system (IEC, 2011).

The system uses a receiver to reflect the sunlight onto a heating chamber used to heat liquid molten salt. Heated liquid molten salt is then stored into the heated fluid storage tank. When electricity is needed, the stored heated salt is then pumped out to a steam-generator to produce superheated steam which is used to power a steam turbine or generator (IEC, 2011).

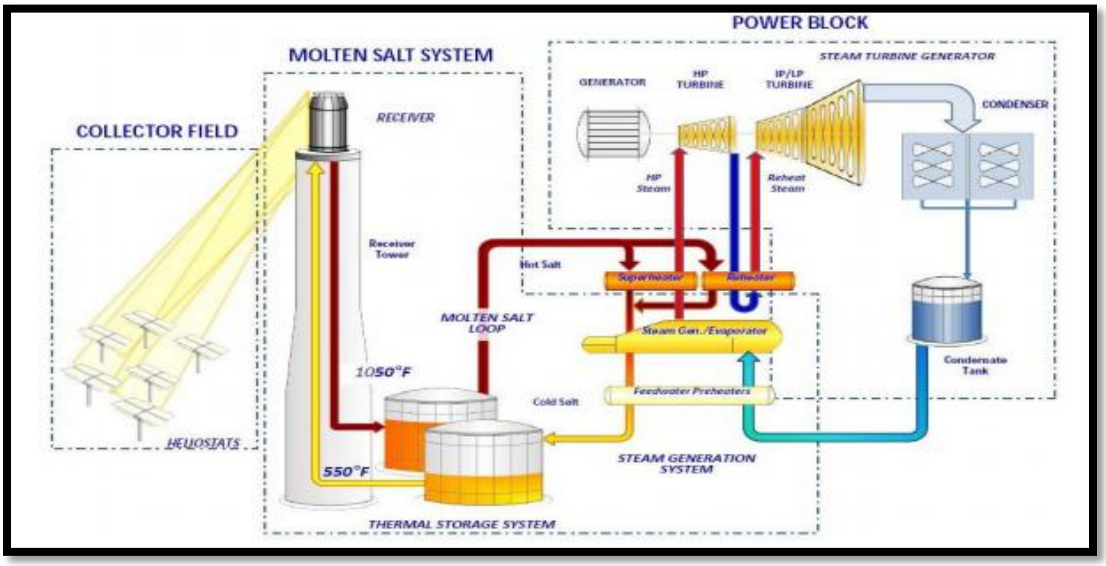


Figure 2.18: Concentrated Solar Power (CSP) plant with a thermal storage cycle (Global Energy Network Institution, 2012).

The most common form of thermal energy storage is ice energy storage, where off-peak electricity is used to freeze water into ice and the frozen ice is used during peak period for air conditioning system cooling as a way to avoid the need for grid power for air conditioning during peak demand periods. In this document, the focus will be on the molten salt thermal energy storage technology. Molten Salt thermal energy storage technology allows the use of thermal energy retained using a solar tower to generate electricity when the sunlight is not available. The system uses two tanks: a cool tank and a heated fluid tank (Carnegie et al. 2013).

- Applications

Disadvantages include: risk of liquid salt freezing at low temperatures, risk of salt decomposition at higher temperatures (Carnegie et al. 2013).

- Applications

Thermal energy storage is used for space heating or cooling, hot water production, electricity generation, helps overcome mismatch between demand and supply of thermal energy (IEC, 2011).

2.7 Definitions and Terms

Response time and Discharge duration

Response time relates to how fast a storage system can discharge energy when it is needed.

Discharge duration relates to how long can storage system supply energy in a single charge-discharge cycle.

Although for most applications the rated power (the power output of a device) and the discharge duration are the biggest concern, in some applications where energy is needed for emergency, the response time is also very important (Carnegie et al. 2013).

Depth of discharge and frequency of discharge

Depth of discharge relates to the percentage of the full storage capacity of a system discharged before the storage system is recharged (Carnegie et al. 2013).

Frequency of discharge relates to how many times a storage system power is discharged.

Depending on the type of the storage technology, the depth of discharge can be something to worry about. Deep discharge can reduce the lifetime of some electromechanical batteries and cause damage to the battery cells. Other technologies operate best under full or 100 percent depth of discharge (Carnegie et al. 2013).

Efficiency

Efficiency relates to the energy ratio of the input to the output for a charge-discharge cycle.

Energy efficiency determines how good a storage system by indicating how much energy will be lost through the storing and discharging process. Energy can also be lost when the storage system is not being used. This type of energy loss is known as standby loss, which is a measure of how much energy is lost before the stored energy is discharged (Carnegie et al. 2013).

Chapter 3: Methodology

3.1 Chapter Overview

This chapter describes the design adopted by this research to achieve the aims and objectives as stated in chapter 1. The first section of this chapter discusses the research and development methodology used in this research project, the stages by which the methodology was implemented, and the research design; the second section details the task analysis; the third section details the software used in this research project; finally, the last section discusses the assessment of consequential effects and ethical responsibilities.

3.2 Research and Development Methods

The research and development methodology used in this design project was based on various literatures. The aim of the design project was achieved based on knowledge from previous work. Different methodologies were used to achieve the goal of this research project.

At energy consumers' level, an energy audit was conducted on several households in order estimate the average power demand per household throughout the day. The collected data was used to determine the average energy required to run a typical household over the course of the peak demand period. From the collected data, power consumption graphs were generated using Microsoft Excel. Generated graphs helped visualise power demand patterns, the average demand (used as base load), determine where the peak demand occurs and the size of the peak demand. The results from the graphs were used to design an energy storage system to meet the power and energy requirements for a typical household over the course of the peak period.

At utilities level, an analysis was conducted on the NSW network to determine the size of the peak demand and the available capacity to charge energy storage systems in the off peak period without creating a peak demand during both summer and winter. NSW demand data was retrieved from the Australian Energy Market Operator (AEMO) network demand database. The retrieved demand data was used to determine the network average load, the size of the peak demand under winter and summer conditions, the available capacity to charge energy storage systems in the off peak period without creating a peak demand.

A MATLAB algorithm was used to analyse network power flow under different conditions. This enabled analysis of voltage levels at different nodes of the network to evaluate voltage regulation capability of distributed energy storage systems.

Cost effectiveness of energy storage systems was simulated using HOMER ENERGY software in order to determine whether using energy storage systems is beneficial to energy consumers compared with purchasing energy from the electricity grid.

3.3 Task Analysis

- The project methodology was simplified into the following major steps.
- Determine energy required to run a typical household over the course of the peak demand period.
- Design an energy storage system to meet power and energy requirements for a typical household.
- Determine network peak demand size.

- Determine network available capacity to charge energy storage systems without creating a peak demand in the off peak period.
- Determine the maximum number of households that the network can charge during the off peak period.
- Determine the minimum number of households required to use energy storage systems during peak periods in order to avoid the network peak demand.
- Model the effectiveness of distributed energy storage systems on the NSW network.
- Analyse power flow within the network to evaluate voltage regulation capability of distributed energy storage systems.
- Simulate cost effectiveness of energy storage systems.
- The tasks identified above were set as major sections of the project design and used to assess the progress of the design project.

3.4 Software

The software used in this research project includes:

- Microsoft Excel for data processing
- MATLAB for power flow analysis
- HOMER ENERGY for cost effectiveness of energy storage systems

3.5 Assessment of consequential effects and ethical responsibilities

3.5.1 Sustainability

In this project, no manufacturing is required other than using the available resources. The use of this system is reflective of the current sustainability regulations and guidelines.

3.5.2 Ethical Responsibilities

According to Engineers Australia (2010), all members of Engineers must commit to practice in accordance with the following four Code of Ethics.

1. **Demonstrate integrity:** Act on the basis of a well-informed conscience, be honest and trustworthy, respect the dignity of all persons.

2. **Practise competency:** Maintain and develop knowledge and skills, represent areas of competence objectively, act on the basis of adequate knowledge.

3. **Exercise leadership**: Uphold the reputation and trustworthiness of the practice of engineering, support and encourage diversity, communicate honestly and effectively, taking into account the reliance of others on engineering expertise.

4. **Promote sustainability:** Engage responsibly with the community and other stakeholders**,** practise engineering to foster the health, safety and wellbeing of the community and the environment, balance the needs of the present with the needs of future generations.

3.5.3 Safety

In this research project, prolonged use of a personal computer was involved. When using a computer, it is recommended that proper use of a computer is followed to avoid any stress related injury, degenerative eye problem or back and posture problems.

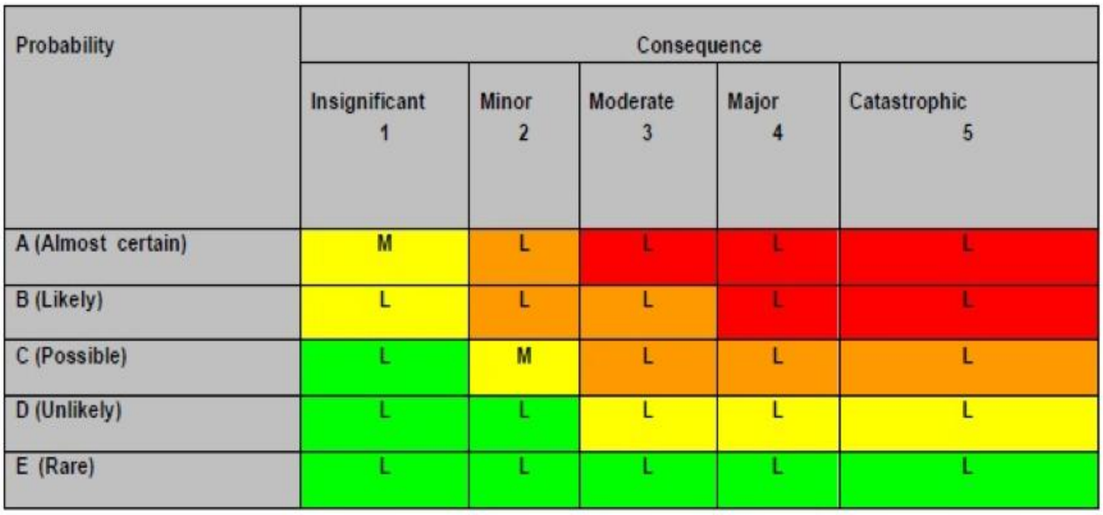
3.5.4 Risk Assessment

This research project involved prolonged use of a computer. The activity required risk assessment of a computer. The risk assessment induction was conducted to identify risks involved with prolonged use of a computer. In this case, factors that can affect a computer user were assessed.

Table 3.1 : Risk Assessment for a computer

Problem	Existing control	Consequences	Probability
Eye strain	**General Precautions**	**-Visual fatigue** **-Blurred or double vision** **-Burning and watering eyes** **-Headaches and frequent changes in prescription glasses**	**Rare**
Musculoskeletal	**General precautions**	**-Upper limb disorder** **-Back and neck pain and discomfort** **-Tension stress headaches and related ailments**	**Rare**

Table 3-2 : Risk rating.



Probability	Consequence				
	Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
A (Almost certain)	M	L	L	L	L
B (Likely)	L	L	L	L	L
C (Possible)	L	M	L	L	L
D (Unlikely)	L	L	L	L	L
E (Rare)	L	L	L	L	L

Using a computer for a prolonged period of time involves potential stress related injury, degenerative eye problem, back and posture problems.

3.6 Chapter summary

The purpose of this chapter was to describe the research methodology of this research project. The tasks required for completion of this research project were outlined and the risk assessment of the project was carried out in relation to prolonged use of a computer.

Chapter 4: Analysis

4.1 Chapter Overview

This chapter discusses the details of the design approach based on the knowledge from the literature reviewed in chapter 2 and the details provided in methodology chapter 3. The discussion in this section is based on the use of distributed energy storage systems to avoid the network peak demand. This was achieved by developing an energy storage system that, when used to store the extra electricity available in the off peak period and discharging it during the peak period in an urban area, can help improve utilisation of network assets.

4.2 Ideal System Design Setup

The system design setup below is a model of a practical energy storage system design that could be implemented in a practical setting.

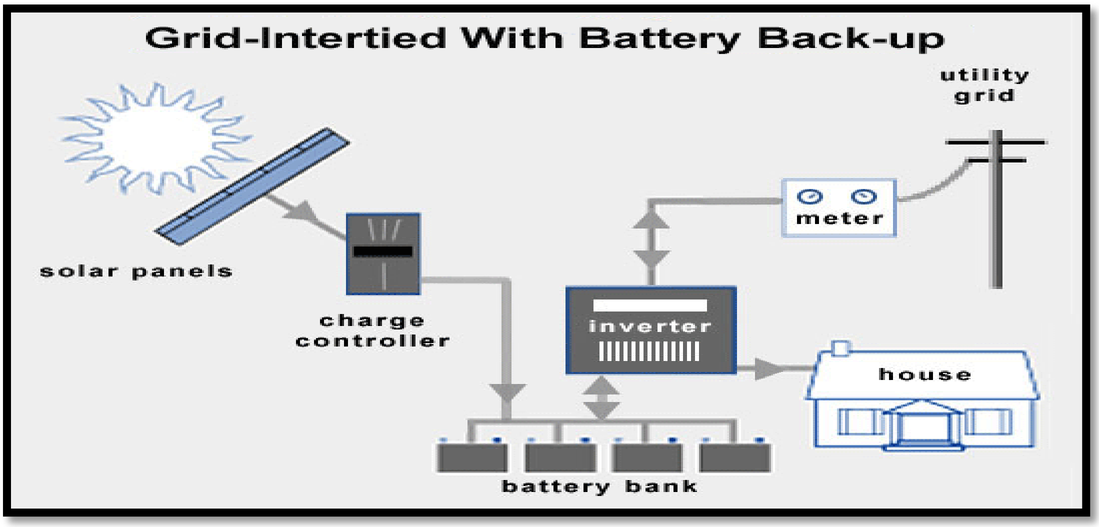


Figure 4.1: Ideal set up of an energy storage system (Home Brew Power, 2014).

4.3 Power Demand and Energy Consumption for a Typical Household

4.3.1 Peak Lopping

This approach looks at the storage capacity required to help maintain energy consumption below the base load over the course of peak demand. In this case, the base load is supplied from the grid while the storage system supplies the extra energy to cover the area above the base load.

4.3.2 Power Demand Analysis for a Typical Household

The amount of energy required to supply the energy above the base load during peak period was approximated by arranging common household appliances by their likely times of use under both summer and winter conditions.

It is good to note that the demand pattern might be different for each state of Australia due to climatic variations, the use of gas for heating and hot water, and different household appliance penetration rates.

The list of common household appliances, their models and power ratings is shown in Table 4.1.

Table 0-1 : Power usage for common appliances likely to be used during peak demand times

Appliances	Model	Power (Watts)	Quantity
Air Conditioner	LG-E18AWN-13-Eco Inverter RC Split System	Cooling :1,390 Heating : 1,540	1
Electric Cooker	Everdure 900X	8900	1
Range (Electric Oven)	Everdure OBES602	3100	1
TV	LG 42LV3500 (42”)	87	1
Microwave Oven	Panasonic	800	1
Refrigerator	LG 951L French Door Fridge	500	1
Washing Machine		1200	1
Dishwasher		500	1
Electric Hot Water	Dux Proflo 400L	3600	1
Dryer	Simpson 39P400M	2100	1
Slice Toaster	Chief CF CT50	870	1
Water Kettle	Homemaker WK8261A	2200	1
Laptop Computers	Dell Optiplex 9010	43	4
Lighting	Crompton FL8D/R	8	8
Phones	Iphone 5C	5	4
Average Standby Mode		81.8	

An Excel spreadsheet of the above listed appliances was created. The appliances were arranged based on their expected operating times in order to approximate a load curve. A time interval of 5 minutes was used to account for appliances that only run for a short period of time such as the water kettle and the slice toaster.

4.3.3 Winter Energy Requirement

The Winter evening peak demand results from a combination of energy consuming activities such as warming the house, cooking, watching TV, making tea, toasting, running a couple of computers and keeping a couple of lights on. The resulting power demand pattern is shown in Figure 4.2.

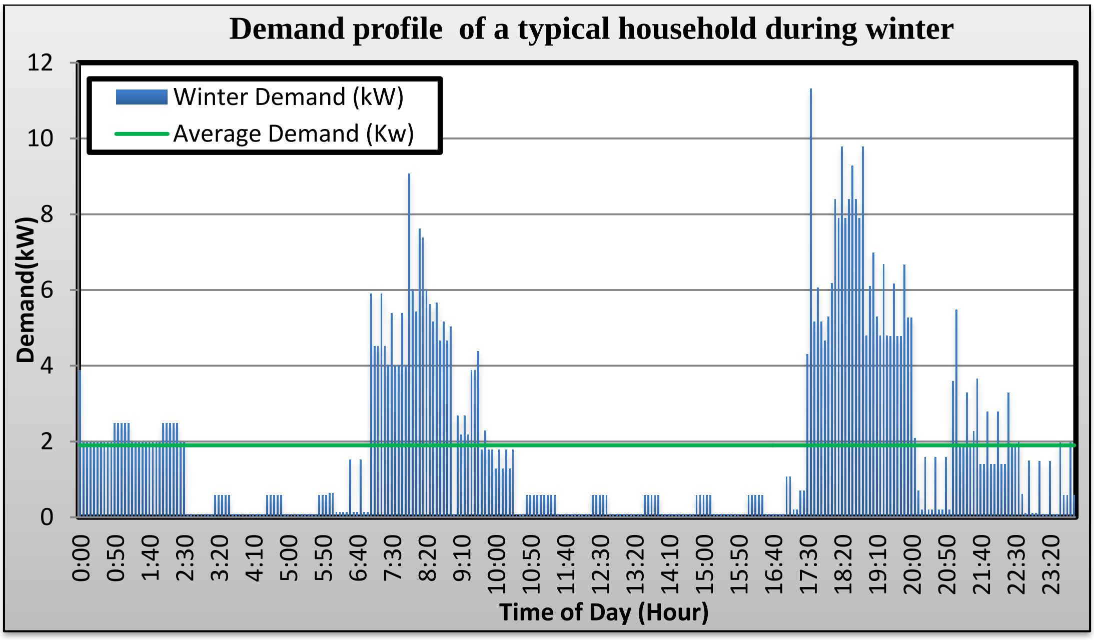


Figure 4.2: Demand profile for a typical household during winter

4.3.3.1 Winter evening peak lopping

The amount of energy to be supplied from the energy storage system during winter was determined by calculating the area above the average demand during the peak period (2:00pm to 8:00pm). The area was approximated using Riemann's sums method.

$$Energy = \sum_{i=0}^{n-1} f(x_i)\Delta x \qquad and \qquad \Delta_x = \frac{b-a}{n}$$

Where:

- Δ_x : the width of the rectangles
- $f(x_i)$: the height of the rectangles
- n : number of subintervals
- Area interval : [a, b]

The obtained energy require

$$\text{Energy required} = \sum_{i=0}^{n-1} f(x_i)\Delta x = 12 \text{ kWh}$$

4.3.4 Summer Energy Requirement

Summer evening peak time power consumption is very comparable to winter evening peak time consumption and they both tend to occur around the same period because in both cases, high power consuming appliances are mostly used at times when people get back from work and start running multiple appliances simultaneously. The summer demand profile for a typical household is shown in Figure 4.3.

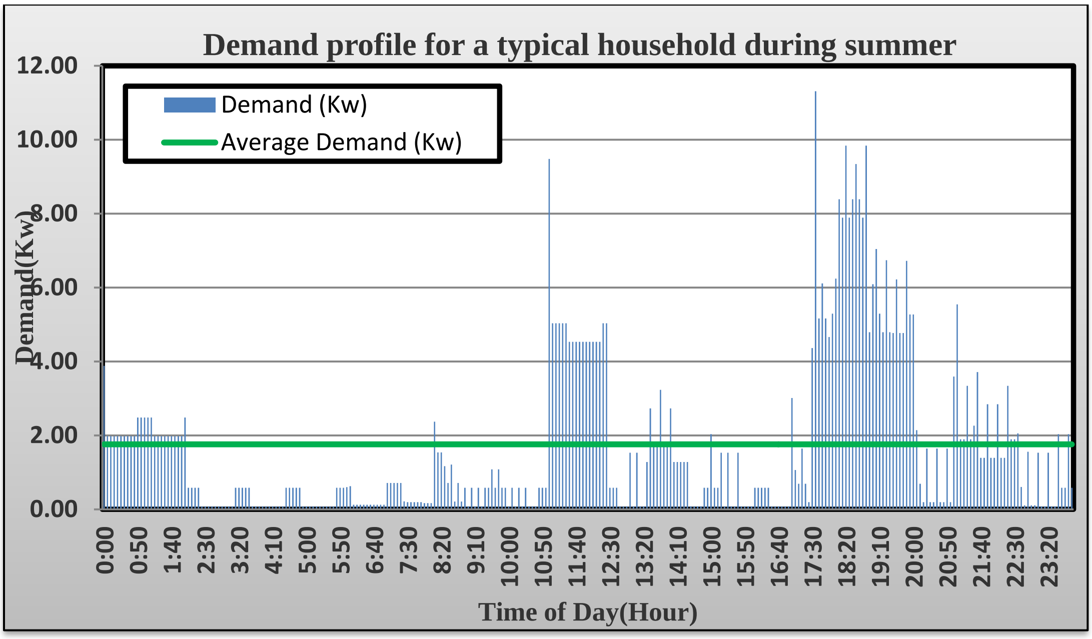


Figure 4.3: Demand profile for a typical household during summer

4.3.4.1 Summer evening peak lopping

The amount of energy to be supplied from the energy storage system during summer was determined sing Riemann sums method as indicated for the winter case.

$$\text{Energy required} = \sum_{i=0}^{n-1} f(x_i)\Delta x \approx 11 \text{ kWh}$$

From the energy requirement calculations, it was observed that the winter evening peak lopping required more energy than the summer evening peak lopping. To ensure the storage system would be able to supply the required energy for peak lopping throughout the year, the worst case between winter and summer was set as the maximum energy required. The energy required was set to 12kWh.

4.4 Network Parameter Assessment

Analysis of the network was conducted based on network demand data from the AEMO (Australian Energy Market Operator). AEMO stores network demand data in CSV format and can be easily graphed using Excel. For the purpose of this research project, the NSW1 Region network was considered.

Based on graphs generated from the demand data, the size of the evening network peak demand was determined. Calculating the size of the peak demand was essential to determine the minimum number of households that would be required to switch to energy storage systems during peak period in order to avoid the peak demand.

The second approach was to calculate the available network capacity to charge the energy storage systems in the off peak period without creating a peak demand. This was essential to determine the maximum number of households that would be charged using the available off peak capacity.

As the aim is to avoid peak demand by using distributed energy storage systems charged during the off peak period, only peak and off peak times were considered. The New South Wales peak and off peak times were used to match the network used for analysis in this research project. According to Ausgrid (2014), the three different time periods in NSW are:

Peak time: 2:00pm - 8:00 pm (week days)

Off peak time: 10:00 pm -7:00 (week days)

Shoulder: 7:00 am -2:00 pm and 8:00 am – 10:00 pm (week days)

The above time periods were used throughout the calculations as limits when determining the range of the curves for which the area was to be calculated.

4.4.1 Network Analysis under Winter Conditions

The NSW winter network demand graph is shown in Figure 4.4.

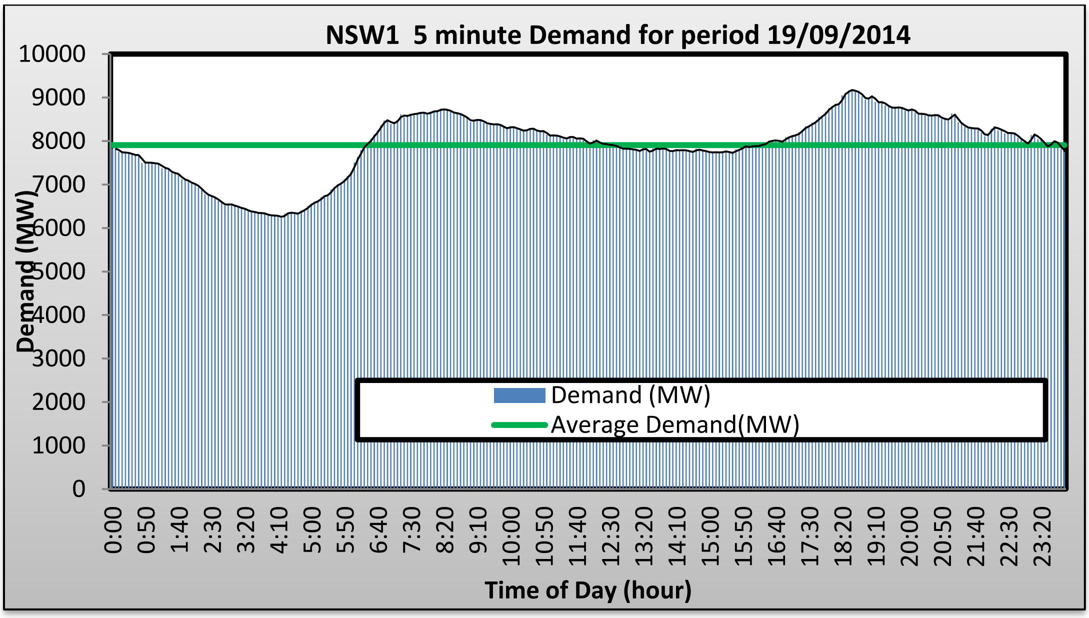


Figure 4.4: NSW1 Demand on a Typical Winter Day (AEMO, 2014)

In order to estimate the network capacity available for charging the energy storage systems during the off peak period and the size of the peak demand, Figure 4.5 was altered in order to highlight the curves for which the areas were to be calculated. The resulting figure is shown in Figure 4.6.

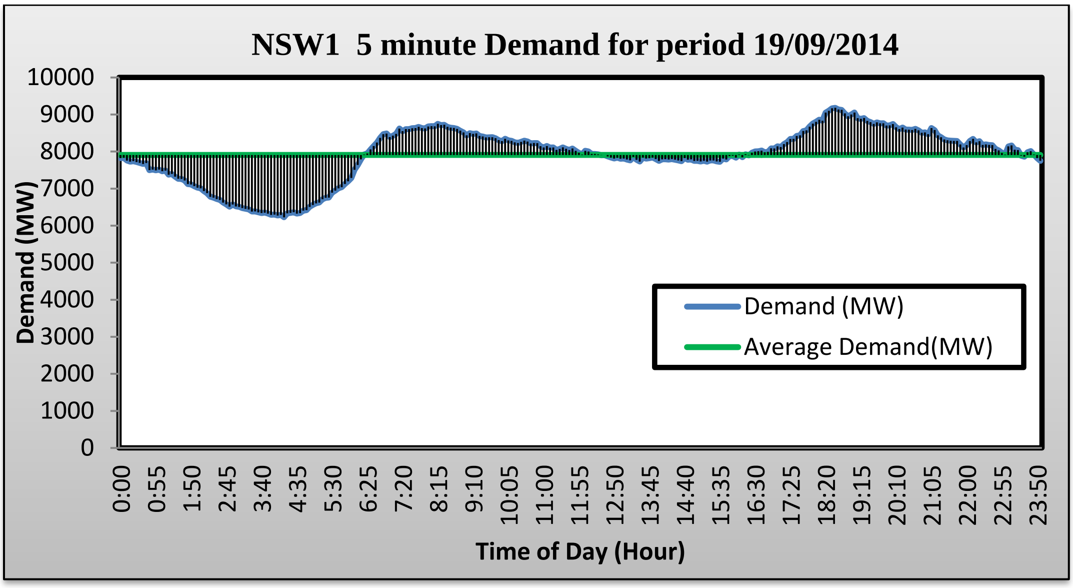


Figure 4.5: Winter Network Peak Demand and Available Capacity

4.4.1.1 Winter Off Peak Charging Capacity

The available network capacity for charging the storage systems during the off peak period was determined by approximating the area below the base load line that falls between 10:00pm -7:00am (off-peak period). This was achieved using the Riemann sums method. The following left-hand sum formula was used.

$$Energy = \sum_{i=0}^{n-1} f(x_i)\Delta x \approx 6{,}250 \text{ MWh}$$

4.4.1.2 Daily energy required to recharge the storage system during winter.

From previous calculations, the energy required to supply the evening peak demand during winter was determined to be 12kWh. From this, the energy from the electrical grid was calculated by applying the corresponding efficiencies of the equipment involved in the charging and discharging processes.

Energy out of the inverter = $\frac{12kWh}{0.9}$ = 13kWh (90% inverter efficiency)

Energy stored in the battery bank = $\frac{13kWh}{0.8}$ =16kWh (80% battery efficiency)

Energy from the electrical grid= $\frac{16kWh}{0.8}$ = 20kWh (80% charger efficiency)

4.4.1.3 Winter Off Peak Charging Limit

Based on the available capacity to charge storage systems in the winter off peak period, the number of maximum households that could be charged was determined. This was achieved by dividing the available capacity by the energy required from the grid to fully charge a single energy storage system.

Maximum households to be charged = $\frac{6{,}250MWh}{20kWh/household}$ $\approx$ 312,500 households

4.4.1.4 Peak Demand Size During Winter

To determine whether the number of households charged during the off peak period would supply enough energy to avoid the network evening peak demand, the network peak energy demand size was calculated using the Riemann left-hand sum method. It should be noted that only the evening peak area that falls between 2:00pm -8:00pm (peak period) was included in the calculation. The following left-hand sum formula was used.

$$Energy = \sum_{i=0}^{n-1} f(x_i)\Delta x \approx 2{,}500\text{MWh}$$

4.4.1.5 Winter Minimum Charging Requirement

To analyse effects of the charged energy storage systems on the grid, the minimum number of households required to use distributed energy storage systems during the evening peak period in order to avoid the peak demand was calculated. This was achieved by dividing the energy required to avoid the network winter peak demand by the energy supplied by storage systems per household.

$$\text{Minimum households required} = \frac{2{,}500MWh}{12kWh/household} \approx 208{,}000 \text{ households}$$

4.4.2 Network analysis under summer conditions

The NSW1 summer network demand graph is shown in figure 4.6.

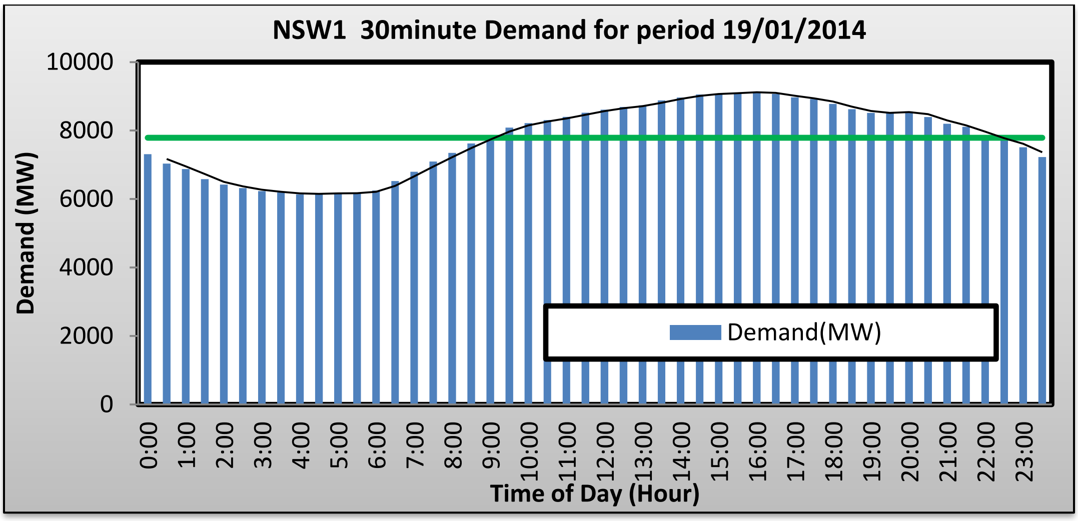


Figure 4.6: NSW1 Demand on a Typical Summer Day (AEMO, 2014)

In order to calculate the available capacity on the network to charge the storage systems during the off peak period and the size of the peak demand, Figure5-8 was altered in order to highlight the curves for which the areas are to be calculated. The resulting figure is shown in Figure 4.7.

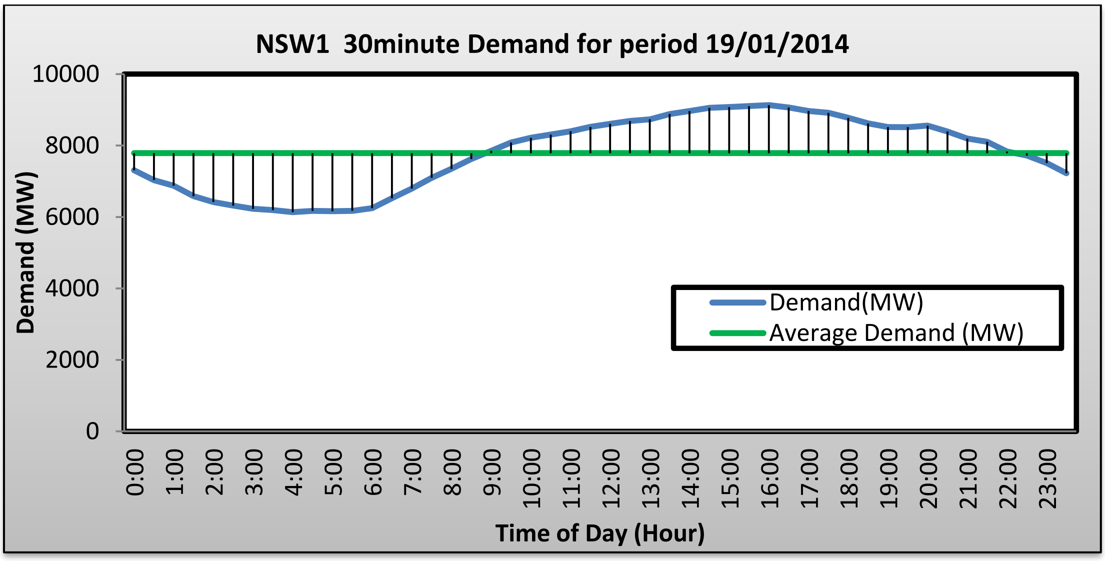


Figure 4.7: Summer Network Peak Demand and Available Capacity

4.4.2.1 Summer Off Peak Charging Capacity

The available network capacity for charging the storage systems during the off peak period was determined by approximating the area below the base load line that falls between 10:00pm -7:00am (off-peak period). This was achieved using the Riemann sums method. The following left-hand sum formula was used.

$$Capacity = \sum_{i=0}^{n-1} f(x_i)\Delta x \approx 10{,}300 \text{ MWh}$$

4.4.2.2 Daily Energy Required to Recharge the Storage System during Summer.

From previous calculations, the energy required to supply the evening peak demand during summer was determined to be 11kWh. From this, the energy from the electrical grid was calculated by applying the corresponding efficiencies of the equipment involved in the charging and discharging processes.

Energy out of the inverter = $\frac{11kWh}{0.9}$ = 12kWh (90% inverter efficiency)

Energy stored in the battery bank = $\frac{12kWh}{0.8}$ =15kWh (80% battery efficiency)

Energy from the electrical grid= $\frac{15kWh}{0.8}$ = 19kWh (80% charger efficiency)

4.4.2.3 Summer Off Peak Charging Limit

Based on the available capacity to charge storage systems in the summer off peak period, the number of maximum households that could be charged was determined. This was achieved by dividing the available capacity by the energy required from the grid to fully charge a single energy storage system.

Maximum households to be charged = $\frac{10{,}300MWh}{19kWh/household}$ ≈ 540,000 households

4.4.2.4 Peak Demand Size During Summer

To determine whether the number of households charged during the off peak period would supply enough energy to avoid the network evening peak demand, the network peak energy demand size was calculated using the Riemann left-hand sums method. It should be noted that only the evening peak area that falls between 2:00pm

-8:00pm (peak period) was included in the calculation. The following left-hand sum formula was used.

$$Energy = \sum_{i=0}^{n-1} f(x_i)\Delta x \approx 7{,}000\text{MWh}$$

4.4.2.5 Summer Minimum Charging Requirement

The minimum number of households to be programmed to use energy storage systems during the peak period was determined by dividing the network peak demand by the amount of energy to be supplied by each household.

$$\text{Minimum households required} = \frac{7{,}000MWh}{11kWh/household} \approx 636{,}000 \text{ households}$$

4.5 Effectiveness of Distributed ESS on the NSW1 Network

4.5.1 Effectiveness During Winter

Based on results from calculations, it was found that during wither the network would be able to charge up to about 312,500 households while the minimum number of households required to use distributed energy storage systems during peak period in order to avoid the peak demand was 208,000 households.

$$\text{Energy supplied by storage systems} = \frac{312{,}500households}{208{,}000households} x100 \approx 150\% \text{ of peak.}$$

The charged households could supply up to about 150 percent of the winter peak demand. This resulted in a demand below the average load.

Evening Peak reduction = (Original peak – Resulting peak)

Original peak demand = 9179 MW

Resulting evening peak demand =7926 MW (Below the average load, 7985MW)

Evening Peak reduction = 9,179 MWh – 7,926 MW

=1,250 MW

Simulation of the effectiveness of distributed energy storage systems on the NSW1 network during winter is shown in Figure 4.8. From the simulated results, it was observed that, charging in the off peak period did not significantly affect the average demand load. As the charged energy storage systems could supply up to 150 percent of the peak demand, the original peak demand could be totally avoided.

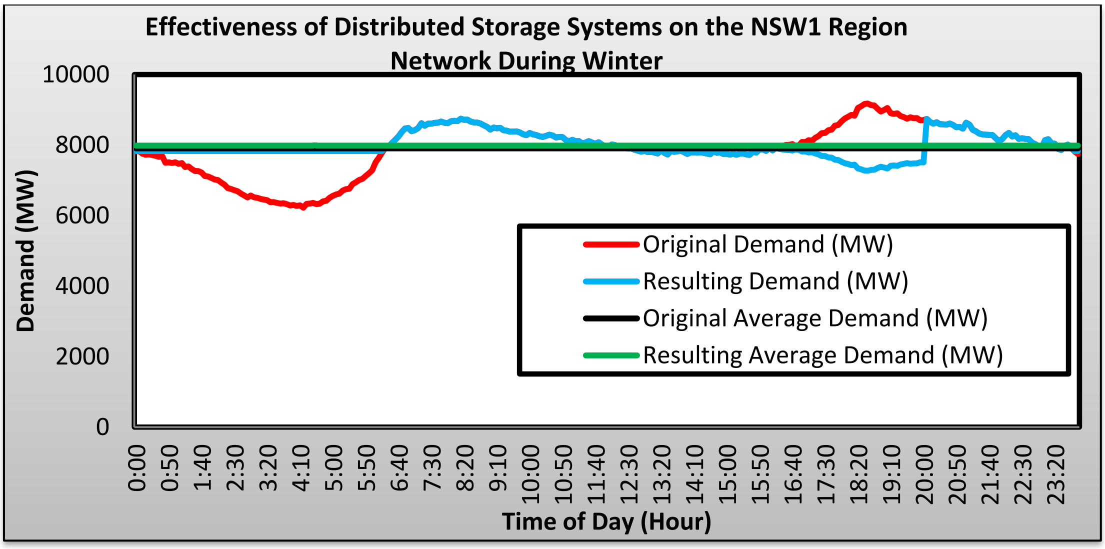


Figure 4.8: Effectiveness of Distributed Energy Storage Systems on the NSW Network during winter.

4.5.2 Effectiveness during summer

During summer the network could charge up to about 540,000 households. The minimum number of households to be programmed to use energy storage systems during peak period was 636,000 households. Percentagewise, charged storage systems could supply up to:

$$\text{Energy supplied by storage systems} = \frac{540{,}000\,households}{636{,}000\,households}\,x100 \approx 85\% \text{ of peak.}$$

Evening Peak reduction = Original peak – Resulting peak

Original peak demand = 9,132 MW

Resulting evening peak demand =7,922 MW (Same as the average load)

Evening Peak reduction = 9,132MW – 7,922MW =1,210 MW

Simulation of the effectiveness of distributed energy storage systems on the NSW1 network during summer is shown in Figure 5-10. As the charged energy storage systems could supply up to 85% of the peak demand, the original evening peak demand could be totally avoided.

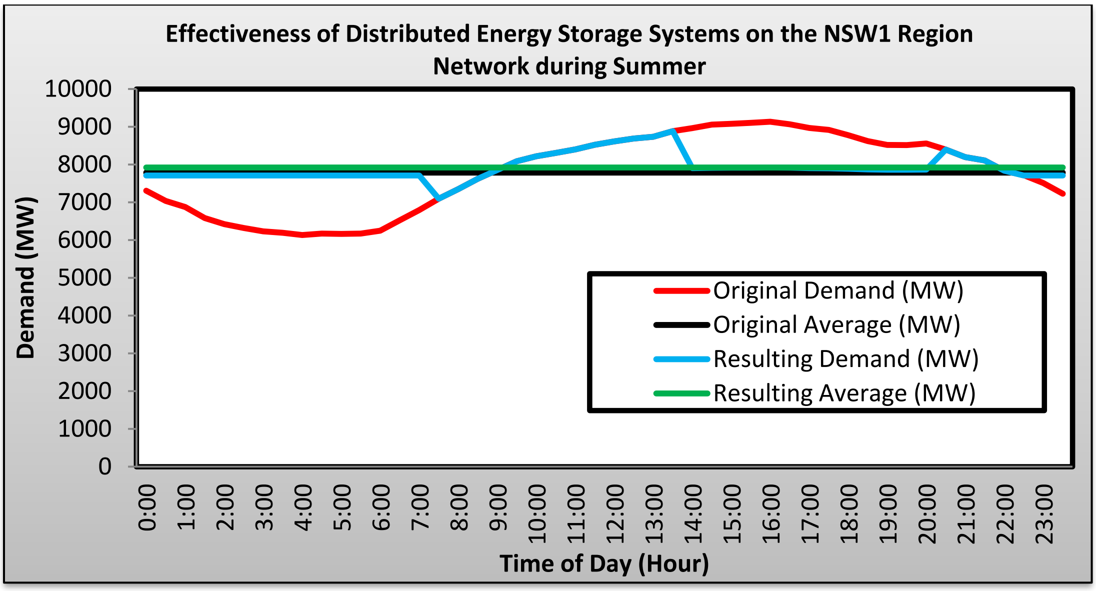


Figure 4.9: Effectiveness of Distributed Energy Storage Systems on the NSW Network during summer.

From the graph, it can be observed that, all the off peak capacity was used to charge the storage systems, which caused the demand to rise up and create a new average demand, which hardly noticeable. Even though, the charged storage systems could only supply up to about 85 percent of the peak demand, the simulated results indicated that the resulting demand during the peak period still would fall a bit below the resulting average demand. This resulted from the fact that the original peak demand significantly decreased while the average demand increased.

The effectiveness of distributed energy storage systems is marked by the difference in levels between the red curve and the blue curve. This indicates where the charging and discharging occurred.

4.6 Network Capacity Utilisation Improvement

Network demand data collected from AEMO (Australian Energy Market Operator) for the day 19th September 2014 was used to represent network demand under winter conditions and the data collected for day 1st January 2014 was used to represent network demand under summer conditions. The information was used to analyse possible improvement on the network capacity utilisation based on the peak demand reduction results. Network capacity utilisation was determined based on the definition given in section 2.2.1.

The network installed capacities to meet the peak demand on the chosen days for analysis were obtained from EMAO database. The scheduled capacity was used as the network installed capacity. The following formula was derived from the capacity utilisation definition and used to determine the network utilisation factor.

$$\text{Capacity utilisation} = \frac{AverageDemand}{InstalledCapacity}$$

4.6.1 Winter Capacity Utilisation Improvement

4.6.1.1 Original Network Capacity Utilisation During Winter

Calculation of network capacity utilisation before application of distributed energy storage systems.

Average network demand = 7,900 MW

Scheduled capacity to meet demand = 9,629 MW

$$\text{Capacity utilisation} = \frac{7{,}9000 MW}{9{,}629 MW} = 82\%$$

Originally, the network capacity utilisation was calculated to be 82 percent of the scheduled capacity to meet the peak demand.

4.6.1.2 Resulting Network Capacity Utilisation During Winter

Calculation of network capacity utilisation after application of distributed energy storage systems.

Resulting average network demand = 8,012 MW
Resulting highest network demand = 8,747 MW

From previous calculations, a 1,250 MW reduction in winter generation capacity was found.

Resulting generation capacity to meet peak demand = (9,629 -1,250) MW

= 8,379 MW

$$\text{Capacity utilisation} = \frac{8{,}747 MW}{8{,}379 MW} = 100\%$$

With the reduction in peak demand, the network capacity utilisation could be improved from the original 82 percent up to 100 percent of the scheduled capacity under winter conditions.

4.6.2 Summer Capacity Utilisation Improvement

4.6.2.1 Original network Capacity Utilisation During Summer

Calculation of network capacity utilisation before application of distributed energy storage systems.

Average network demand = 7,788 MW
Scheduled capacity to meet demand = 11,384 MW

$$\text{Capacity utilisation} = \frac{7{,}788MW}{11{,}384MW} = 68\%$$

Originally, the network capacity utilisation during summer was calculated to be 68 percent of the scheduled capacity.

4.6.2.2 Resulting Network Capacity Utilisation During Summer

Calculation of network capacity utilisation after application of distributed energy storage systems.

Resulting average network demand = 7,953 MW

highest network demand = 8,883 MW

With the highest demand reduced to 8,883 MW, the scheduled capacity to meet the highest demand would reduce accordingly. From previous calculations, a 1,210 MW reduction in summer generation capacity was found.

Resulting generation capacity to meet peak demand is = (11,384-1,210) MW

= 10,174 MW

$$\text{Capacity utilisation} = \frac{7{,}953MW}{10{,}174MW} = 78\%$$

With the reduction in peak demand, the network capacity utilisation could be improved from the original 68 percent up to 78 percent under summer conditions.

4.7 Power Flow Analysis

Network load flow analysis was conducted in order to analyse the effectiveness of distributed energy storage systems when used for voltage regulation. This was achieved using Newton –Raphson load flow method. The system used for analysis reasons consists of a Single Wire Earth Return (SWER) transmission line feeding two distribution lines (feeders). The network is shown in Figure 4.2.

The following parameters were considered at a given bus in the network:

Table 0.2 : Network parameters

PARAMETERS	VALUE
Base power (S_{base})	400kVA
Base voltage (V_{base})	19kV
Transmission transformer	400 kVA (22kV/19kV)
Feeder transformer	200kVA (22kV/19kV)
Length of transmission line	100 km
Length of feeders	50 km
Demand	50 % of transformer
Upper voltage level	1.06 p.u
Lower voltage level	0.94 p.u (+/- 6%)

- A fixed power generation that injects active power (P_g) and reactive power (Q_g) into the bus
- A fixed demand with active power P_d and reactive power Q_d

A MATLAB algorithm based on the Newton Raphson load flow method was used to analyse voltage changes at different nodes on the network. The MATLAB algorithm computes voltages at each node of the network under different load conditions.

The network consists of seven nodes, with nodes 5 and 7 representing load nodes. For the purpose of this research project, the focus was on the change in voltage at nodes 5 and node 7 during peak periods. The initial bus voltage was set at 1.05 p.u . The MATLAB algorithm was used to analyse the voltage change at all the seven nodes of the network when energy storage systems are not used and when energy storage systems are used on nodes 5 and 7.

4.7.1 Power Flow Under No -load Conditions

When no load is applied at nodes 5 and 7, P_d and Q_d =0 ; the results generated by the MATLAB algorithm are shown in Table 4.3.

Table 0.3 : Node voltages under no load conditions

Node number	Voltage (p.u)
Node 1	1.05
Node 2	1.05
Node 3	1.0497
Node 4	1.0489
Node 5	**1.0489**
Node 6	1.0489
Node 7	**1.0489**

The obtained results indicated that, under no load conditions, voltage levels at all nodes of the network are almost the same as the initial voltage of 1.05 p.u.

4.7.2 Power flow under load conditions

. With 50 % of transformer size as load during peak periods, the load at nodes 5 and 7 were set to 100kVA.

Apparent power (S) at nodes 5 and 7 = $\frac{100kVA}{400kVA} = 0.25p.u$

With a power factor (p.f) of 0.9

P_d= $Sxp.f = (0.25p.u)x(0.9) = 0.23p.u$ p

Q_d= $S.\sin\theta = 0.12p.u$

The values of P_d and Q_d were applied at nodes 5 and 7. The results generated by the MATLAB algorithm are shown in Table 4.4.

Table 0.4 : Node voltages with 100 kVA load

Node number	Voltage (p.u)
Node 1	1.05
Node 2	1.0287
Node 3	0.9838
Node 4	0.8865
Node 5	**0.8661**
Node 6	0.8865
Node 7	**0.8661**

With a load of 100kVA applied at nodes 5 and 7, the obtained results indicated that the network suffered a low voltage problem as the voltage levels dropped below the lower voltage level of 0.94 p.u as indicated by the red colour in Table 4-4.

4.7.3 Power Flow with Power Generated by ESS

Power generated by distributed energy storage systems was applied at nodes 5 and 7. With a combined power generation capacity of 25kVA by distributed energy storage systems applied at nodes 5 and 7:

$S_{ESS(5)} = S_{ESS(7)} = 25$ kVA ($S_{ESS(x)}$: apparent power generated by ESS at node x)

Apparent power (S) generated by ESS at nodes 5 and 7 = $\frac{25kVA}{400kVA} = 0.063p.u$

$P_g = Sxp.f = (0.063p.u)x(0.9) = 0.06p.u$

$Q_g = S.\sin\theta = 0.03p.u$

The values of P_g and Q_g were applied at nodes 5 and 7. The results generated by the MATLAB algorithm are shown in Table 4.5.

Table 0.5 : Node voltage with 25 kVA generated by ESS

Node number	**Voltage (p.u)**
Node 1	1.05
Node 2	1.0351
Node 3	1.0037
Node 4	0.9357
Node 5	**0.9214**
Node 6	0.9357
Node 7	**0.9214**

With 25kVA generated from energy storage systems, the results showed improved voltage levels from 0.8661p.u to 0.9214 p.u. Despite the improvement in voltage levels, more power generation was still required to lift the voltage levels up to the lower level of 0.94 p.u.

The generation capacity by distributed energy storage systems was increased to 40kVA.

$S_{ESS(5)} = S_{ESS(7)} = 40$ kVA ($S_{ESS(x)}$: apparent power generated by ESS at node x)

Apparent power (S) generated by ESS at nodes 5 and 7 = $\frac{40kVA}{400kVA} = 0.10p.u$

$P_g = Sxp.f = (0.10p.u)x(0.9) = 0.09p.u$

$Q_g = S.\sin\theta = 0.04p.u$

MATLAB results for increased generation of 40kVA by distributed energy storage systems are shown in Table 4-6.

Table 0.6 : Node voltages with 40kVA generated by ESS

Node number	**Voltage (p.u)**
Node 1	1.05
Node 2	1.0375
Node 3	1.0117
Node 4	0.9565
Node 5	**0.9444**
Node 6	0.9565
Node 7	**0.9444**

Obtained results showed that, for this particular system, increasing the power supplied by energy storage systems at demand nodes 5 and 7 increased voltage levels back to a level that falls within the acceptable range (0.94 p.u < **0.9444 p.u** < 1.06 p.u).

To further increase the voltage levels to more balanced levels within the limits, the distributed energy storage systems generation capacity was increased to 50kVA.

$S_{ESS(5)}$ = $S_{ESS(7)}$= 50 kVA ($S_{ESS(x)}$: apparent power generated by ESS at node x)

Apparent power (S) generated by ESS at nodes 5 and 7 = $\frac{50kVA}{400kVA} = 0.13p.u$

P_g= $Sxp.f = (0.13p.u)x(0.9) = 0.12p.u$

Q_g= $S.\sin\theta = 0.06p.u$

MATLAB results for a further increase in generation of 40kVA by distributed energy storage systems are shown in Table 4.7.The obtained results from MATLAB algorithm are shown in Table 4.7.

Table 0-7 : Node voltages with 50kVA generated by ESS

Node number	**Voltage (p.u)**
Node 1	1.05
Node 2	1.0407
Node 3	1.0211
Node 4	0.9789
Node 5	**0.9700**
Node 6	0.9789
Node 7	**0.9700**

Figure 4.10 shows the state of voltage levels at all the seven (7) network nodes under different conditions against the limit levels. Figure 4.10 gives a summary of MATLAB algorithm results as detailed from Table 4-3 through to Table 4.7. As shown in the figure, under no load condition, the voltage levels are well maintained at the upper end of the limits. With a 100 kVA load at demand nodes 5 and 7, the voltage levels drop significantly well below the lower end of the limits. Regulation of voltage levels improved with increase in power generation by distributed energy storage systems.

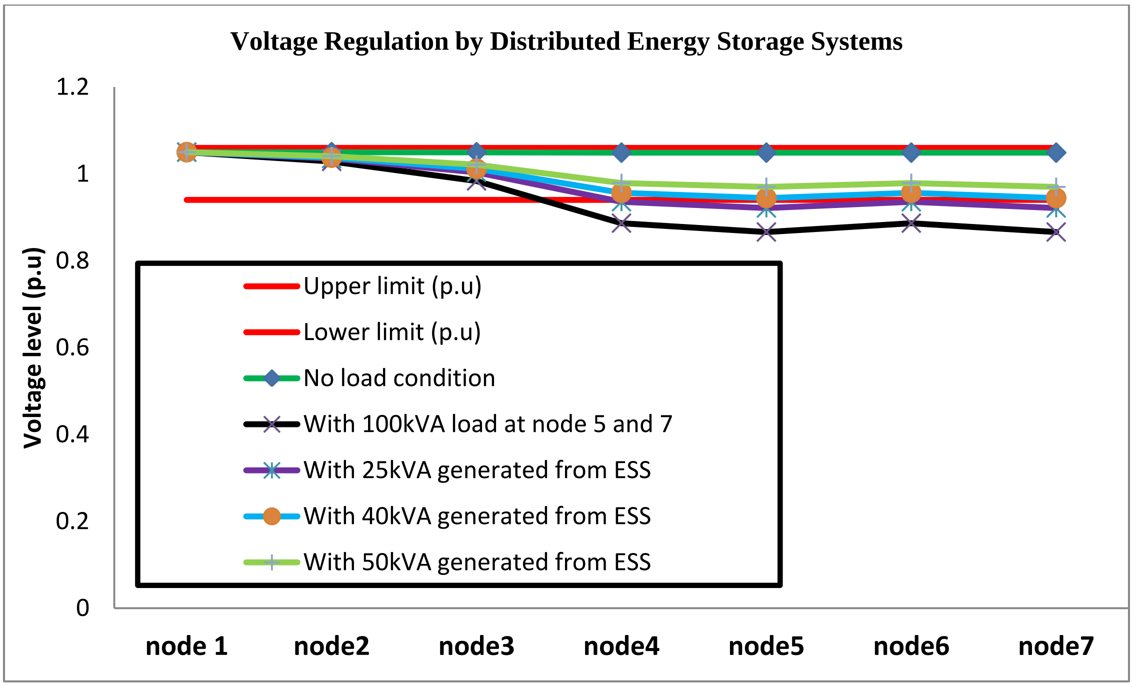


Figure 4.10: Voltage regulation by distributed energy storage systems

4.8 Design of an ESS to Meet Peak Demand Energy Requirements

In this section, an energy storage system to meet the design project energy requirements was designed. The size of a battery bank to store the amount of energy required to supply the peak demand was determined.

4.8.1 Sizing Battery Banks

4.8.1.1 Maximum Power Demand

The maximum power demand is the highest amount of power drawn at a particular time over the peak period. As the aim of the design project is based on supplying the extra energy above the base load, the maximum power was obtained by calculating the difference between the highest peak and the base load. From the winter and summer demand data, the highest power demand was found to be 9kW.

Inverter maximum power demand= 9kW

4.8.1.2 Battery Maximum Power Out

In order to determine the maximum power to be delivered by the inverter, The Battery power out was obtained by dividing the inverter maximum power demand by the efficiency of the inverter. An inverter efficiency of 90 % was considered.

Battery Maximum Power Out = (Inverter Maximum Demand) / (Inverter Efficiency)

$$= \frac{9kW}{0.9}$$

$$\approx 10\text{kW}$$

4.8.1.3 Battery Bank Discharge Rate

The battery discharge rate was obtained by dividing the battery power out by the battery voltage. To keep the size of components small and the cost of the system low, a current lower discharge rate was targeted. At the same current, power can be doubled by doubling the voltage. In this report, a 48V system was chosen.

From the relationship between Power, Voltage and Current:

$$\text{Amps (A)} = \frac{Power(W)}{Volt(V)}$$

$$\text{Discharge Rate} = \frac{10kW}{48V} \approx 200\,Amps$$

(Required under peak power conditions).

4.8.1.4 Energy To Be Stored For Peak Time

There are different types of losses that occur during the charging, storage, discharging and conversion of energy. The total energy required from the storage system must take into account these losses. These losses were added to the calculated energy needed to supply the peak demand.

4.8.1.5 Energy Out Of Inverter

The amount of energy that the inverter delivers to the grid is affected by the inverter efficiency. To be able to get the required energy from the inverter, the energy loss due to inverter efficiency was considered. A general inverter efficiency of 90% was considered.

$$\text{Energy out of the Inverter} = \frac{12kWh}{0.9} \approx 13\text{kWh}$$

4.8.1.6 Energy Stored In The Battery Bank

Due to battery efficiency, not all the energy stored into the battery will available for use. To account of this type of energy loss, a general battery efficiency of 80% was considered.

Energy stored in the battery = $\frac{13kWh}{0.8} \approx$ 16kWh

This is the energy that the battery system needs to be able to deliver at its depth of discharge. This is the adjusted energy required per day.

$\therefore$ 16kWh $\geq$ Energy at x % DoD.

- **For Lead Acid**, a DoD of 30% was considered.

Energy stored in the battery = $\frac{16kWh}{0.3} \approx$ **53kWh**

- **For Nickel-Ion**, a DoD of 60% was considered.

Energy stored in the battery = $\frac{16kWh}{0.6} \approx$ **27kWh**

- **Li-Ion**, a DoD of 60% was considered.

Energy stored in the battery = $\frac{16kWh}{0.6} \approx$ **27kWh**

4.8.1.7 Battery Bank Capacity

The battery bank size was chosen based on two criteria. These being energy storage and power delivery capability. From the calculations above we can deduce the following:

a) From peak demand calculations:

Using a C5 discharge rate:

AH Capacity= (200Ampsx5hr) =1,000AH

Energy rating= (1,000AH x 48V) = 48kWh

b) From energy storage calculations:

Energy required for AGM Lead Acid = 53kWh

AH Capacity = $\frac{53kWh}{48V} \approx 1100\text{AH}$

Energy required for Ni-Ion and Li-ion=27kWh

AH Capacity = $\frac{27kWh}{48V} \approx 560\text{AH}$

4.8.1.8 Battery Bank Specifications

Battery bank specifications based on calculation results are shown in Table4-8. As indicated in the table, the AGM L.A technology requires nearly twice the capacity and storage of Lithium-Ion or Nickel-Ion. This is mainly due to the fact that the depth of discharge (DoD) for Lead Acid was limited at only 30 percent while the depth of discharge for Nickel-Ion and Lithium-Ion was limited at twice as much (60 percent).

Table 0-8 : Battery Bank Specifications

Technology	DoD	Energy to Store	Discharge Rate	Capacity	System Voltage
AGM L.A	30%	55kWh	200 Amps	1150AH	48V
NiFe	60%	30kWh	200Amps	650AH	48V
LiFe	60%	30kWh	200Amps	650AH	48V

4.8.1.9 Battery Selection

Battery selection was based on the C10h capacity rating. The C-rate corresponds to the period over which the battery bank was to be discharged. In this design project, the C-rate considered represents the evening peak demand period from 5pm to about 9pm, which is 5 hours. To account for variations in energy demand, battery banks were oversized using a C10h rating instead of the actual C5h rating.

4.9 Cost Effectiveness Analysis Using HOMER ENERGY Software

4.9.1 Assumptions and Model Inputs

4.9.1.1 Load Profile

The load profile is based on average daily power consumption for a typical household. The data used was obtained by conducting an energy audit based on power demand pattern by time of use of common appliances over 24 hours.

The baseline, which is a one-year time series representing the average electric demand in kW for each time step of the year, was used in HOMER. The hourly load profile was obtained by creating a set of 24 hourly values of electric load, to represent the average hourly demand over 24 hours. HOMER synthesizes data by adding random values to the entered values for daily variability and time-step-to-time-step variability. The hourly load profile is shown in Figure 4.11.

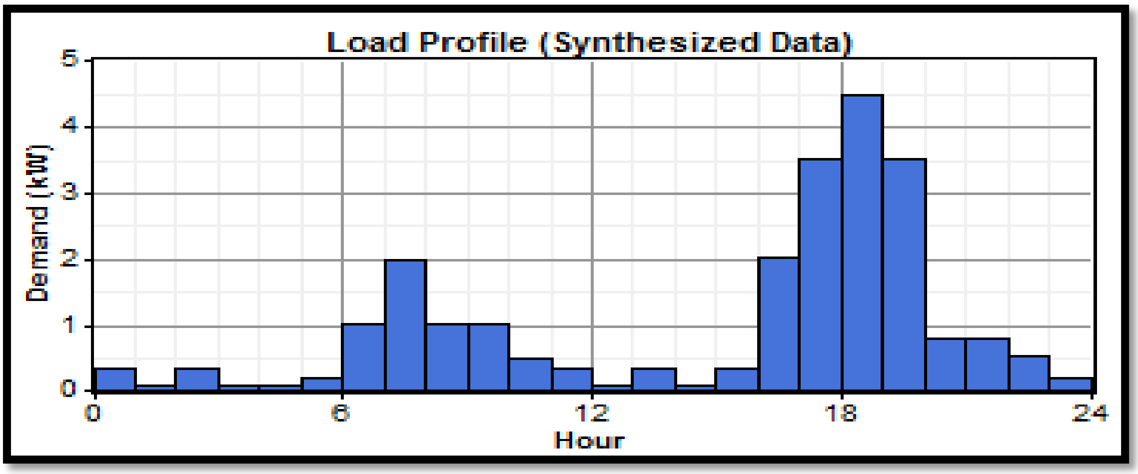


Figure 4.11: Hourly Load Profile

4.9.1.2 Solar Radiation Profile (Sydney)

Solar radiation data was obtained from NASA. The geographical position of Sydney is: latitude 33^0 52$^’$ S, longitude 151^0 13’ E. The scaled annual average solar radiation for Sydney of 4.45 kWh/m^2/ d. Homer uses the latitude value calculates the average daily radiation from the clearness index. Figure 4.12 shows solar radiation profile over a one year period.

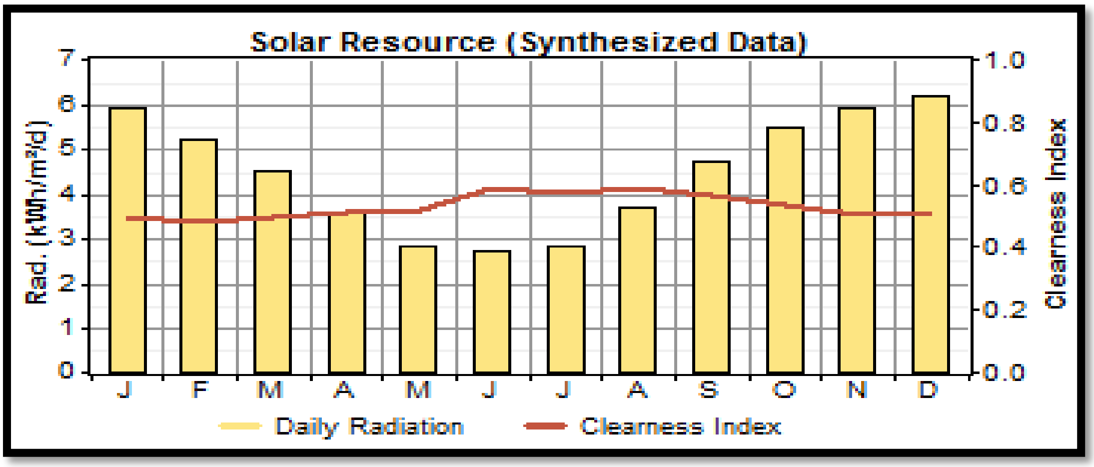


Figure 4.12: Solar Radiation Profile for Sydney (NSW)

4.9.1.3 Economics

An annual interest of 6% was assumed. The real interest is determined by the difference between the nominal interest rate and the inflation rate. The project lifetime of 20 years was considered. As the NSW network was considered for this design project, the NSW tariff was used to determine the cost of electricity.

4.9.1.4 System schematic

The list of equipment considered in the optimization is shown in Figure 4.13.The system includes a photovoltaic system, a converter, a battery bank and the load.

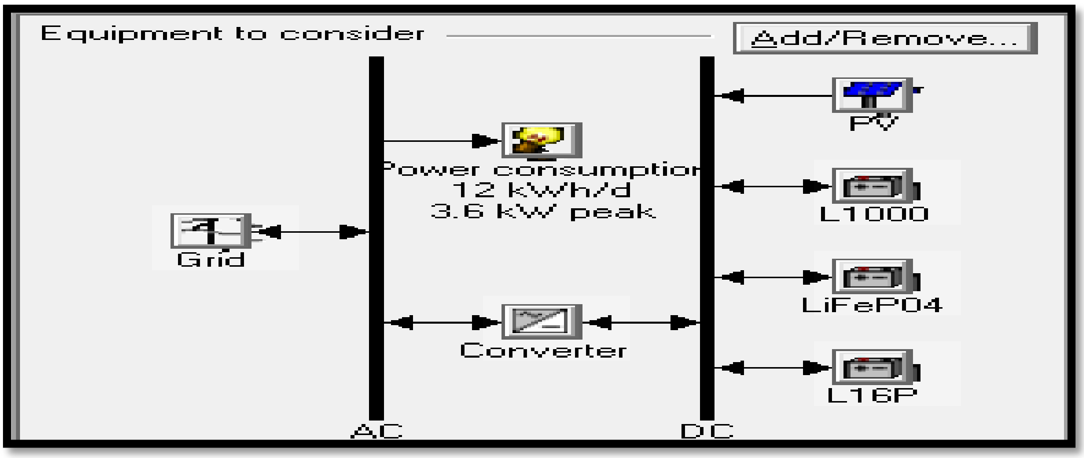


Figure 4.13: System schematic

4.9.1.5 Solar Power Feed-in Tariffs

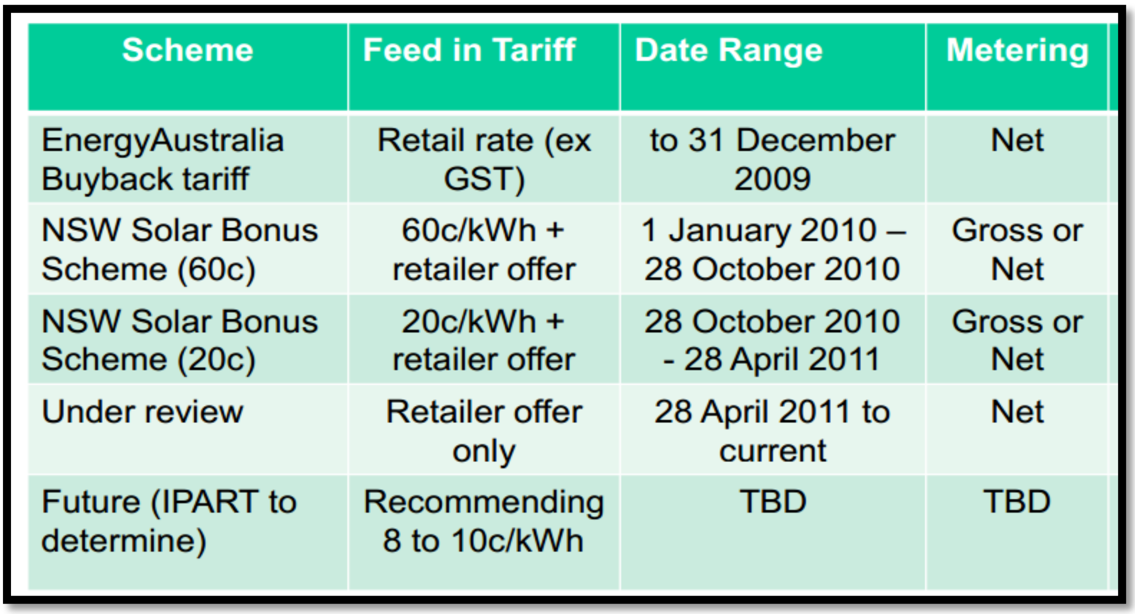
In NSW, feed-in rates are paid based on the solar system set up. This can be either Net or Gross Metering System.

Under a Net Metering System, electricity generated by the solar system is used first and if the system generates more than what is needed, the excess is fed into the electricity grid. A feed-in tariff per kWh is used to determine the cost, which is paid as credits on the customer’s bill.

Under a Gross Metering System, all the electricity generated by the solar system is fed into the electricity grid and the feed-in tariff per kWh is used to determine the cost, which is also paid as credits on the customer’s bill. In this case, the electricity purchased from the electricity grid is not reduced by the electricity produced by the solar system.

The history of feed in tariffs for the Ausgrid area is shown in Table 4-9.

Table 0.9 : History of feed in Tariff (Ausgrid, 2011)



Scheme	Feed in Tariff	Date Range	Metering
EnergyAustralia Buyback tariff	Retail rate (ex GST)	to 31 December 2009	Net
NSW Solar Bonus Scheme (60c)	60c/kWh + retailer offer	1 January 2010 – 28 October 2010	Gross or Net
NSW Solar Bonus Scheme (20c)	20c/kWh + retailer offer	28 October 2010 - 28 April 2011	Gross or Net
Under review	Retailer offer only	28 April 2011 to current	Net
Future (IPART to determine)	Recommending 8 to 10c/kWh	TBD	TBD

As of 2014, a voluntary feed-in tariff of 6c/kWh is offered for energy exported on the Ausgrid distribution zone (Origin Energy, 2014). This rate was used in HOMER as sellback rate.

4.9.1.6 Grid Inputs Profile

The rates at which electricity is charged in NSW during peak, off peak and shoulder periods were used to determine the cost of electricity. The rates were scheduled to determine when to charge and when not to charge the battery bank. The rates used were from Origin Energy Domestic TOUT effective 15 September 2014 (NSW Residential Energy Price Fact Sheet, 2014).

Table 0.10 : Grid Input Profile

Rate	**Power Price**	**Sellback Rate**	**Demand Rate**	**Applicable**
	$/kWh	$/kWh	$/kW/mo.	
Off Peak Rate	0.137	0	0	Jan-Dec All week 00:00-07:00, 22:00-24:00
Peak Rate	0.537	0.06	0	Jan-Dec Weekdays 14:00-20:00
Shoulder Rate	0.224	0.06	0	Jan-Dec Weekdays 07:00-14:00, 20:00-22:00 Jan-Dec Weekends 07:00-22:00

4.9.1.7 Photovoltaic Inputs

Different sizes of photovoltaic systems were input for HOMER to search for the most optimal system. The photovoltaic arrays considered included a 1.5Kw, 2Kw, 3kW, 4kW and 10kW. A derating factor of 90% was applied to the electric production from each panel. This factor accounts for reduced output in real-world operating conditions compared to operating conditions at which the array was rated. A lifetime of up to 25 years was considered.

4.9.1.8 Batteries

For the purpose of this research project, three main types of battery storage technologies were considered. This includes Lead Acid, Nickel Ion and Lithium Ion. For Lead Acid technology the Trojan L16 battery was considered, for the Nickel Ion technology the L1000AH was considered, and for the Lithium Ion technology the Smart Battery SB300 was considered.

Battery selection was based on different techniques. This included the battery capacity at the desired C-rating or the capacity available at the system discharge rate of 200 Amps.

4.9.1.9 Converters

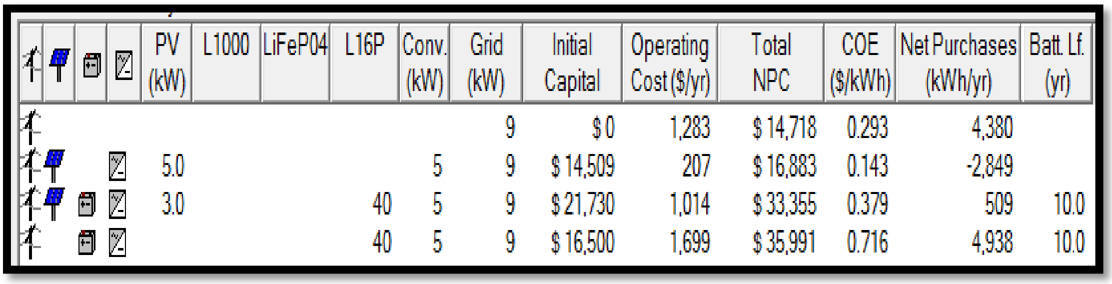
As the system contains both AC and DC elements, a converter is required. This allows conversion of DC electricity to AC electricity. Inverter and rectifier efficiencies were assumed to be 90 percent for all sizes considered. The sizes considered were 5kW, 8Kw and 16kW.

4.10 Simulation Results and Discussion

This section discusses simulation results. The discussion is based on the system performance and the cost analysis based on simulation results.

4.10.1 Results

The simulation results shown in Figure 4.14 were obtained from the system set up detailed in Figure 4.13. The simulation results in Figure 4.14 indicate possible system configurations and a list of configurations sorted by lifecycle cost.



PV (kW)	L1000	LiFeP04	L16P	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Net Purchases (kWh/yr)	Batt. Lf. (yr)
					9	$ 0	1,283	$ 14,718	0.293	4,380	
5.0				5	9	$ 14,509	207	$ 16,883	0.143	-2,849	
3.0			40	5	9	$ 21,730	1,014	$ 33,355	0.379	509	10.0
			40	5	9	$ 16,500	1,699	$ 35,991	0.716	4,938	10.0

Figure 4.14: Simulation results

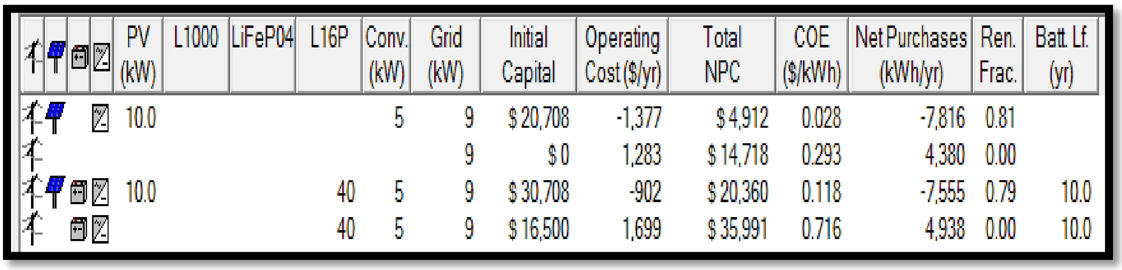
Simulated results can be used to compare possible system design options. The results indicated that purchasing electricity from the electric grid offers the least Net Present Cost and a levelized cost of electricity per kWh of 0.293.

Installing a photovoltaic system of 5kW without using a battery bank produced more energy than required with the excess energy being sold to the electricity grid at a voluntary feed-in tariff rate of 6c/kWh. Installing a 3kW photovoltaic system with a battery bank reduced the net energy purchases from 4,380kWh/year to only 509kWh/year. Using a battery bank to store electricity purchased from the electric grid was found to be the least cost effective option with the highest operating cost, total net present cost as well as cost of energy per kWh. This is mainly due to energy losses occurred during the charging and discharging processes.

4.10.1.1 Effects of Feed-in Tariffs on System Cost-effectiveness

For comparison reasons, former NSW Solar Bonus Schemes were used. The same system set up was used with the only difference being the feed-in tariff in order to analysis the effects of tariffs on simulation results.

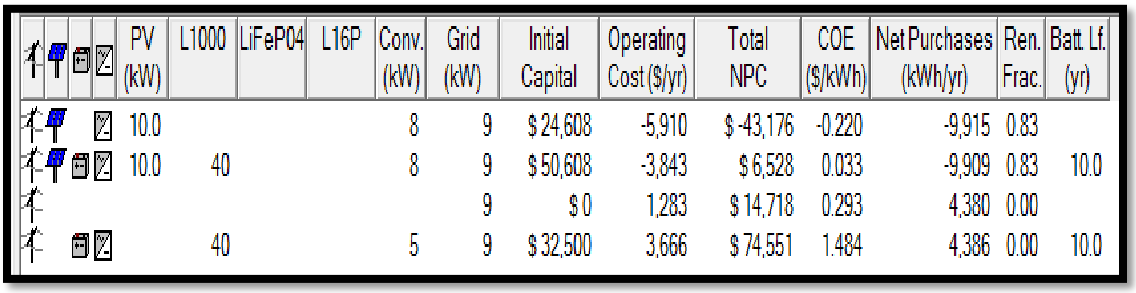
Under the NSW Solar Bonus Scheme of 20c/kWh feed-in tariff, simulation results indicated that installing a photovoltaic system without a battery bank was most cost-effective than purchasing electricity from the electric grid. However, at this feed-in tariff, purchasing from the electric grid still performed better than systems with battery banks. Simulation results at the NSW Solar Bonus Scheme (20c/kWh) are shown in Figure 4.15.



				PV (kW)	L1000	LiFeP04	L16P	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Net Purchases (kWh/yr)	Ren. Frac.	Batt. Lf. (yr)
				10.0				5	9	$ 20,708	-1,377	$ 4,912	0.028	-7,816	0.81	
									9	$ 0	1,283	$ 14,718	0.293	4,380	0.00	
				10.0			40	5	9	$ 30,708	-902	$ 20,360	0.118	-7,555	0.79	10.0
							40	5	9	$ 16,500	1,699	$ 35,991	0.716	4,938	0.00	10.0

Figure 4.15: Simulation results at NSW Solar Bonus Scheme (20c/kWh)

Under the NSW Solar Bonus Scheme of 60c/kWh, simulation results indicated that any system with a photovoltaic system would offer more benefits than relying on the electricity grid.



PV (kW)	L1000	LiFeP04	L16P	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Net Purchases (kWh/yr)	Ren. Frac.	Batt. Lf. (yr)
10.0				8	9	$ 24,608	-5,910	$ -43,176	-0.220	-9,915	0.83	
10.0	40			8	9	$ 50,608	-3,843	$ 6,528	0.033	-9,909	0.83	10.0
					9	$ 0	1,283	$ 14,718	0.293	4,380	0.00	
	40			5	9	$ 32,500	3,666	$ 74,551	1.484	4,386	0.00	10.0

Figure 4.16: Simulation results under the NSW Solar Bonus Scheme (20c/kWh)

4.11 Payback Period

Economic merit of the energy storage system was evaluated by calculating the payback period. This relates to the number of years of energy cost savings required to recover the initial investment cost of the energy storage system. Different cases were considered to evaluate the payback period. This included:

- Storage system without a photovoltaic system installed
- Storage system with a photovoltaic system installed

4.11.1 Storage system without a photovoltaic system

For a system without a photovoltaic system installed, the electricity to charge the storage systems is purchased during the off peak period at the off peak rate and discharged during the peak period to supply the extra energy required to keep the grid demand at the base load.

Based on energy requirement calculations, to be able to supply the required 12kWh during peak period, it requires 20kWh from the electric grid to charge the storage systems, with 8kWh lost in the charging and discharging process. If the storage system is to be charged daily, the total energy purchases per year will be 7,300 kWh.

If all the energy is purchased during the off peak period at the off peak price of 0.137$/kWh, the total cost of electricity to operate the storage system would be $1,000/ year.

4.11.1.1 Payback Period Without a PV System Installed

System initial investment=$16,500

Annual energy supplied from battery bank = (12kWh/day x365days) = 4,300kWh

Annual cost of energy during peak period = (0.537$/kWh x 4,300kWh) =$2,309

Annual avoided cost of energy = ($2,309-$1000) =$1,309

$$\text{Payback period} = \frac{\$16{,}500}{\$1{,}309 / year} \approx 13 years$$

4.11.2 Storage System With Photovoltaic System

If a 4 kWh PV system was installed, the energy required from the electric grid to charge the storage system would be significantly reduced. From the simulation results, a 4 kW photovoltaic system produced 5,774 kWh/ year (details in Appendix C). With the PV system as an additional energy source, only the difference would be required from the electric grid.

4.11.2.1 Payback Period With a PV System Installed

System initial capital = $23, 057

Energy required from the grid per year = (7,300kWh – 5,774kWh)

= 1,526 kWh/ year

Cost of char energy from the electric grid = (0.137$ /kWh) x (1,526 kWh/year)

= $209

Annual cost of energy if purchased during peak period :

= (0.537$/kWh x 4,300kWh)

=$2,309

Annual avoided cost of energy = ($2,309-$209) =$2,100

Payback period = $\frac{\$23{,}057}{\$2{,}100 / year} \approx 11 years$

4.12 Effectiveness of PV Systems as a Secondary Energy

Based on results obtained from households without PV systems and households with PV systems installed, it was found that including a PV system as a backup source of energy to charge the energy storage system reduced the amount of energy required from the electric grid as well as the overall payback period of the system.

At the utility level, having consumers producing some of the required energy and relying less on the electric grid to charge the battery banks reduces the stress on the electric grid during the charging hours and leaves more energy available for the network to accommodate more households.

4.12.1 Effectiveness of PV systems during winter

With an annual production of up to 5,774 kWh from a 4kW PV system, the winter energy demand per household was significantly reduced.

Energy from the electric grid during winter =20kWh/day

Annual energy consumed =20kWhx365days=7,300kWh

Annual energy from the electric grid = (7,300kWh - 5,774kWh) =1,526kWh/ year

New daily energy required from the grid $=\left(\frac{1,526kWh/year}{365days/year}\right)$ = 4kWh/day

As temperature effect is very significant during winter, PV performance is not the same as during summer due fewer hours of sunlight and cloudy days. For that reason, twice the required energy was considered.

Levelized daily energy required from the grid = 8kWh/day

Available network capacity during winter =6,250 MWh

Maximum households to be charged $=\left(\frac{6,250MWh}{8kWh/household}\right)$

= 781,250 households

Additional households to be accommodated = (781,250 -312,500)

= 468,750 households

With the demand from the electric grid reduced down to only 8 kWh/day, the electric grid would be able to charge up to two and a half times as many households as when there was no PV system installed. With only 208,000 households required to use storage systems during winter in order to avoid the evening peak demand, the charged storage systems are able to supply more than twice the size of the peak demand.

4.12.2 Effectiveness of PV Systems During Summer

With the extra 5,774 kWh produced by the photovoltaic system, the summer energy demand per household could also be significantly reduced.

Energy from the electric grid during summer =19kWh/day

Annual energy consumed =19kWhx365days=6,935kWh

Energy from the electric grid = (6,935kWh – 5,774kWh) = 1,161kWh/ year

Resulting daily energy required from the grid = $\left(\frac{1{,}161 kWh / year}{365 days / year} \right)$ =3 kWh/day

Available network capacity during summer =10,300 MWh

Maximum households to be charged = $\left(\frac{10{,}300 MWh}{3 kWh / household} \right)$

= 3,433,000 households

Additional households to be accommodated = (3,433,000 – 540,000)

=2,893,000 households

During summer, installing a 4kW PV system reduced the energy required from the grid down to only 3kWh/day. The available off peak capacity was able to charge more than six times as many households as when no PV system was installed. More than five times more household would be accommodated as compared with the care where no PV system was considered.

With only 636,000 households required to use storage systems during peak periods to be able to avoid the summer evening peak demand, the charged households were able to supply more than five times the size of the summer peak demand.

Chapter 5: Results and Performance Evaluation

5.1 Chapter Overview

This chapter discusses main results of this research project. Details of main findings for each section of the research project are provided. This chapter also discusses the effectiveness of distributed energy storage system on the NSW1 electricity network and the cost effectiveness of distributed energy storage systems.

5.2 Main Cause of Network Underutilised Network Capacity

From the research conducted, it was found that underutilisation of network capacity is caused by high peak demand. Balancing supply with demand requires upgrades of network generation, transmission and distribution capacity in order to keep up with the increasing peak demand. When experiencing extreme weather conditions, major spikes in demand are also observed due to extensive use of air conditioning systems on top of regular appliances as people try to cool down or warm their work places and homes. These high peak demands are handled using back up infrastructure. Extreme weather conditions are only experienced a couple of hours or days a year, meaning the additional capacity is only used for a couple of hours or days annually.

5.3 Energy Storage Technology

Selection of energy storage technology to be used for this project was based on the different factors such as space requirement, simplicity, capacity, safety and cost. Based the requirements for this research project, battery technology was selected for energy storage. Three main technologies were compared for cost effectiveness. This included: Lead Acid, Nickel Ion and Lithium Ion technologies.

5.4 Energy Requirement

An energy audit was conducted to approximate how much energy would be required to supply the demand above the base load. Under winter conditions, it was found that about 12kWh would be required from the battery bank to supply the evening demand while about 6kWh would be required to supply the morning peak demand. Under summer conditions, about 11kWh would be required from the battery bank to supply the evening peak demand while 7kWh would be required to supply the afternoon peak demand. The obtained results are summarised in Table 5.1.

Table 5.1 : Energy requirement

Season	**Peak Period**	**Energy required**
Winter	Morning Peak	6kWh
	Evening Peak	12kWh
Summer	Afternoon Peak	7kWh
	Evening Peak	11kWh

5.5 Battery Bank Specifications

Based on energy requirement, an energy storage system was designed. Specifications of the energy storage system are shown in Table 5.2.

Table 5.2 : Battery Bank Specifications

Technology	DoD	Energy to Store	Discharge Rate	Capacity	System Voltage
AGM L.A	30%	55kWh	200 Amps	1150AH	48V
NiFe	60%	30kWh	200Amps	650AH	48V
LiFe	60%	30kWh	200Amps	650AH	48V

As indicated in Table 5.2, the depth of discharge for AGM Lead Acid technology was limited at 30 percent while a depth of discharge of 60 percent was considered for Nickel Ion and Lithium Ion technologies. The depth of discharge is important for extending the lifecycle of batteries. Due to a limited depth of discharge for Lead Acid, the storage size and the battery bank capacity required are nearly double the size required for Nickel Ion and Lithium Ion technologies.

5.6 Network Analysis Results

The NSW1 network was considered for this research project. An assessment was conducted to determine the size of the demand above the base load and the available capacity to charge energy storage systems during the off peak period. Both winter and summer conditions were considered.

Under winter conditions, the size of the evening demand above the base load was found to be about 2,500MWh. The available capacity to charge energy storage systems during the off peak period was found to be about 6,250MWh. The minimum number of households to be programmed to use energy storage system during peak period was found to be about 208,000 households. The maximum number of households that the network could charge without creating a peak demand in the off peak period was found to be about 312,500 households. Charged energy storage systems could supply up to 150 percent of the peak demand. As the network could charge more than the minimum number of households required to be programmed to use energy storage systems during peak periods in order to avoid the peak demand, it was found to be possible to avoid the evening peak demand and the generation capacity could be reduced by 1,250MWh. With reduced power generation capacity requirement, the network capacity utilisation was improved from 82 percent to 100 percent of the scheduled capacity.

Under summer conditions, the size of the evening demand above the base load was found to be about 7,000MWh. The available capacity to charge storage systems during the off peak period was found to be about 10,300MWh. The minimum number of households to be programmed to use energy storage system during peak periods was found to be about 636,000 households. The maximum number of households that the network could charge without creating a peak demand in the off peak period was found to be about 540,000 households. Charged energy storage systems could supply up to 85 percent of the peak demand. With only 85 percent of the peak demand supplied, it was still possible to avoid the peak demand and reduce the generation capacity by 1,210 MW. This was mainly due the fact that the average demand increased due to off peak charging, which resulted in the resulting demand falling within the resulting base load limit. With reduced power generation capacity requirement, the network capacity utilisation was improved from 68 percent to 78 percent of the scheduled capacity. Network analysis results are shown in Table 5.3.

Table 5.3 : Summary of the network assessment.

Season	**Winter**	**Summer**
Evening Peak Demand Size	2,500MWh	7,000MWh
Network Available Capacity	6,250MWh	10,300MWh
Min. Households Required	208,000 households	636,000 households
Max. Households to be charged	312,500 households	540,000 households
Percentage of peak demand supplied	150%	85%
Evening Peak Reduction	1,250MWh	1,210MWh
Capacity Utilisation Improvement	From 82 % to 100%	From 68% to 78 %

5.6.1 Effects of PV Systems

Installing a PV system was found to be very effective and allowed total avoidance of peak demand under both winter and summer conditions. A 4 kW PV system was considered for analysis. Calculation results are summarised in Table 5.4.

Table 5.4 : Effects of a 4 kW PV system on the network

Season	**Winter**	**Summer**
Maximum number of households to be charged	781,250 households	3,433,000 households
Additional households to be accommodated by the network	468,750 households	2,893,000 households
Evening Peak demand reduction	More than twice the peak demand	More than five times the peak demand.

5.7 Voltage Regulation Results

Power flow analysis was conducted using a MATLAB algorithm. For the purpose of this research project, the main focus was on demand nodes 5 and 7. Voltage levels at these nodes were observed in order to analyse voltage regulation capability of distributed energy storage systems. An upper voltage level of 1.06 u.p was used and a lower voltage level of 0.94 p.u was used. The aim was to maintain voltage levels at demand nodes within these limits.

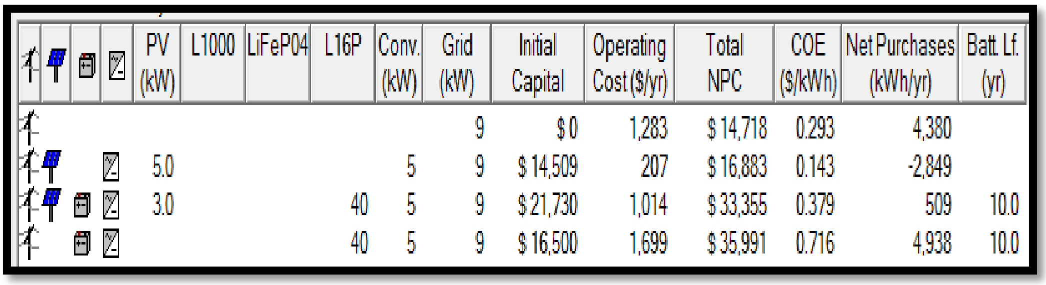
The network was first analysed under no load condition. The obtained results showed that, when no load is applied at the distribution nodes 5 and 7, the voltage levels at all the network nodes remained almost the same. The second analysis analysed the network when suppling 100kVA load at the demand nodes 5 and 7. Under this condition, the results showed significant decrease in voltage levels. The voltage at nodes 5 and 7 dropped from 1.0489 p.u to 0.8661 p.u, which indicated a low voltage condition. The second analysis analysed the network with an apparent power of 25kVA generated by distributed energy storage systems and applied at the demand nodes 5 and 7. The results showed improved voltage levels at nodes 5 and 7 from 0.8661 p.u to 0.9214 p.u, which was still below the lower voltage level limit. The power generated by distributed energy storage systems was increased to 40kVA. The results showed more improvement in voltage levels from 0.9214 to 0.9444 p.u, which was a bit above the lower voltage level limit and within the acceptable voltage level range. Finally, to further improve the voltage level, an even larger generation of 50kVA from distributed energy storage systems was considered. Results indicated well balanced voltage levels between the limit levels. The voltage regulation results as observed at demand nodes 5 and 7 are summarised in Table 5-5.

Table 5-5 : Voltage regulation results summary

Condition	**Voltage level at demand nodes 5 and 7**
No load supplied	**1.0489**
With a S=100kVA supplied	**0.8661**
With S= 25kVA generated by ESS	**0.9214**
With S= 40kVA generated by ESS	**0.9444**
With S=50kVA generated by ESS	**0.9700**

5.8 Economic Analysis Results

HOMER ENERGY simulation results are shown in Figure 5.1.



PV (kW)	L1000	LiFeP04	L16P	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Net Purchases (kWh/yr)	Batt. Lf. (yr)
					9	$ 0	1,283	$ 14,718	0.293	4,380	
5.0				5	9	$ 14,509	207	$ 16,883	0.143	-2,849	
3.0			40	5	9	$ 21,730	1,014	$ 33,355	0.379	509	10.0
			40	5	9	$ 16,500	1,699	$ 35,991	0.716	4,938	10.0

Figure 5.1: Economic analysis results

Simulation results indicated that purchasing from the electric grid offered the cheapest total TNP (Net Present Cost) for the lifetime of the project (20 years) compared with other options. Simulation results are based on the current NSW voluntary feed-in tariff of 6c/kWh. Installing a PV system without a storage system was found to be the second best option. Any combination involving an energy storage system was found to be among the least preferred option. Feed-in tariff was found to have a big impact on cost effectiveness for systems that include a PV system. A comparison was conducted between the previous 60 c/kWh and 20c/kWh NSW Solar Bonus Schemes with the current voluntary feed-in tariff of only 6c/kWh. Simulation results are shown in Table 5.6.

Table 5-6 : Effects of feed-in tariff on system cost effectiveness

Scheme	**Voluntary feed-in tariff (6/c /kWh)**	**NSW Solar Bonus Scheme (20c/kWh)**	**NSW Solar Bonus Scheme (60c/kWh)**
Cost effectiveness	Grid	Grid + PV	Grid + PV
	Grid + PV	Grid	Grid + PV + Storage system
	Grid + PV + Storage system	Grid + PV + Storage system	Grid
	Grid + Storage system	Grid + Storage system	Grid + Storage system

As indicated in the comparisons table above, as the feed-in tariff increases, the cost effectiveness of systems change. At the current voluntary feed-in tariff of 6c/kWh , purchasing from the grid was preferred. As the feed-in tariff was increased to 20c/kWh, a combination of the electric grid and a PV system was preferred. Further increase in feed-in tariff simply solidified the performance of a combination of the electric grid and a PV system and increased the performance of a combination of a combination of the grid, a PV system and a storage system. As marked by the colour code, the choice for the electric grid dropped with increase in feed-in tariff. As the feed-in tariff was increased, any combination with a PV system performed better. A storage system that only relies on the electric grid for charging was the least preferred.

From the comparison results, Table 5-6 also showed how the decrease in feed-in tariffs has affected cost effectiveness of energy storage systems compared with previous NSW Solar Bonus Schemes (20c/kWh and 60c/kWh) that have been discontinued.

5.9 Results Discussion

The results presented in this chapter are indicative of the feasibility of distributed energy storage systems to improve utilisation of network assets in an urban area. To best understand the benefits of distributed energy storage systems in improving network capacity utilisation, a comparison between the network performance when no storage systems are applied and when storage systems are applied is required. Although there might be variations in network demand, the performance of distributed energy storage systems has shown greater potential in improving network capacity utilisation under both summer and winter conditions. With significant improvements under seasons with great variations in power demand, the system proved to reliable solution throughout the year. Distributed energy storage systems have shown excellent performance in controlling voltage levels at demand nodes as well as the rest of the nodes on the network.

Although distributed energy storage systems performed well in generation capacity reduction and voltage control, the technology also has some disadvantages. The main problem with energy storage systems is the investment cost due to high cost of batteries. With reduced prices of batteries, distributed energy storage systems can be widely implemented at low cost.

5.10 Chapter Summary

In this chapter, the system performance and simulation results were discussed. Using distributed energy storage systems to improve network assets utilisation in an urban area proved to be an effective solution. The cost effectiveness of energy storage systems is still affected by the cost of battery technologies.

Chapter 6: Conclusions

6.1 Summary

The aim of this research project was to improve network capacity utilisation with distributed energy storage systems. To accomplish the aim of this project it became necessary to reach some prerequisite goals. An energy audit was conducted to determine how much energy is required to supply the demand above the base load for a typical household. Based on peak period energy and power requirements, and energy storage system was designed.

The NSW1 network was analysed to determine the size of the evening peak demand and the available capacity to charge energy storage systems during the off peak period. The maximum number of households that the network was able to charge during the off peak period was determined and the minimum number of households required to use energy storage systems during peak periods to avoid the peak demand were determined. The effectiveness of distributed energy storage systems on the network was evaluated by modelling the resulting demand pattern. A MATLAB algorithm was developed to conduct a power flow analysis to evaluate voltage regulation capabilities of distributed energy storage systems at demand nodes on the network. Cost effectiveness of energy storage systems was evaluated using HOMER ENERGY software.

6.2 Conclusions

Analysis and simulation results show that distributed energy storage systems are a potential solution to improving network capacity utilisation. Distributed energy storage systems performed well under both winter and summer conditions and were able to reduce the generation capacity required to meet the peak demand. Adoption of distributed energy storage systems can help avoid or delay the need for network capacity upgrades and improve utilisation of existing network assets.

6.3 Recommendations

To more accurately evaluate the performance of distributed energy storage systems on the network, more accurate network parameter are required. The average network demand over 24 hours was considered as the base load. It is recommended that actual network parameter such as the base load and installed capacity are used for more accurate results.

6.4 Future Research and Development

The completion of this project leaves other major sections for further work. The future work includes:

- Investigation of other effectiveness of distributed energy storage systems on the electricity grid.
- Determination of a more accurate load profile
- Implementation of the designed storage system for performance analysis on a single household.
- Finding of more accurate network parameter.

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Appendix A

Project Specification

University Of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project

PROJECT SPECIFICATION

For : Tony Bonaventure Sunzu

Topic : Improving Network Capacity Utilisation with Distributed Energy Storage Systems

Supervisor : Dr Les Bowtell

Sponsorship : Faculty of Health, Engineering and Sciences

Project Aim : To improve utilisation of network assets in an urban area with distributed energy storage systems.

- Research electricity network utilisation issues
- Research Energy Storage Technologies
- Design an Energy Storage System to meet Peak Demand Energy Requirements
- Analyse Electricity Network
- Model Effectiveness of Distributed Energy Storage Systems on the Network
- Assess Cost Effectiveness of Energy Storage Systems using HOMER ENERGY Software

GREED:

Student Name: Tony B. Sunzu

Date:

Supervisor Name : Les Bowtell

Appendix B

MATLAB Code for Power Flow Analysis

```
% Matlab code adopted from Sayde and changed by Tony B. Sunzu
% Simple SWER line 7 nodes
% PF = 0.9;   %0.9 power factor for simulation
%
% Initialise transformer parameters in VA
%===============================================================

clear all
home
Sbase = 400000;       % Base Power
Vbase = 19000;        % Base voltage in V
Ibase = Sbase/Vbase;  % Base current
Zbase =  Vbase/Ibase; % Base Impedance
S400 = 400e3;         % (400kVA) Size of transformer
S200 = 200e3;         % (200kVA) Size of transformer
S25 = 25e3;           % (25kVA) Size of transformer
S10 = 10e3;           % (10kVA) Size of transformer
%%
%400 kVA isolation transformer
Zt_400percent = 0.05; XRt_400 = 4.5; Rtesx_400 = 3;     % 400kVA isolation transformer (22kV/19kV)
Zt_400ohm = Zt_400percent*(19e3^2)/S400;
Rt_400ohm = sqrt(Zt_400ohm^2/(1+XRt_400^2));
Xt_400ohm = XRt_400*Rt_400ohm;
noload_loss400= 960; %W
MSC400= ((noload_loss400/Vbase^2)/(1/Zbase));
%Per unit values
Zt_400 = (Rt_400ohm+Rtesx_400 + Xt_400ohm*i)/Zbase;

Zt_200percent = 0.05; XRt_200 = 4.5; Rtesx_200 = 3;      % 200kVA isolation transformer (22kV/19kV)
Zt_200ohm = Zt_200percent*(19e3^2)/S200;
Rt_200ohm = sqrt(Zt_200ohm^2/(1+XRt_200^2));
Xt_200ohm = XRt_200*Rt_200ohm;
noload_loss200= 960; %W
MSC200= ((noload_loss200/Vbase^2)/(1/Zbase));           %Magnetising Shunt Conductance
% Per unit values
Zt_200 = ((Rt_200ohm+Rtesx_200) + (Xt_200ohm*i))/Zbase;

% 25 kVA rural transformer
Zt_25percent = 0.0375; XRt_25 = 2; Rtesx_25 = 30;          % 25kVA rural transformer (19kV/0.4kV)
Zt_25ohm = Zt_25percent*(19e3^2)/S25;
Rt_25ohm = sqrt(Zt_25ohm^2/(1+XRt_25^2));
Xt_25ohm = XRt_25*Rt_25ohm;
noload_loss25 = 133; %W
MSC25=  ((noload_loss25/Vbase^2)/(1/Zbase));                  % Magnetising Shunt Conductance.
% Per unit values
Zt_25 = (Rt_25ohm + Rtesx_25 + Xt_25ohm*i)/Zbase;
```

```
% 10 kVA rural transformer
Zt_10percent = 0.0375; XRt_10 = 2; Rtesx_10 = 30;          % 10kVA
rural transformer (19kV/0.4kV)
Zt_10ohm = Zt_10percent*(19e3^2)/S10;
Rt_10ohm = sqrt(Zt_10ohm^2/(1+XRt_10^2));
Xt_10ohm = XRt_10*Rt_10ohm;
noload_loss10 = 133; %W
MSC10=                          ((noload_loss10/Vbase^2)/(1/Zbase));
%MagnetisingShuntConductance
% Per unit value
Zt_10 = (Rt_10ohm + Rtesx_10 + Xt_10ohm*i)/Zbase;

%%---------------------------------------------------
% ----Initialise conductor Parameters-----------------
%----------------------------------------------------
%SCAC (7m)
R1_SCAC = 6.03;                 %(ohms/km)
X1_SCAC = 1.061938;             %(ohms/km)
L1_SCAC = X1_SCAC/(2*pi*50);    %(H/km)
BC1_SCAC = 2.73*10^-6;          %(mhos/km)
XC1_SCAC = (BC1_SCAC)^(-1);     %(ohms/km)
C1_SCAC = 1/(2*pi*50*XC1_SCAC); %(F/km)

%SULTANA (7m, GMD = 1.8m)
R1_SUL = 1.14;                  %(ohms/km)
X1_SUL = 0.414938;              %(ohms/km)
L1_SUL = X1_SUL/(2*pi*50);      %(H/km)
BC1_SUL = 2.92*10^-6;           %(mhos/km)
XC1_SUL = BC1_SUL^(-1);         %(ohms/km)
C1_SUL = (2*pi*50*XC1_SUL)^(-1);%(F/km)

R0_SUL = 1.28295;               %(ohms/km)
X0_SUL = 1.83424;               %(ohms/km)
L0_SUL = X0_SUL/(2*pi*50);      %(H/km)
BC0_SUL = 1.39*10^-6;           %(mhos/km)
XC0_SUL = BC0_SUL^(-1);         %(ohms/km)
C0_SUL = (2*pi*50*XC0_SUL)^(-1);%(F/km)

%BANANA (7m, GMD = 1.8m)
R1_BAN = 0.56;                  %(ohms/km)
X1_BAN = 0.383938;              %(ohms/km)
L1_BAN = X1_BAN/(2*pi*50);      %(H/km)
BC1_BAN = 3.03*10^-6;           %(mhos/km)
XC1_BAN = BC1_BAN^(-1);         %(ohms/km)
C1_BAN = (2*pi*50*XC1_BAN)^(-1);%(F/km)

R0_BAN = 0.70295;               %(ohms/km)
X0_BAN = 1.80324;               %(ohms/km)
L0_BAN = X0_BAN/(2*pi*50);      %(H/km)
BC0_BAN = 1.41*10^-6;           %(mhos/km)
XC0_BAN = BC0_BAN^(-1);         %(ohms/km)
C0_BAN = (2*pi*50*XC0_BAN)^(-1);%(F/km)

%%
tol= 1e-8 ; % convergence condition in terms of pu active power
mismatch and reactive power mistmatch at each bus
maxiter = 100 ; % maximum nunber of iterations(prevents looping
forever in the event of convergence not happening)
%Impedance matrix Z (P.U)
%%
```

```
z1_2=Zt_400;                                              % z1_2
=(400KVATransformer resitance+earth stake resistance+j*tranformer
reactance
z2_3=((R1_BAN*100)+(X1_BAN*100*i))/Zbase;                % z2_3 = pu
series 100km BAN conductor
z3_4=((R1_SCAC*50)+(X1_SCAC*50*i))/Zbase;                % z3_4 = pu
series 50km SCAC
z4_5=Zt_200;                                              % z4_5
=(200KKVA Transformer resitance+earth stake resistance)+j*tranformer
reactance
z3_6=((R1_SCAC*50)+(X1_SCAC*50*i))/Zbase;                % z3_6 = pu
series 50km SCAC
z6_7= Zt_200;                                             % z6_7
=(200KVA Transformer resitance+earth stake resistance+j*tranformer
reactance

%%---------------------------------------------------------------------
-------
% Shunt Admitence
%---------------------------------------------------------------------
-------
y1_1= 0+0i;                                                          %
400KKVA Transformer at bus 1
y2_2= MSC400+ 0.5*(100*(BC1_BAN/(100*pi*(1/Zbase))))*i;              %
100km BAN +400KKVA Transformer at bus 2.
y3_3=
0.5*((100*(BC1_BAN/(100*pi*(1/Zbase))))+(50*(BC1_SCAC/(100*pi*(1/Zba
se))))+(50*(BC1_SCAC/(100*pi*(1/Zbase)))))*i;  %  100km  BAN+  50km
SCAC+ 50km SCAC at bus 3.
y4_4= MSC200+ 0.5*((50*(BC1_SCAC/(100*pi*(1/Zbase)))))*i;            %
50km SCAC+ 200KKVA Transformer at bus 4.
y5_5= 0+ 0i;                                                         %
Load at bus 5.
y6_6= MSC200+ 0.5*((50*(BC1_SCAC/(100*pi*(1/Zbase)))))*i;            %
50km SAC+ 200KKVA Transformer at bus 6.
y7_7= 0+ 0i;                                                         %
Load at bus 7.



%%---------------------------------------------------------------------
-------
% v contains the bus voltage matrix; entries for v are complex
numbers in pu
%     1      2      3     4     5     6    7
v=[  1.05   1.0    1.0   1.0   1.0   1.0  1.0].';

%%
% nn= 0;
% mm =-0.05
% .... contains initial estimates for load(PQ) buses and specified
values for slack bus (ie bus 1)
% If all v's are initially set to 1, we refer to the start of the
iterative
% ... process as a flat start.
% v(1) is not calculated, the rest of the v's are.
%Pg contains the user specified generator active power at each
bus;entries for Pg are real numbers;Pg(1) can be any value.
%The value entered does not matter because Pg(1), unlike the other
Pg's is re-calculated by the power flow program since bus 1 is the
slack bus.
```

```
% Values in Pg are positive for generated active power or injected
active power.
%       1       2      3      4      5         6        7
Pg=[    0       0      0      0      0         0        0];% values
are pu


%%
%Qg contains the user specified generator reactive power at each
bus.
%Entries for Qg are real numbers.
%Qg(1) and entries for voltage controlled buses can be any value
because these are re-calculated by the power flow program ;
%Positive for generated reactive power
%       1       2       3       4      5      6      7
Qg=[    0       0       0       0      0      0      0];        %
values are pu


%%
%Pd contains the user specified load active power at each
bus;entries for Pd should be real numbers
%       1      2     3       4       5         6       7
Pd=[    0      0     0       0       0         0       0];        %
values are pu positive for power consumed by load


    %%
% Qd = zeros(n:6);

%       1     2      3     4      5         6       7
Qd =[   0     0      0     0      0         0       0];

% for nn = -50:2
%     n = length(nn)
%     for i = 1:n
%      %Qd contains the user specified load reactive power at each
bus;entries for Qd should be real numbers
% %           1      2      3       4             5        6
%      Qd =[   0       0       0        nn*0.02    0         0 ]./0.5;
%....values are pu; positive lagging power factor load
%
%     end

% PgB83 = Sbatt*pfsys;
% QgB83 = Sbatt*sin(acos(pfsys));
%%
%%%%%%% calculation of the Y matrix;
Y= zeros(7,7);

Y(1,1)= y1_1 + (1/z1_2);                         Y(1,2)= -1/(z1_2);
Y(2,1)=Y(1,2);
Y(2,2)= y2_2 + (1/z1_2)+(1/z2_3);                Y(2,3)= -(1/z2_3);
Y(3,2)=Y(2,3)
Y(3,3)= y3_3 + (1/z2_3)+ (1/z3_4)+ (1/z3_6);     Y(3,4)= -(1/z3_4);
Y(4,3)=Y(3,4); Y(3,6)= -(1/z3_6); Y(6,3)=Y(3,6);
Y(4,4)=   y4_4   +   (1/z3_4)+(1/z4_5)   ;     Y(4,5)=   -(1/z4_5);
Y(5,4)=Y(4,5);
Y(5,5)= y5_5 + (1/z4_5);
```

```
Y(6,6)= y6_6 + (1/z3_6)+(1/z6_7);   Y(6,7)= -(1/z6_7);Y(7,6)=Y(6,7);
Y(7,7)= y7_7 + (1/z6_7);

%%
iter=0;% set to zero to start from scratch, choose other than zero
value to continue from last iteration;
maxpqmm=10*tol;
while (iter<maxiter) & (maxpqmm > tol)
if iter ~= 0
   load psa9p12sr
else
end

jaco11=zeros(7,7);%jaco11,jaco21,jaco12,jaco22 are as per eq 9.45 in
textbook
jaco21=zeros(7,7);% size is set to 5 because five buses are involved
jaco12=zeros(7,7);
jaco22=zeros(7,7);
jsize=12;% size of the jacobian= 2*(number of buses)-2(due to slack
bus)-number of voltage controlled buses
jaco=zeros(jsize,jsize);%  jaco  combination  of  jaco11,jaco12,jaco21
and jaco22 as per textbook equation 9.45

% calculation of power mismatches

for j=1:7
   P(j)=0;
   Q(j)=0;
   for k=1:7
   vvy=v(j,1)'*v(k,1)*Y(j,k);
%P(j)is  estimation  of  injected  active  power  into  bus  j  based  on
current estimates of bus voltages (eq 9.4 in textbook, n=j and i=j)
   P(j)=P(j)+real(vvy);
%Q(j)=-abs(v(j,1))*abs(v(j,1))*imag(Y(j,j));%Q(j)  is  estimation  of
injected reactive power into bus j based on current estimates of bus
voltages (eq 9.4 in textbook, n=j and i=j)
   Q(j)=Q(j)-imag(vvy);
   end
end

pmm=Pg-Pd-P;%pmm  is  active  power  mismatch  based  on  equation  9.8  in
textbook
qmm=Qg-Qd-Q; % qmm is reactive power mismatch based on equation 9.9
in textbook
pqmm(1:6)=pmm(2:7);  %  do  not  consider  active  power  mismatch  for
slack  bus  ;  pqmm  is  combination  of  active  and  reactive  power
mismatches
pqmm(7:jsize)=qmm(2:7);  %  do  not  consider  reactive  power  mismatch
for voltage controlled buses
pqmm=pqmm; %allows display of active and reactive power mismatch in
workspace so user can decide whether to continue iterating

%evaluation of the jacobian
for j=1:7
   for k=1:7
      vvy=v(j,1)'*v(k,1)*Y(j,k);
      if j~=k
      jaco11(j,k)=-imag(vvy);%based on equation 9.52 of textbook
      jaco21(j,k)=-real(vvy);%based on equation 9.55 of textbook
      jaco12(j,k)=-jaco21(j,k);%based on equation 9.58 of textbook
```

```
      jaco22(j,k)=jaco11(j,k); %based on equation 9.62 of textbook
   else
   end
   end
end

for j=1:7
   jaco11(j,j)=-sum(jaco11(j,:)); % based on equation 9.53 of
textbook, note jaco11(j,j)=0
   jaco21(j,j)=-sum(jaco21(j,:)); % based on equation 9.56 of
textbook, note jaco21(j,j)=0

jaco12(j,j)=jaco21(j,j)+2*abs(v(j,1))*abs(v(j,1))*real(Y(j,j));%base
d on equation 9.61 of textbook
   jaco22(j,j)=-jaco11(j,j)-
2*abs(v(j,1))*abs(v(j,1))*imag(Y(j,j));%based on equation 9.63 of
textbook
end

jaco(1:6,1:6)=jaco11(2:7,2:7); % slack bus not to be considered
jaco(7:jsize,7:jsize)=jaco22(2:7,2:7); % voltage controlled buses
not to be considered
jaco(1:6,7:jsize)=jaco12(2:7,2:7); % slack bus and voltage
controlled buses not to be considered
jaco(7:jsize,1:6)=jaco21(2:7,2:7); % slack bus and voltage
controlled buses not to be considered



% evaluation of angle and voltage corrections

avcor= inv(jaco)*pqmm'; % based on equation 9.45
%avcor(jsize+1:48,1)=0; % voltage corrections for voltage controlled
buses set to zero

% evaluation of new angles and new voltages

newangle(2:7)=angle(v(2:7,1))+avcor(1:6,1); % based on equation 9.49
of textbook
newmag(2:7)=abs(v(2:7,1)).*(ones(6,1)+avcor(7:12,1)); % based on
equation 9.50 of textbook

for j=2:7
v(j,1)=newmag(j)*exp(i*newangle(j));
end

iter=iter+1;

save psa9p12sr v pqmm iter

pqmm = abs(pqmm);

maxpqmm= max(pqmm);

end

if (iter== 200) & ( maxpqmm > tol )

    warning (' failed to converge')
```

```
end

absv=abs(v)
kWResistivelosses = sum(P)
kVAReactivelosses = sum(Q)
TotActPd= sum(Pd)
TotalReactQd= sum(Qd)
TotalNetworkCustLoad= sqrt(sum(Qd)*sum(Qd) + sum(Pd)*sum(Pd))
TotalNetworkPower=
sqrt((sum(Qd)+sum(Q))*(sum(Qd)+sum(Q))+((sum(Pd)+sum(P))*(sum(Pd)+su
m(P))))

%%

rho = zeros(1,7);
delvp = zeros(1,6);
delvq = zeros(1,6);
delp = 0;
delq = 0;
delvpq = zeros(2,7);
A = zeros(6,6);
A11 = zeros(6,6); % extract submatrices
A12 = zeros(6,6);
A21 =  zeros(6,6);
A22 =  zeros(6,6);
newA21 = zeros(7,7);
newA22 = zeros(7,7);
A2 = zeros(7,1);
A1 = zeros(1,6);
A21x = zeros(7,6);
A22x = zeros(7,6);
newA21 = zeros(7,7);
newA22 = zeros(7,7);
A = inv(jaco); % some square matrix
ii=6; % partition indices: row 24, column 24
jj=6;
A11 = A(1:ii,1:jj); % extract submatrices
A12 = A(1:ii,jj+1:end);
A21 = A(ii+1:end,1:jj);
A22 = A(ii+1:end,jj+1:end);

delvp = diag(A21);                          % voltage sensitivity with
respect to active power, P
delvq = diag(A22);                          % voltage sensitivity with
respect to reactive power, Q

A21x = [A1; A21];
newA21 = [A2 A21x]

A22x = [A1; A22];
newA22 = [A2 A22x]

DiagA21= diag(newA21)
DiagA22=diag(newA22)
absv
```

Appendix C

HOMER ENERGY

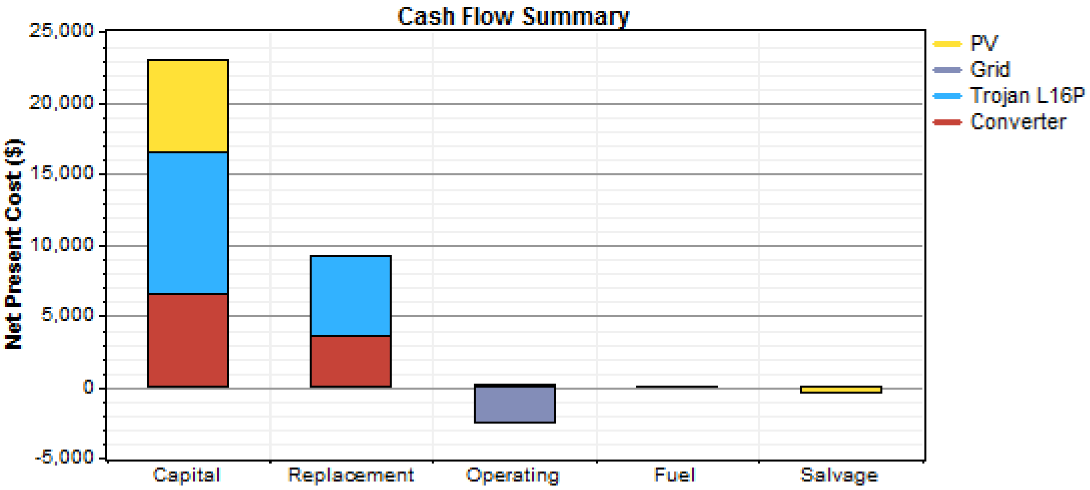
System Report - Cost Effectiveness

System architecture

PV Array	4 kW
Grid	9 kW
Battery	40 Trojan L16P
Inverter	5 kW
Rectifier	5 kW

Cost summary

Total net present cost	$ 29,621
Levelized cost of energy	$ 0.308/kWh
Operating cost	$ 572/yr

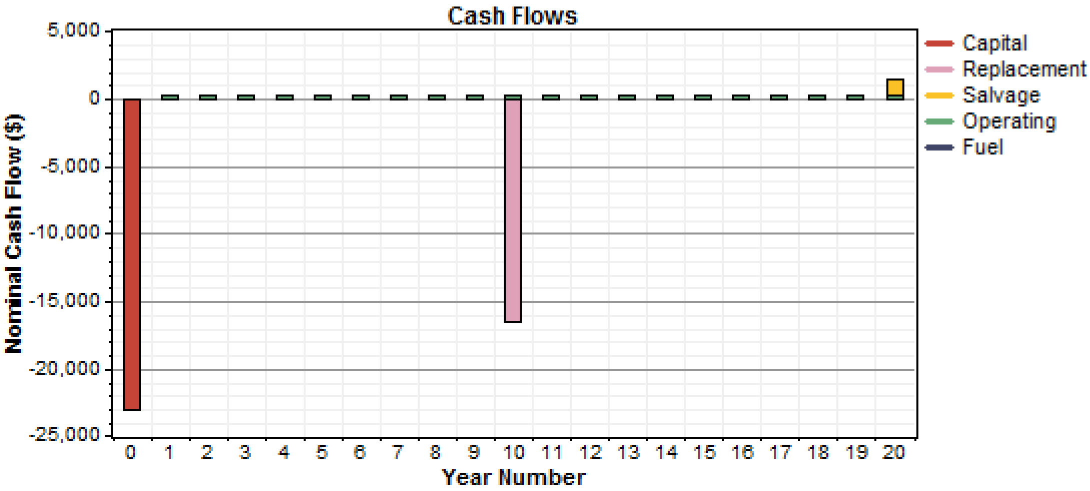


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
PV	6,557	0	0	0	-409	6,148
Grid	0	0	-2,470	0	0	-2,470
Trojan L16P	10,000	5,584	229	0	0	15,813
Converter	6,500	3,630	0	0	0	10,130
System	23,057	9,214	-2,240	0	-409	29,621

Annualized Costs

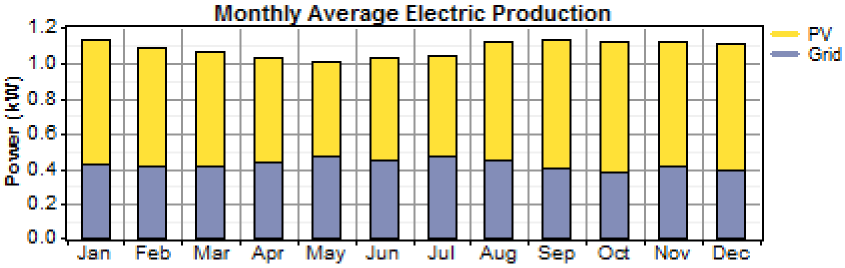
Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
PV	572	0	0	0	-36	536
Grid	0	0	-215	0	0	-215
Trojan L16P	872	487	20	0	0	1,379
Converter	567	316	0	0	0	883
System	2,010	803	-195	0	-36	2,583



Electrical

Component	Production	Fraction
	(kWh/yr)	
PV array	5,774	61%

Grid purchases	3,707	39%
Total	9,481	100%



Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	4,380	52%
Grid sales	4,015	48%
Total	8,395	100%

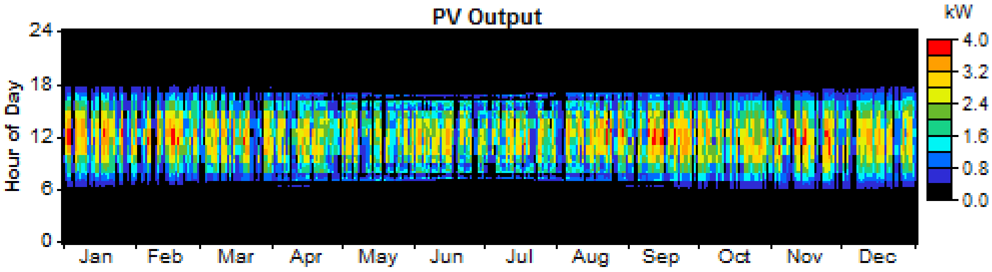
Quantity	Value	Units
Excess electricity	0.0000165	kWh/yr
Unmet load	0.00000184	kWh/yr
Capacity shortage	0.00	kWh/yr
Renewable fraction	0.558	

PV

Quantity	Value	Units
Rated capacity	4.00	kW
Mean output	0.659	kW
Mean output	15.8	kWh/d
Capacity factor	16.5	%
Total production	5,774	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	3.88	kW
PV penetration	132	%
Hours of operation	4,381	hr/yr

Levelized cost	0.0928	$/kWh

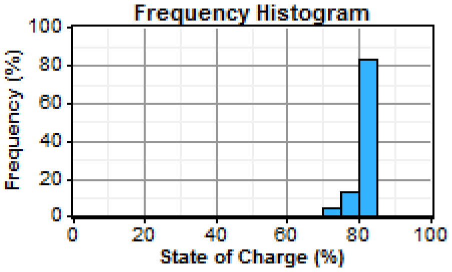


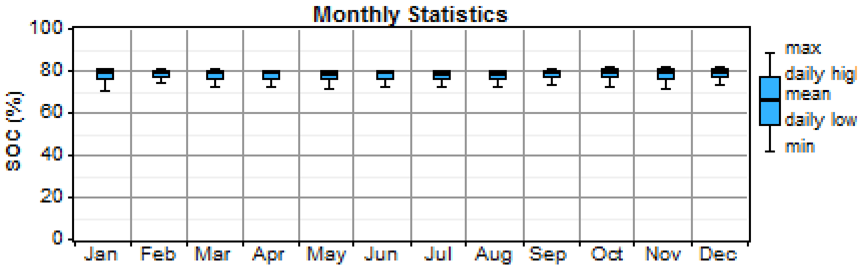
Battery

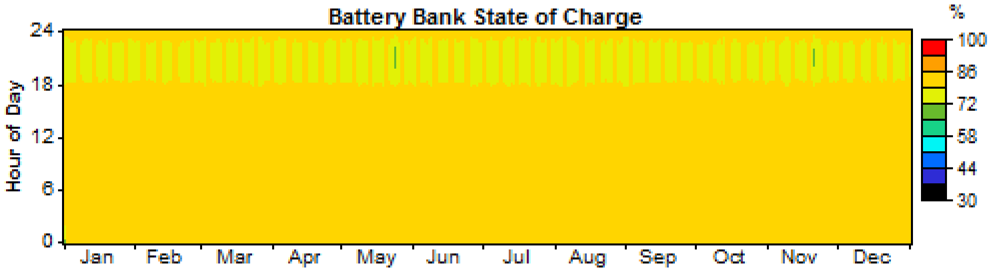
Quantity	Value
String size	8
Strings in parallel	5
Batteries	40
Bus voltage (V)	48

Quantity	Value	Units
Nominal capacity	86.4	kWh
Usable nominal capacity	60.5	kWh
Autonomy	121	hr
Lifetime throughput	43,000	kWh
Battery wear cost	0.252	$/kWh
Average energy cost	0.174	$/kWh

Quantity	Value	Units
Energy in	1,480	kWh/yr
Energy out	1,249	kWh/yr
Storage depletion	11.1	kWh/yr
Losses	220	kWh/yr
Annual throughput	1,355	kWh/yr
Expected life	10.0	yr



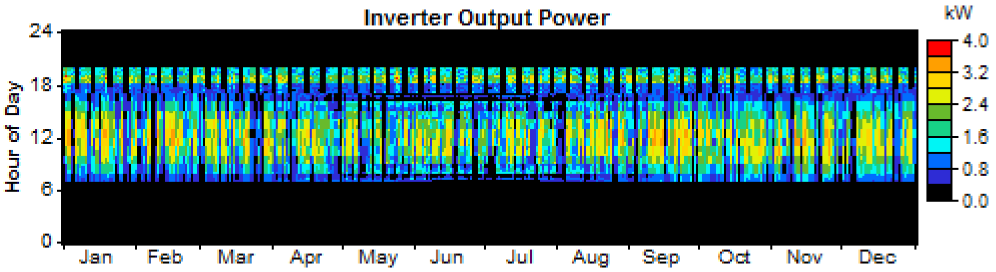


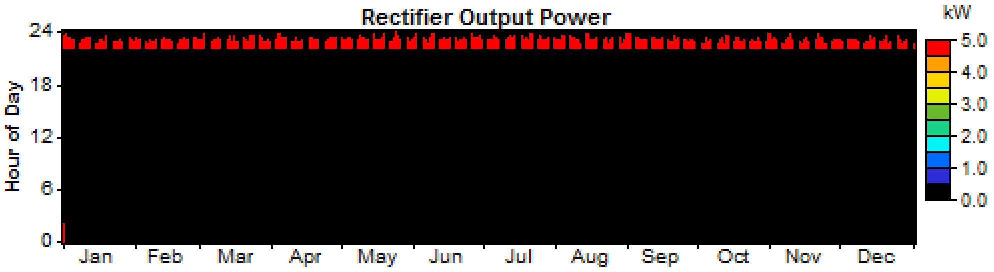


Converter

Quantity	Inverter	Rectifier	Units
Capacity	5.00	5.00	kW
Mean output	0.72	0.16	kW
Minimum output	0.00	0.00	kW
Maximum output	3.65	4.69	kW
Capacity factor	14.3	3.3	%

Quantity	Inverter	Rectifier	Units
Hours of operation	4,924	304	hrs/yr
Energy in	6,969	1,584	kWh/yr
Energy out	6,272	1,425	kWh/yr
Losses	697	158	kWh/yr





Grid

Rate: Off Peak Rate

Month	Energy Purchased	Energy Sold	Net Purchases	Peak Demand	Energy Charge	Demand Charge
	(kWh)	(kWh)	(kWh)	(kW)	($)	($)
Jan	217	0	217	6	30	0
Feb	175	0	175	6	24	0
Mar	203	0	203	6	28	0
Apr	198	0	198	6	27	0
May	226	0	226	6	31	0
Jun	209	0	209	6	29	0
Jul	224	0	224	6	31	0
Aug	220	0	220	6	30	0
Sep	185	0	185	6	25	0
Oct	192	0	192	6	26	0
Nov	197	0	197	6	27	0
Dec	183	0	183	6	25	0
Annual	2,428	0	2,428	6	332	0

Rate: Peak Rate

Month	Energy Purchased	Energy Sold	Net Purchases	Peak Demand	Energy Charge	Demand Charge
	(kWh)	(kWh)	(kWh)	(kW)	($)	($)

Jan	0	71	-71	0	-14	0
Feb	0	62	-62	0	-12	0
Mar	0	63	-63	0	-13	0
Apr	0	57	-57	0	-11	0
May	0	54	-54	0	-11	0
Jun	0	49	-49	0	-10	0
Jul	0	56	-56	0	-11	0
Aug	0	72	-72	0	-14	0
Sep	0	66	-66	0	-13	0
Oct	0	70	-70	0	-14	0
Nov	0	66	-66	0	-13	0
Dec	0	69	-69	0	-14	0
Annual	0	753	-753	0	-151	0

Rate: Shoulder Rate

Month	**Energy Purchased**	**Energy Sold**	**Net Purchases**	**Peak Demand**	**Energy Charge**	**Demand Charge**
	(kWh)	(kWh)	(kWh)	(kW)	($)	($)
Jan	101	281	-180	3	-36	0
Feb	104	251	-147	3	-29	0
Mar	103	276	-174	3	-35	0
Apr	110	244	-134	3	-27	0
May	122	227	-105	3	-21	0
Jun	116	256	-140	3	-28	0
Jul	124	249	-125	3	-25	0
Aug	109	293	-183	3	-37	0
Sep	101	307	-206	3	-41	0
Oct	89	308	-219	4	-44	0
Nov	97	279	-182	3	-36	0
Dec	103	292	-189	3	-38	0
Annual	1,278	3,262	-1,983	4	-397	0

Rate: All

Month	Energy Purchased	Energy Sold	Net Purchases	Peak Demand	Energy Charge	Demand Charge
	(kWh)	(kWh)	(kWh)	(kW)	($)	($)
Jan	318	351	-33	6	-20	0
Feb	279	312	-33	6	-18	0
Mar	305	340	-34	6	-20	0
Apr	309	301	8	6	-11	0
May	348	280	68	6	-1	0
Jun	325	305	20	6	-9	0
Jul	348	305	43	6	-6	0
Aug	329	364	-36	6	-21	0
Sep	285	372	-87	6	-29	0
Oct	281	379	-98	6	-32	0
Nov	294	344	-50	6	-23	0
Dec	285	361	-75	6	-27	0
Annual	3,707	4,015	-308	6	-215	0

Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	-195
Carbon monoxide	0
Unburned hydocarbons	0
Particulate matter	0
Sulfur dioxide	-0.845
Nitrogen oxides	-0.413