University of Southern Queensland

School of Mechanical and Electrical Engineering

Demand Management Storage Project (DMSP) –

An Application of Grid Scale Battery Energy Storage Systems

Dissertation submitted by

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ABSTRACT

Grid scale BESS (battery energy storage system) has been identified as one of the key technologies in the utility network of the future. There are significant benefits associated with their ability to store energy. This study aims to use economic models to evaluate grid scale BESS benefits and to sum them up into value propositions.

DMSP project is planning to install one of the largest BESS systems at a 22kV distribution feeder in Australia. According to (Eyer & Corey, 2010) guide, energy storage systems could have 17 electric grid related applications which across 5 categories: electrical supply, ancillary services, grid system, end user/utility customer and renewable integration. Among all the applications, DMSP project focuses on two major applications: using grid scale BESS for energy time-shift and feeder construction deferral applications.

In order to quantify the economic feasibility of the DMSP BESS system, studies were done to analyse the distribution system, energy market and BESS system. Two data models had been created to quantify the two BESS applications with the factors such as energy prices, feeder load data and battery parameters. With the data models, methods were found out about how to simulate electrical and economic performance of the battery energy storage system and quantify these performances into market value.

The simulation results had been presented and analysed in the document. From the simulation, it concluded that economic feasibility of BESS energy time-shift application is depended on active level of energy market and also the BESS system cost; Feeder construction deferral application can bring significant benefits if the feeder upgrade construction costs are high.

Further in the research an optimal battery control scheme was developed using the forward dynamic programming approach. Based on the data models, this scheme provided the optimal battery control strategy to achieve the maximum benefits from BESS application.

The research shows that BESS can bring positive benefits for combined energy storage applications. The potentials of using BESS systems in Australian utility network shall be extended specially with the system costs decreased in the future.

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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.

J.Jiang

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1. INTRODUCTION

1.1.Research Scope

Battery energy storage systems (BESS) based on rechargeable/secondary batteries are not a new technologies introduced to the electricity distribution network. They were widely used before AC network becoming the main power supply system at the turn of 20th centuries, where generating stations would often shut down overnight, with lead acid accumulators supplying the residual loads on the DC networks (BAKER, J. and Collinson, A., 1999). But grid scale utility battery storage has been uncommon until fairly recent time because before the systems had disadvantages of low energy densities, small power capacity, high maintenance costs, a short cycle life and a limited discharge capability (CHEN, H. et al., 2000).

With the new developments of battery technologies, there are great improvements of battery energy storage system on both the physical forms and system functions. Today there are significant benefits associated with BESS systems. They not only provide construction flexibility and environmental benefits, but also offer a number of important operating benefits to the electricity utility with their system ability of controllable energy storage and energy releasing. Grid scale BESS system has attracted a lot of interests from electricity industry and been identified as one of the important technologies for the utility network of the future. Within less than 50 years, BESS technology has been adopted in many electrical applications including peak shaving/load shifting through targeted demand management, renewable integration through two way power flows capability, frequency regulation, reactive power support and voltage stability support etc.

Grid scale battery energy storage system displays economic potentials for applying on the electricity network. Battery energy storage system (BESS) commonly contains battery system and battery power conversion system which is generally initiated with the comparable large amount of investment especially for grid scale BESS. From finance point of view, an economic analysis is essential to exam the potential benefits of battery energy storage system. The analysis will exhibit the economic feasibility of BESS systems in grid scale applications. However, due to the differences in BESS system design and complexity of distribution network and electricity market environment, these benefits are hard to be quantified. A general economic analysis method and model needs to be further studied.

This research is using a case study of a grid scale BESS application - DMSP (Demand Management Storage Project) to evaluate grid scale BESS benefits and then to sum them up into value propositions. The DMSP system has been planned to install at the distribution feeder with 2.5MVA / 2MW / 2MWh battery capacity. This system is targeted to achieve:

1) Energy time-shift: energy arbitrage from power price difference between off-peak times and on-peak times;
2) Feeder construction deferment: use BESS system to bring down the feeder peak load demand level through peak shaving at the point of connection to the utility distribution system to provide feeder construction deferment.

The key focuses of the research with this case application lies on several aspects:

1) What benefits can be brought by battery storage systems (BESS) impacted on distribution network;
2) How to quantify the impacts of a BESS system using mathematical models;
3) How to simulate the BESS system operation to demonstration the potential benefits.

To accomplish these tasks, a comprehensive background study needs to be performed.

1.2.Research Objectives

In order to quantify the economic feasibility of the BESS system applications, the data models need to be created to reflect the distribution system, energy market and BESS system. With the data models, methods need to be found out about how to simulate electrical and economic performance of the battery energy storage system and quantify these performances into market value.

The objectives of this thesis can be summarized as following:

1. Investigate the applications of battery energy storage system (BESS) on distribution network and analyse their impacts.

2. Explore the parameters and mathematic models of BESS systems energy time-shift and feeder construction deferral applications and evaluate their potential economic benefits.

3. Use a method to simulate the BESS system operations over a period of time to demonstrate the potential benefits through analysis.

1.3.Summary of Thesis

This thesis contains total six chapters.

The first chapter gives an introduction relevant to the objectives of this thesis. A brief explanation is given for the background and motives of the study.

Chapter two provides the literature review of previous researches which are related to the thesis's objectives. It will cover previous researches about the area of BESS applications, BESS economic analysis and BESS operation simulation. In this chapter, two major applications are reviewed along with the economical beneficial analysis overviews and battery control strategy discussion.

DMSP project's details are provided in chapter three. In this chapter, a general description will be given for system setting of the BESS system installed by DMSP project. The specifications and parameters of BESS system are provided including the information for system primary equipment such as 22kV switchgear, transformer, power conversion system, battery system and system secondary parts such as battery management system. Further in this chapter, the potential applications for a BESS system are discussed. The focus of DMSP project lies on two major applications which are energy time-shift and distribution construction deferral.

In the chapter four, the BESS system economic analysis principles are first introduced. The analysis principles include BESS system cost modelling, benefit present worth factor and BESS system investment payback period. The chapter also describes the mathematic models used for the economic analysis of the two major applications of BESS system: energy time-shift and feeder construction deferral with the essential parameters. The chapter also present the BESS system control method based on the forward dynamic programming algorithm which address optimum operation to maximum the benefits of both applications.

Chapter five outlines results from simulation systems using the models described in chapter 4. Both applications are simulated in HOMER microgrid simulation software. The HOMER simulation works are completed with three different types of energy market datasets and the typical feeder load dataset over one year period. The results are analysed to demonstrate the electrical and economic optimum operation of the BESS system. The optimal battery control algorithm is programmed using MATLAB. The algorithm is to generate a battery control strategy to outcome the maximum benefits.

Chapter six gives the conclusion for the study and discusses the further works and future research directions.

2. LITERATURE REVIEW

This chapter shows the broad background studies of battery energy storage system (BESS) and its applications in power industry. The study investigates the history of battery energy storage systems (BESS) and BESS technologies. The study range covers several aspects of battery energy storage system (BESSs). One aspect is to find out the reasons of why BESSs are important for our electrical network stability, its current existing technologies and how to implement a grid scale BESS to our network. The second aspect is to investigate the previous researches related to mathematically modelling the BESS system's economic performance. The last aspect is to previous works related to BESS system operations and optimization

2.1.Battery Technologies and Battery Energy Storage System

2.1.1. Introduction

Energy storage system uses devices to convert and store exceeded energy for future usages. During the process, energy transforms from one form to another form which is suitable for storage in the particular physical media. Nowadays energy storage has been play an important role because with the good energy storage technology we can get flexible, convenient and constant energy supplies in many fields.

In the electricity industry energy movement followings generation, distribution and customer supply procedures. The energy generation may be produced by the following types of power generation installations (TER-GAZARIAN, A., 2011):

- hydro plants;
- gas turbine plants;
- conventional thermal plants;
- renewable plants;
- nuclear power plants (which we don't have them in Australia);

Because of the environment consideration and energy resource exhaustion, human being is ugly to seek an alternate solution for providing us with energy. Australia has the initiatives to use renewable energies. The renewable energies such as wind or solar energies are clean and safe, and above all have extensive resources. Table 2.1 shows the statistics of Australian electricity production. From the table we can see that during these year electricity produced by renewable energy have been enlarged dramatically where solar PV has been increased 40 times; and wind generation has been increased 100 times from 2000 – 2012. However the introduction of large quantities of electricity generated by intermittent sources poses great challenges to our electrical networks (OOI, C.A. et al., 2015). The electrical network needs a solution to smooth the power supply. The energy storage system can be used for this purpose.

Table 2.1: Electricity Generation in Australia (IEA, 2012)

Production from	Electricity (Unit: GWh)		
	Year 2000	Year 2006	Year 2012
Coal	174245	185301	171239
Oil	1784	3058	4069
Gas	16245	22726	49602
Biofuel	1134	3911	2343
Hydro	16720	16029	14083
Solar PV	38	90	1489
Solar Thermal	0	1	3
Wind	58	1713	6113
Total	210224	232829	248941

From another point of view, the electrical generation facilities are designed to meet the supply side demand which stands as an unfixed amount as the typical weekday load diagram example shown in Figure 2-1. From the diagram, we can see that the load demand could be varied through period of day time or by different seasons. In the other hand, the energy generation itself could not be constant either. Due to the generation – supply manner of the electricity network, the electricity distributors need to provide sufficient facilities and capabilities to meet the maximum demand from the customers which is called peak demand. Further to the requirement of meeting the load peak demand, the electricity distribution networks are designed to have abilities to continue operations after loss of a single circuit. When the circuit loss happens, the remaining circuits can provide supply capacities to take over its load. It means that electrical generation for an area will have energy supply capacity above the maximum load demand with a certain margin. This maximized generating capacity makes sure that the customers will have electrical power supplied in most scenarios. But most time of the day, the load would be below 50% of the installed generation capacity (STRBAC, G, 2008). In overall the usage of the electrical generating facilities is not sufficient. If part of electric energy capacity during the non-peak time could be shifted to the peak time, then the pressures on the peak time electric generation will be eased. Energy storage system is one of the most common technologies to achieve the energy time-shift.

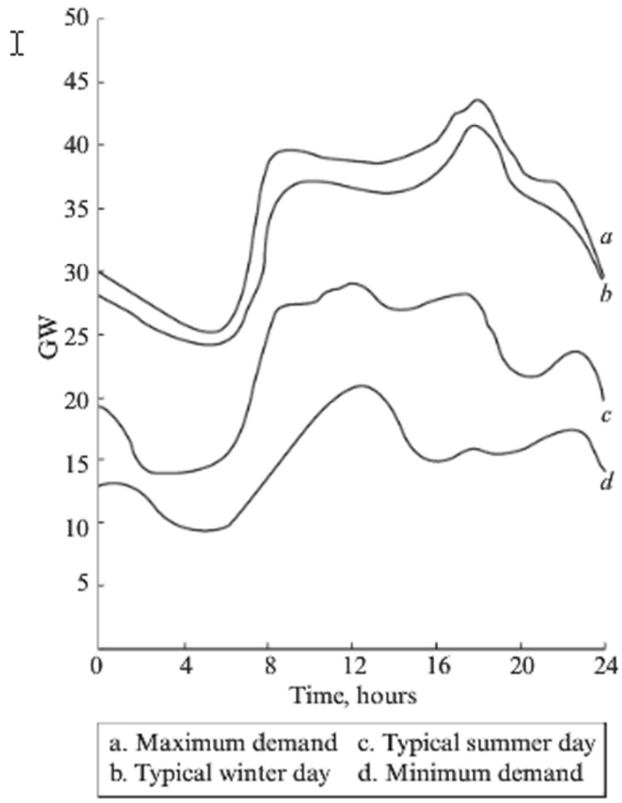


Figure 2-1: Summer and winter demand on a typical system, including days of maximum and minimum demand (TER-GAZARIAN, A., 2011)

Electrical energy can't be stored directly. But with the energy storage system, it can be transferred to and stored as another form of energy and converted back to electrical energy when need. That is why energy storage system is required as an essential unit in the electrical network to coordinate the balance between energy generation and supply. This kind of units can be defined as electrical energy storage is "any installation or method in a power system, usually subject to independent control, with the help of which it is possible to store energy, generated in the power system, keep it stored and use it in the power system when necessary" (TER-GAZARIAN, A., 2011). Electrical energy is stored when energy supply exceeds the consumption and released at the peak load.

There are many forms and means of energy storage applied in the electricity industry. The most common technologies used in power system include (TER-GAZARIAN, A., 2011):

- Thermal energy storage

- Flywheels energy storage
- Pumped hydro energy storage
- Compressed air energy storage
- Hydrogen and other synthetic fuels
- Electrochemical energy storage
- Capacitor bank storage
- Superconducting magnetic energy storage

Among all these technologies, electrochemical energy storage has the advantages of providing the flexibility in capacity, siting, and rapid response which are required to meet application demands over a much wider range of functions than many other types of storage (LAWDER, M. et al., 2014). As one of electrochemical energy storage, battery energy storage system (BESS) has shown a lot of potentials and attracts a lot of interests from electricity industry. It is due to their versatility, high energy density and high efficiency (DIVYA, K. C. and Ostergaard, Jacob, 2009). As the more and more popular used technology applied to the electrical network, the costs of BESS system has decreased a lot along with the improvement of battery life and performance (EPRI, 2003).

2.1.2. Battery Technologies

The electric batteries are devices made of a series of electrochemical cells where chemical energy can be converted to or from electrical energy. Important features of batteries are the power and energy capacities, efficiency, their life span, operating temperature, depth of discharge, self-discharge, and energy density (DIVYA, K. C. and Ostergaard, Jacob, 2009). Batteries has a long history in the electrical supply but was disappeared long time ago due to the cost and lack of efficiency at that time. From the late time of last century, batteries as the energy storage medium are back to the electrical applications. It is because that the power generation scenario has been changed where renewable energy is preferred by publicity and the proportion of renewable energy has been progressively increased. Since then significant development has occurred in the battery technology. Currently, BESS system has played as a more and more important role in the electrical industry.

There are many different types of batteries. The batteries used in power system applications are deep cycle batteries with energy capacity ranging from 17 to 40 MWh and having efficiencies of about 70–80% (LINDEN, D. and Reddy, T.B., 2002). Two dominated battery technologies have been used widely for power system applications and they are discussed briefly below:

1) Lead acid: each cell of a lead-acid battery comprises a positive electrode of lead dioxide and a negative electrode of sponge lead, separated by a micro-porous material and immersed in an aqueous sulphuric acid electrolyte (DIVYA, K. C. and Ostergaard, Jacob, 2009). The lead acid battery system is a mature technology and has widely used in the power system applications. The advantages of this type battery are low cost with high voltage per cell and good capacity life. While the disadvantages are its heavy weight, poor low-temperature characteristic and easy to get damaged at the discharge state (CROMPTON, T.R., 2000). The 10MW BESS built in Chino Substation Facility by Southern California Edison at 1988 is using lead acid battery banks (BHARGAVA, B. and Dishaw, G., 1998).

2) Lithium ion (Li ion): the cathode in these batteries is a lithiated metal oxide and the anode is made of graphitic carbon with a layer structure. The electrolyte is made up of lithium salts dissolved in organic carbonates. When the battery is being charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where the combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge (DIVYA, K. C. and Ostergaard, Jacob, 2009). Li-ion has the very high level of energy density which has the potential to reduce the application unit's size and weight and be more suitable for portable devices (CROMPTON, T.R., 2000). 64MW AES Laurel Mount Storage array is using Lithium battery technology (AES STORAGE).

2.1.3. Battery Energy Storage Applications

There are many different types of energy storage system application. In the report of (EYER, J. and Corey, G., 2010), it summarises and groups the most popular energy storage application into five catalogues as shown in Table 2.2:

Table 2.2: Five Categories of Energy Storage Applications

Category 1 — Electric Supply
1. Electric Energy Time-shift
2. Electric Supply Capacity
Category 2 — Ancillary Services
3. Load Following
4. Area Regulation
5. Electric Supply Reserve Capacity
6. Voltage Support
Category 3 — Grid System
7. Transmission Support
8. Transmission Congestion Relief
9. Transmission & Distribution (T&D) Upgrade Deferral
10. Substation On-site Power
Category 4 — End User/Utility Customer
11. Time-of-use (TOU) Energy Cost Management
12. Demand Charge Management
13. Electric Service Reliability
14. Electric Service Power Quality
Category 5 — Renewables Integration
15. Renewables Energy Time-shift
16. Renewables Capacity Firming
17. Wind Generation Grid Integration

A lot of researches have been through for these technologies. Among all these technologies, electrochemical energy storage devices offer dependence, capacity, or response capabilities to meet application demands over a much wider range of functions than many other types of storage (HUGGINS, R.A., 2010). Electrochemical energy storage especially battery energy storage systems (BESSs) currently have seen great growth recently due to their versatility, high energy density, and efficiency (DIVYA, K. C. and Ostergaard, Jacob, 2009).

The use of battery systems for energy storage has long history. Back to more than 100 years ago, energy storage batteries were used as primary energy supply (TER-GAZARIAN, A., 2011). Grid scale battery storage system refers to battery energy storage within an electrical power grid.

Electrical energy is stored during times when production exceeds consumption and released when load is greater than the combined power generation.

There are some main applications can be used in grid scale BESS (AGUERO, Julio Romero et al., 2013):

- Frequency regulation: Using battery energy storing and releasing to adjust the frequency variation.
- Spinning reserve: Using battery energy storage to reduce the spinning reservation amount.
- Peak shaving/load shifting: Battery energy storage system stores the energy during the off-peak demand period and releases the energy during the peak period which can reduce the maximum capacity of whole utility network and then further reduce the operation cost and infrastructure expense.
- Renewable integration: As stated previously, the battery energy system can provide rapid response to the large amount of intermittent energies injected to the grid.
- The future developments for grid scale BESSs are relied on these aspects:
- Developments upon the new battery technologies.
- Developments for analysis and examine the technical and economic feasibility of integrating battery in electrical networks (DIVYA, K. C. and Ostergaard, Jacob, 2009).
- Further researches on real-time intelligent control algorithms for grid scale battery energy storage system.
- Development of integration of grid scale BESS within the smart grid.

There are many grid scale BESSs applications developed worldwide. Here briefly review some of these projects:

1) In 1986 a 17MW 14MWh lead acid battery storage system was installed at BEWAG in Berlin. The system was designed for frequency regulation and spinning reserve. It operated for 8 years and had a capacity turnover of 7000 times of normal capacity and the total energy turnover of about 100GWh (WAGNER, R., 2004).
2) In southern California Edison, USA, a 10MW 40MWh lead acid battery storage system was built at Chino substation in 1988. The application was for load levelling and load following. The storage system operated 8000 cells in 56000 square feet of warehouse for 8 years (SOUTHERN CALIFORNIA EDISON).

3) Puerto Rico Electric Power Authority (PREPA) was installed in 1995 in Puerto Rico. Its system size is 20MW 14MWh. The battery system is using lead-acid battery for the spinning reserve and frequency control (TAYLOR, P. et al., 1997).
4) Japan Wind Development Company built the 51MW Rokkasho-Futamata wind farm integrated with 34MW battery storage system. The battery energy system consisted of 17 sets of 2MW NaS battery units. The purpose of this battery system was for load levelling and enabling the storage for low cost off-peak power for sale/distribute during peak demand time (CLEANENERGY ACTION PROJECT, 2015).
5) In 2011, AES Gener completed construction on a 544MW thermal power plant in the town Mejillones in Northern Chile. To ensure grid reliability against transmission or generation losses, a 20MW/5MWh battery energy storage system was installed for load following purpose (ESA, 2011).
6) In 2011 AES built a 98MW wind power generation plant in Laurel Mountain Belington to supply more than 260GWh of renewable energy annually. To achieve the grid reliability, AES installed a 64MW/8MWh grid energy storage system at the Laurel Mountain facility to provide frequency regulation. The system used Lithium battery technology (ESA, 2011) (AES STORAGE).

Australian has only started to promote and support green energy decades ago. There are some battery energy storage system applications installed in Australian. But compared with USA and Europe, the size of our applications and the technologies used are far away behind of them. Our battery energy storage system technology is still in the experimental and starting stage. There is still a long way to go for us to establish a mature grid scale BESS system. By all these years, utility companies have put in a lot of efforts to introduce this new technology into our electrical utility network. Hydro Tasmania have installed an electrochemical battery system on King Island, capable of 3 MW of power contribution and storing 1.6 MWh of useable energy. The battery system adopts vanadium redox battery (VRB) technology. It was a large scale battery installed in Australia. It provides the load levelling function to support King Island wind farm (HYDRO TASMANIA). Another example is that, Ergon Energy of Queensland is going to install the first grid scale battery system GUSS. The system is going to be constructed on the single wire high voltage distribution voltage line to improve the quality and reliability of electricity supply to rural customers (ERGON ENERGY, 2015). Energy storage offers the potential means to support our existing electricity networks, facilitate the efficient operation of electricity markets, improve the stability of our grid as it becomes more dependent on intermittent renewable generation sources, and meet the private needs of residential and commercial customers (MARCHMENT HILL CONSULTING, 2012). And the DMSP project described in this document is going to install a 2.5MVA/2MW/2MWh battery energy storage system for feeder construction deferral and energy time-shift.

2.2.BESS Economic Benefits

2.2.1. Introduction

The electric power system is the network of electrical components used in electricity generation, transmission and distribution. The purpose of an electric power system is to deliver electricity energy to the customers in the manners of reliability and economy. The reliability of power supply refers to two kinds of aspects: security is the system's ability to withstand sudden disturbances; adequacy is the property of providing customers with continuous service with a voltage and frequency within regulated ranges (STOFT, S, 2002). Improvements in system reliability can be achieved by using better design or components and increasing capacity to incorporate redundancy (PRADA, J.F., 1999).

The economics of the electric power system is another challenge to the power industry. How to achieve good electrical services with less investment is always the topic in the industry. The alternative economic strategies must be gained within the bound of reliability, safety and environment aspects.

The use of battery energy storage system into electrical network brings the potentials of improving power system reliability and economics. Over these years, many utilities and research organizations have done a lot of work on developing and evaluating new technologies of grid scale battery energy storage system. Especially for recent years, the battery energy storage techniques have been developed rapidly and many new application areas have been identified (YANG, Z. et al., 2001) (TELEKE, S. et al., 2009) (HILL, C.A. et al., 2012). It can be foreseen that battery energy storage system applications will keep increasing through the year with the application types from short term to long term time period and scales varied from domestic to large grid scale (DIVYA, K. C. and Ostergaard, Jacob, 2009). With this trend, an economic feasible study about battery energy storage system has become necessary. The study will provide the indication for future applications and projects.

2.2.2. BESS for Electric Energy Time-Shift

By National Electricity Law and Rules, the wholesale electricity market exists as a spot market where competing generators offer their electricity output to retailers. The retailers then sell the gas and electricity and take it to end consumers through retail market. The Australian Energy Market Operator (AEMO) is the national electricity market and system operator in southern and eastern Australia. AMEO decides 5min period dispatch price according to the generators' bids. Then six dispatch prices are averaged which determines the spot price at each half-hourly trading interval for each region. In brief, the spot price reflects the balance between the electricity demand and supply. The spot market prices spikes happen due to unexpected generation or transmission outages (EEX.GOV.AU). The electricity spot price can vary through days and seasons. The price difference presents a potential financial incentive to store electric energy when the price is relatively cheap and then sold them for higher price in the future.

With the electricity spot price difference, an energy storage system (ESS) can be connected to the grid to attend electricity market operations and achieve energy time-shift benefits. ESS can shift the energy from the low price time to the high price time through the controlled energy storage charge/discharge processes (EYER, J. and Corey, G., 2010).

There are different forms of energy storage system can be used for energy time shift application. Battery energy storage system (BESS) as one of the mature and flexible ESS can be used in power system applications ranging from providing high power to high energy output (ZHANG, S. et al., 2013). One of the advantages of BESS is its controllable energy storage and energy releasing with high ramp rate (THIEN, T. et al., 2015). Using battery based ESS systems in energy time-shift applications, electric energy can be charged/discharged by control scheme with relatively high response speed. BESS's controllability and flexibility makes it suitable for this type of application. BESS system control scheme and benefit evaluation will be further discussed in section 4 & 5.

The main purpose of installing BESS system for energy time-shift is to achieve the maximum revenues. The maximization of revenues relays largely on the suitable capacities of BESS system and charging/discharging durations (ZHANG, S. et al., 2013). The amount of revenues for BESS energy time-shift is the profits gained from spot market deducted the system operation and maintenance costs. Because BESS systems always require a chemical storage medium, which makes them more costly in terms of operation and maintenance, therefore using BESS systems for electric energy time-shift only is not going to be economic benefits (MOSELEY, P.T. and Garche, J., 2014). In previous researches (ABDELRAZEK, S. and Kamalasadan, S., 2014) (PARRA, D. et al., 2015), it has been found out that one BESS system can be functional in combined applications. For the BESS system, electric energy time-shift application is well compatible with other applications such as increasing electric supply capacities, voltage supporting, transmission congestion relief and transmission/distribution construction deferral (EYER, J. and Corey, G., 2010). In this research, feeder construction deferral is the one combined with electric energy time-shift application.

2.2.3. Feeder Construction Deferral

Feeder construction deferral is one of the most attractive applications for BESS system because it might bring very high economic benefit. When feeders have shortage capacities compared with the peak demand level, the general solutions in electrical industry are either using diesel generator to provide more supplies or upgrade the feeder equipment (MOSELEY, P.T. and Garche, J., 2014). But both solutions are expensive especially for the equipment upgrade option. The large investments for electrical equipment and constructions make economic opportunities for using energy storage system to avoid the feeder upgrade.

The main concept of feeder construction deferral application is using relatively small storage system to defer the major investments on the distribution feeders. For a distribution system when its peak demands of loading are getting close with the system's capacity rating, installing a small amount of energy storage near the overloaded node will defer the need for feeder upgrade (EYER, J. and Corey, G., 2010). For an example, a feeder rated 10 MW is with the load growth of 2% per year, and the feeder operation is nearly approaching its rating this year. In this case, one method is to upgrade the feeder with additional 2.5 MVA – 4 MVA capacities (general arranged in 25%-40% of the original rating); or the alternative method is to install the energy storage system to cover the load growth in few years. Installing a 500 KVA BESS system will defer the construction in this feeder for about 2 years. Another economic intention of feeder construction deferral application is that the implementation of energy storage such as BESS system on the demanding feeder line may extend the life of existing feeder lines, through the avoidance of overloading (ESA, 2011). The need for the aged equipment replacement will be delayed because of the feeder life extension. In addition, the feeder construction deferral is not only to avoid the large investment for the utility upgrade, but also to avoid the supply interrupt and construction risks. With the current battery technologies, BESS system generally can service for 10 to 30 years. Compared with other forms of energy storage, BESS system has its own advantages. As the energy storage installed for feeder construction deferral, BESS doesn't need to be retired when the load level has reached a certain level and the feeder has to be upgraded. Because it is viable to multiple applications, BESS system can be re-applied for other applications. It also can be re-constructed to another feeder required deferment because of current modular design and ease of construction.

Some studies and researches have been devoted to the T&D construction deferral applications. One very important aspect of researches is to identify the size and location of the energy storage system. An elimination algorithm was analysed and presented to optimally defer T&D expansion even though in that research the algorithm was used to identify distribution generators in paper (BROWN, R.E. et al., 2001). A model for identify the size and power of the energy storage system is presented in paper (NOURAI, A et al., 2008).The purpose of this model aims to maximize the economic benefits of the energy storage used for T&D construction deferral.

Other important aspects of researches are to value the economic benefits of installing energy storage system for T&D construction deferral and to create a suitable control schemes. Both aspects will be discussed in section 4 & 5.

2.2.4. BESS Economic Beneficial Analysis

There are many papers and researches have addresses the economic beneficial analysis of BESS applications. A lot of researches are emphasised on the economic benefit analysis of BESS systems coordination with renewable energy (Shaahid, 2013) (Hoppmann, et al., 2014) (Bortolini, et al., 2014). In (Han, et al., 2015) paper, it evaluated the economic beneficial of BESS system for load shifting application by different types of batteries.

In paper (EYER, J. and Corey, G., 2010), it gave a general guide lines of economic benefit analyses for seventeen popular energy storage applications. There is another research (ZHANG, T., 2013) studied economic benefits derived from BESS applications: energy purchase Shifting and distribution feeder deferral and outage avoidance. The research used theoretical modelling of the BESS and distribution system to analyse the benefit.

The annual financial benefit for electric energy time-shift application is derived by using storage to make electric energy transactions. Through buy low/sell high process, the benefit can be gained either as profit if the application is on the utility side; or as lower energy cost if the application is on the demand side (MOSELEY, P.T. and Garche, J., 2014).In research report (EYER, J. and Corey, G., 2010) it used a simple storage dispatch algorithm is used to estimate the time-shift benefit. The algorithm contains the logic of defining charge/discharge storage in order to optimize the financial benefit. In the paper, it also three data items were key-parameters in dispatch algorithm: market price, energy storage round-trip efficiency and storage system discharge duration. Another research (BOLADO, J.F. et al., 2014) simply examined a liner programming model to identify the arbitrage potential. However, as indicated by (DUSONCHET, L. et al., 2012), at the current costs of storage technologies and at the current electricity tariffs, the use of battery systems for electric energy time-shift applications is not economically advantageous. To change this situation, it needs the aggregation of different benefits for the same BESS system such as deferral of investment in T&D network upgrades.

For BESS system economic benefits for feeder construction deferral is largely depended on the pressure level of feeder upgrading, the construction cost and the type and size of storage system installed. In the previous researches (EYER, J. and Corey, G., 2010) (ZHANG, T., 2013), present worth model was used commonly for estimated the benefits for T&D construction deferrals. In the paper it presented a one-year deferral method for estimating avoided transmission and distribution costs and explored the non-integer deferral time in the present worth method.

There are another important aspect should be covered in benefit estimation which is the cost estimation. The cost estimation should include the capital cost and operation cost estimation. The report (SCHOENUNG, S., 2011) covered a comprehensive understanding for the cost estimation concepts and provided estimation models.

In (Dufo-López & Bernal-Agustín, 2015) research paper, it presents a methodology to evaluate the technical and economic performance of a grid-connected battery system. The data modelling and system simulation was achieved under a time-of-use (TOU) electricity tariff in the Europe electrical supply system. Another research by (Ma, et al., 2014) examined and compared two energy storage technologies: battery energy storage system (BESS) vs. pumped hydro storage (PHS), for the renewable energy powered microgrid power supply system in Asia. It concluded that PHS was the feasible option for the area. In (Fares & Webber 2014) research developed the BESS behavioural-circuit model and simulated the model in US electrical power supply environment.

Australian electric energy supply has its own characters. In the current time, there are no research has been done to show the economic feasibility of using grid scale BESS system on distribution network in Australia. This research is aimed to have the data modelling and simulation completed in the real Australian energy and economic environment. It will give the indications for further BESS projects about the system size, battery type and project location.

2.2.5. BESS Charge/Discharge Strategies

To achieve maximum benefits from a BESS system, BESS control scheme needs to be designed optimal according to the distribution network characteristics, BESS system size and type, and to which specified BESS application. The control scheme is the unit which can ensure BESS system operates battery charging/discharging process economically.

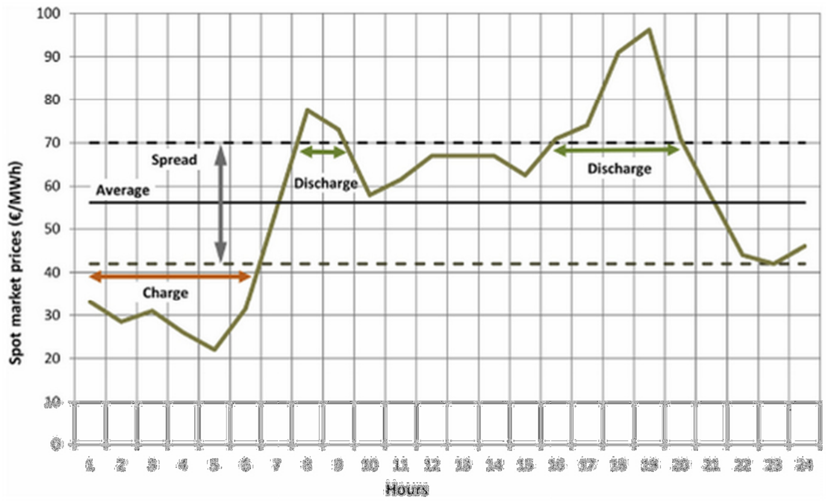


Figure 2-2: A simple electric energy time-shift strategy (MOSELEY, P.T. and Garche, J., 2014)

Many papers have revealed the previous researches of BESS control approaches for electric energy time shift application. Figure 2-1 shows a simple application which uses the straightforward strategy. BESS system was charged / discharged by the set values of spot market price (MOSELEY, P.T. and Garche, J., 2014). In another paper, a similar linear optimization algorithm was used based on the mean price of day-ahead market to determine the best operating strategy (BOLADO, J.F. et al., 2014). But in many cases, electric market price changes through the year. It depends on the balance of consume demands and electric generate abilities. In the paper of (ZHANG, S. et al., 2013), the research for an optimal control strategy was presented where few typical control algorithms were setup for their BESS system control. The spot market pattern was studied and analysed which resulted into four control scheme of typical summer, winter, weekday and weekend.

To achieve feeder construction deferral, one common method is through peak shaving which shifting load from the peak to the off peak period (NOURAI, A et al., 2008). BESS control scheme is very similar as for the electric time-shift application as above. The difference between two applications is the data applied for control schemes. For electric time-shift application, control scheme is based on the electric market price to set the charge/discharge points. On the other hand, for feeder construction deferral application, it is the load demand used for control scheme database.

The BESS control algorithm is a popular research topic. The paper (Haddadian, et al., 2015) proposed a methodology for day-ahead energy resource scheduling and the coordination between distributed battery storage and thermal generating units. The proposed model can be expanded to large-scale systems with additional constraints. In (Ray et al. 2014) research, an operation algorithm was proposed to optimize the operation of the BESS to maximize operating profit. This optimized operation method would make the BESS more economically feasible to power system operators, and lead to smoother integration of BESS. This research used control set points to control battery charge or discharge. Another research show in the paper (CIADEA, S.M. et al., 2013), introduced a mathematic method to optimize the BESS control scheme, called backward dynamic program algorithm. The research used this algorithm applied on the electric market price data to find out BESS operating path at its highest economic potentials.

This research is going to use forward dynamic programming algorithm to find the optimal battery control strategy. Similar to backward dynamic programming algorithm, the forward dynamic programming will find the best battery charge/discharge operation routine to achieve the best economic benefits. The difference between the two methods is that: backward dynamic programming algorithm is from the knowing end point of energy movement tracing backward to find the best solutions from different start points; forward algorithm is from the knowing start point to find the best solutions to different end points. The forward dynamic programming fits more with the operation of the electrical distribution and will be useful for the battery operation planning.

3. DMSP PROJECT - STUDY OF BESS APPLICATION IN DISTRIBUTION SYSTEM

3.1. Introduction

DMSP is the project setup by the utility company for improving the reliability and economic of distribution services by connecting a battery energy storage system (BESS) into the distribution system. The zone substation of this distribution system is one of the heaviest loaded substations in the utility that supplies the domestic and commercial area in Victoria rural area. Currently, the zone substation is comprised of two 20/27/33MVA and one 25/33 MVA transformers operating at 66/22 kV. The estimation has been processed for the zone substation of its magnitude and impact of loss of load by considering the energy at risk and the annual hours at risk. The result, which is shown in the table 3.1, indicates that the maximum demand is going to exceed highly of its capacity in the summer time and this zone substation would not be able to supply all its customers during high load periods following the loss of a transformer at substation.

Table 3.1: Estimated energy at risk for the studied zone substation (POWERCOR, 2014)

	2016	2017	2018	2019	2020
Summer demand (MVA)	85.0	86.1	85.8	84.3	84.9
Summer overload (%)	11.9	13.3	12.9	11.0	11.7
Annual energy at risk (MWh)	53	69	65	44	51
Annual hours at risk (hrs.)	15	18	17	14	15

Currently the solution to address this system constraint is to transfer load away via 22kV links to adjacent zone substation. But data shows that that adjacent substation will reach its own capacity limits soon. So the studied zone substation is facing upgrade in the near future. To relief the load pressure of this zone substation, DMSP project decides to choose the alternative solution that installs a BESS system connecting to the distribution service supplied from this zone substation. After multiple criteria analysis, a 2.5MVA / 2MW capacity BESS has been selected to be connected into one 22kV radial type distribution feeder.

3.2.DMSP System Components and Specification

The DMSP system contains five main components: switchgear, transformer, power conversion system, battery system and battery management system. A general connection diagram is shown in figure 3-1.

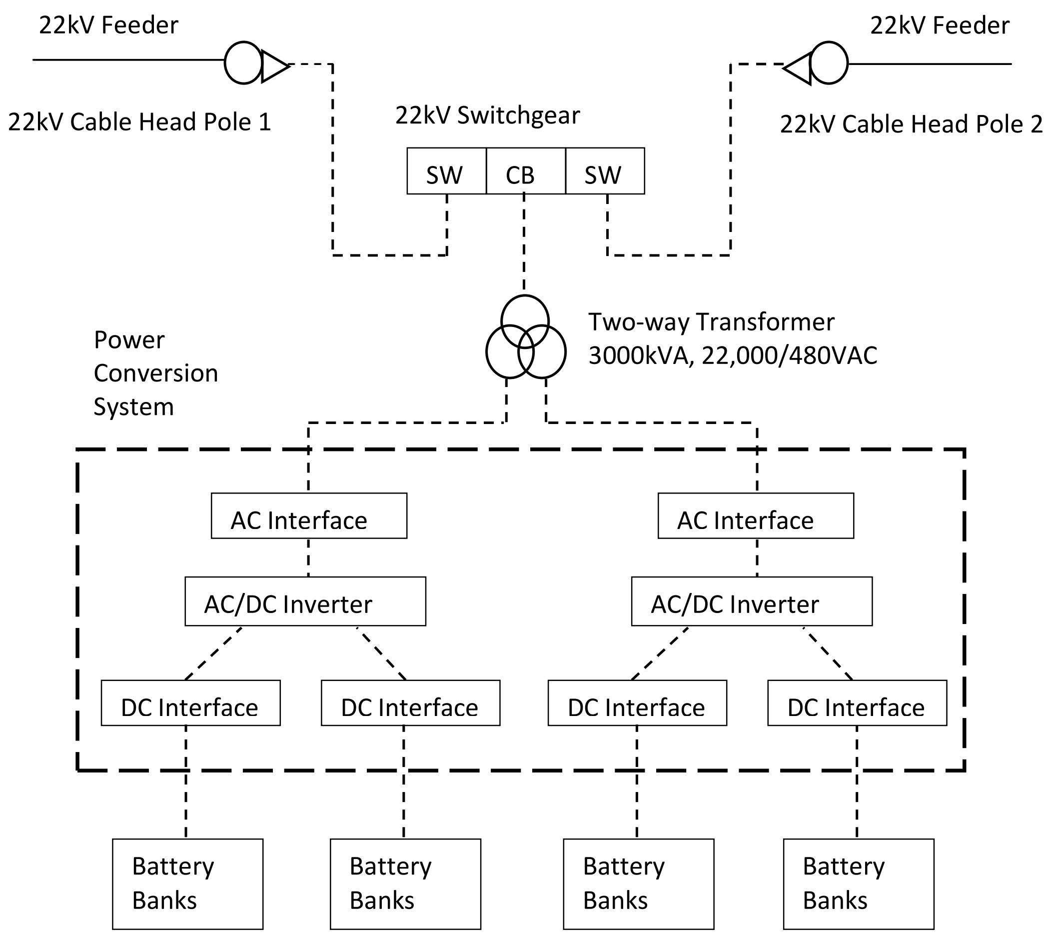


Figure 3-1: DMSP System Connection Diagram

3.2.1. 22kV Switchgear

In DMSP BESS system, the 22kV switchgear is selected to provide the interface between BESS system and the distribution network. The switchgear contains two motorized disconnect switches and one circuit breaker which is used to control, protect and isolate BESS system. It can deenergize DMSP system manually or automatically during the maintenance or fault conditions. The protection relay installed in the switchgear will protect and monitor DMSP system. Table 3.2 lists the general information for the 22kV switchgear used in DMSP project.

Table 3.2: DMSP 22kV Switchgear Specifications

Number of ways	3 (2 x SW, 1 x CB)
IP rating	IP54
Nominal operating voltage	22kV
Frequency	50Hz
Rated short time current withstanding rating	20kA, 1sec
Rated internal arcing resistance withstanding	20kA, 1sec
Bus rating(@40C)	630AAC
IP rating (overall)	IP54
IP rating (cable compartment)	IP2XC
Spring charging voltage	125VDC
Protection relay	125VDC

3.2.2. Transformer

The main power transformer of DMSP system is a two-way transformer. It will decrease the network voltage level to DMSP system operation voltage level when battery is charging or increase DMSP system operation voltage to the network voltage level when battery is discharging. The transformer is connected to the circuit breaker of the 22kV switchgear and the AC interface of power conversion system. Table 3.3 lists the general information of transformer used in DMSP project.

Table 3.3: DMSP Step-up/Step-down Transformer Specifications (manufacture data)

Number of phase.	3 ph.
Transformer type	Outdoor
Protection to Standard AS 60529 or IEC 60529	IP46, IP2X
Rated frequency.	50Hz
Rated ONAN power at all tapping & yearly average temperature of 20°C.	3000kVA
Minimum energy performance	99.4 %
Voltages:	
Primary winding voltage	22kVAC
Secondary winding voltage	480VAC
Secondary current rating	3007AAC
Short time current withstand level for 2s (Primary & Secondary)	25 times I_N
Distribution transformer vector group.	YNd11
Insulating medium.	Oil
Method of cooling.	ONAN

3.2.3. Power Conversion System

In the DMSP system, an AC/DC bidirectional inverter is required to store or release energies to the distribution network. The inverter is controlled by the power conversion system. DMSP system uses battery banks as the storage medium. The power conversion system connects to the chargeable batteries through the DC interfaces. When the network has more productive exceeded the demand, the inverter is acting as a charger to store the electrical energy to battery banks. When the network needs the power support, it is acting as a voltage generator to release the energy to grid. Table 3.4 lists the general information of power conversion system.

Table 3.4 DMSP Power Conversion System Specification (manufacture data)

Nominal VA rating	+/ - 1250kVA
Nominal power rating	-2MW (charge) to 2MW (discharge)
Nominal connection voltage	480VAC ± 10%
DC Input voltage range	640VDC to 800VDC
Nominal AC current rating	3007AAC
DC current range (each of 2 sets)	-1145ADC (Charge) to 1150 ADC (Discharge)
AC frequency range	48.5Hz to 51Hz
Response speed	< 16ms
Control accuracy	Maximum error = ±1% of the Power or VAR set point value
Harmonics	Designed to meet IEEE 519
Communication	Modbus, DNP3

3.2.4. Battery System

DMSP project chooses Lithium polymer battery as the storage medium. Lithium polymer battery has the characters of high power and high energy density with good power to energy balance and long cycle life which make it suitable for large scale energy storage applications. This type of battery presents advantages in system safety with its low weight, low impedance and heat generation. It also shows economic potentials with the high efficiency in battery charge/discharge processes. The following table 3.5 3.6 3.7 3.8 and figure 3-2 show the general information of the DMSP battery system.

Table 3.5: Battery System Specification (manufacture data)

Energy capacity.	2MWh
Energy Capacity (end of life).	1.44MWh
Battery System Maximum C-rate (CP)	1.5C
Battery System Max SOC	95%
Battery System Min SOC	5%
Max Capacity Degradation	Approx. 20%
No. of full cycles between min & max SOC restriction for which emergency can be guaranteed.	4500
Cycle per day based on Depth of Discharge 90% (SOC 5% - 95%).	1
Minimum charge rate.	no min. limit
Maximum charge rate.	1C
Minimum discharge rate.	no min. limit
Maximum discharge rate.	1C
Recharge times from full depth of discharge (DOD), based on the beginning of life performance, to 100% maximum power.	1.1~1.2 h
GESS DC voltage output efficiency level.	>94%

Table 3.6: Battery System Power Delivery Capacity

(Manufacture data)

2-hours period.	1,046kW
3-hours period.	701kW
4-hours period.	527kW
5-hours period.	416kW
6-hours period.	347kW

Table 3.7: Battery System Maximum Long Term Recharge Power

(Manufacture data)

20% depth of discharge (DOD)	2,200kW
50% depth of discharge (DOD)	2,200kW
90% depth of discharge (DOD)	2,200kW

Table 3.8: Battery Cell Specification (manufacture data)

Battery cell type	Lithium polymer
Battery cell chemistry composition	NMC
Nominal voltage	3.7V
Battery cell charge cut-off voltage.	4.2V
Battery cell discharge cut-off voltage.	2.7V
Nominal current capacity	75Ah
Energy density	156Wh/kg
Nominal energy per battery cell	277.5Wh
Power density	320Wh/l
Battery cell cycle life	up to 7,500 cycle @ 80%DoD @ 60% of remaining capacity
Weight per battery cell.	Max. 1,780g
Volume per battery cell.	0.301mL

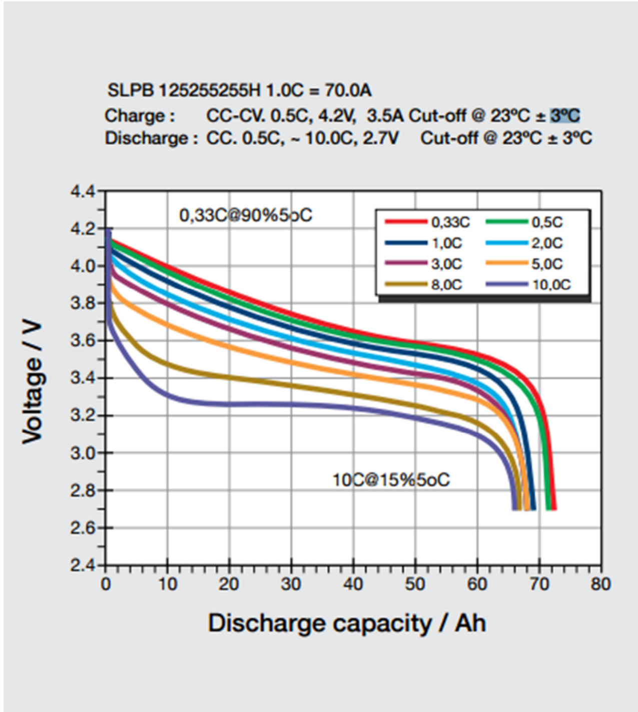


Figure 3-2: DMSP Lithium polymer battery discharge curve (PERRY, B., 2012)

3.2.5. Battery Management System

Besides all these equipment, battery management system (BMS) acts an essential role in the DMSP system. The battery management system (BMS) is to monitor and maintain the operation of the battery units. The basic functions of BMS are controlling battery banks to meet the demand of system applications. BMS interfaces with the power conversion system and provides the programs for the battery charge/discharge routines. The applications of DMSP need the assistance of BMS to be accomplished. Further to this, BMS includes a group of protection equipment to provide protection functions to the system and prevent DMSP system damaged from the external network faults and internal errors. BMS communicates with the utility master station for operations or transmitting monitoring data. The communication goes through SCADA system via Ethernet. The master station can control the management system to switch on/off the DMSP system for maintenance or under emergency conditions.

3.3.DMSP System Control Mode

3.3.1. Scheduled Mode

One of the DMSP operation modes is scheduled mode. DMSP system has the ability to set battery system charge/discharge schedules by using programmable profiles. The battery management system has the capability to schedule the battery control scheme with the profiles programmed in HMI. Battery management system has the ability to make seven day schedules while each daily can contain eight profiles for charging or discharging.

Each profile contains scheduled timing and amount of power or energy programmed using the local HMI which communicates to control centre through SCADA. The timing is the stating time for battery operations. The level of power or energy tells the battery system how and how many to charge or discharge. Positive power or energy values cause the battery management system to discharge the battery, negative values cause the battery to charge. There are controlling logics and alarm system built in the battery management system to prevent the scheduled profiles overlapping. In addition, a metering device needs to be installed and monitor the power or energy level of the battery system.

The DMSP scheduled mode can be used for energy time-shift application. With the predicated spot market prices, profiles can be setup to charge and discharge batteries in order to gain arbitrage from the difference of energy spot prices.

3.3.2. Peak Shaving Mode

Another mode of DMSP system is peak shaving mode. The purpose of this mode is to reduce peak demand of the load. During the operation of this mode, SCADA inputs load power set point, discharge power threshold and charge power threshold to battery management system to setup battery charging or discharging processes. When the load power exceeds a discharge threshold, batteries will be discharged to reduce total power demand. In the other hand, battery management system will send out charge command to the battery system when the Load Power drops below a charge threshold which will store energy into batteries for future discharges.

Peak shaving mode can be applied to reduce the load power peaks. The load power level is varied by time when peaks might only be average 40 hours yearly. When peak load power level is reduced, the requirement can be deferred for increasing of feeder capacity to supply the peaks. Utilities reduce the operational cost of generating power during peak periods. So peak shaving mode is suitable for feeder construction deferral application.

To accomplish this mode, battery management system needs to communicate with the power measurement units for the feeder load power level constantly.

4. BESS SYSTEM MODELLING

4.1. Introduction

This chapter addresses system modelling of BESS system and the BESS applications. One of the aims of the chapter is on finding the mathematic models which can be used to model battery storage system and battery charge/discharge operations. With the BESS system operation models, the economic approaches can be formed to evaluate the economic benefits which can be delivered through two major DMSP applications: energy time-shift and feeder construction deferral.

4.2.BESS Economic Analysis Principles

4.2.1. BESS System Cost Modelling

To model the battery energy storage cost model, these parameters are used:

- Cost for the battery storage unit, C_{BS}
- Unit cost for the battery storage unit, $Unit\_C_{BS}$
- Cost for the power conversion system, C_{PCS}
- Unit cost for the power conversion system, $\mathrm{Unit\_C}_{PCS}$
- Costs for system operation and maintenance, $\mathrm{C}_{BS-O\&M}\ \&\ \mathrm{C}_{PCS-O\&M}$
- The energy rating of BESS system, E_{BESS}
- The power rating of BESS system, P_{BESS}
- Battery system round-trip efficiency, η_{BESS}

There are two types of cost for the BESS system capital investment:

- Cost for the battery storage unit which is related to the energy capacity of BESS system.

$$\mathrm{C}_{BS} = Unit\_C_{BS} \times (E_{BESS} / \eta_{BESS}) \tag{1}$$

- Cost for the power conversion system which is related to the power capacity of BESS system.

$$\mathrm{C}_{PCS} = Unit\_C_{PCS} \times P_{BESS} \tag{2}$$

The total capital cost of BESS system can be calculated by the sum of two types of cost:

$$C_{Capital} = \mathrm{C}_{BS} + C_{PCS} \tag{3}$$

Where there are always cost for system operation and maintenance, so in general the total charges for a BESS system can be described as:

$$\begin{aligned} C_{Total} &= C_{Capital} + C_{BS-O\&M} + C_{PCS-O\&M} \\ &= \mathrm{C}_{BS} + C_{BS-O\&M} + C_{PCS} + C_{PCS-O\&M} \end{aligned} \tag{4}$$

4.2.2. Present Worth Factor

Using economic model to analyse the benefit from BESS applications, the concept of present worth value needs to be introduced. Due to the existing of interest rate and electrical price escalation rate, the value of current electrical investment and benefit is not the same as in the future. To be able to compare the time related benefit values correctly with the current costs in the cash flow, a present value factor needs to be multiplied to the average revenue of the BESS system.

The method of valuing the future revenue to the present value uses several parameters:

- Year, i
- year i revenue, REV_i
- The present worth value of year (i) revenue, PV_i
- The annual discount rate, d
- The annual electrical price escalation rate, e

Assume the discount rate and price escalation rate keeps constantly, then the present value of year (i) revenue can be calculated as below:

$$PV_i = REV_i \times \left(\frac{1+e}{1+d}\right)^i \tag{5}$$

The present value of revenue summary from year (1) to year (n) is shown as below:

$$PV = \sum_{i=1}^{n} PV_i = \sum_{i=1}^{n} REV_i \times \left(\frac{1+e}{1+d}\right)^i \tag{6}$$

Let's assume the yearly revenue is the constant value, the equation (6) can be written as:

$$PV = REV \times \sum_{i=1}^{n} \left(\frac{1+e}{1+d}\right)^i \tag{7}$$

The present value factor can be defined as:

$$PV_{factor} = \sum_{i=1}^{n} \left(\frac{1+e}{1+d}\right)^i \tag{8}$$

For the BESS system installed, the total benefit through the operation lift time can be calculated by the annual revenue multiplied with the present worth factor.

4.2.3. BESS System Payback Period

One of important aspects of the economic analysis is to find out if the investment can be money-making. For BESS system, the total cost and the present value of system revenue is described. If the revenue is high than the total cost, then the BESS system is profitable. The minimum profits made by BESS system can be presented in equation (9):

$$REV \times \sum_{i=1}^{N_{\min}} \left(\frac{1+e}{1+d} \right)^i = \mathrm{C}_{Total} \tag{9}$$

For a BESS system which is making profits, it is also important to find out for how many years the investment can get payback. The payback period can be found out through the following derivations. Equation (9) can be simplified to:

$$\begin{aligned} &REV \times \sum_{i=1}^{N_{\min}} k^i = \mathrm{C}_{Total} \\ &k = \frac{1+e}{1+d} \end{aligned} \tag{10}$$

In equation (10), the geometric series can be changed to a simpler format:

$$\sum_{i=1}^{n} k^i = \frac{k}{1-k}(1-k^n) \tag{11}$$

$$\frac{k}{1-k}(1-k^n) = \frac{\mathrm{C}_{Total}}{REV} \tag{12}$$

Using equation (4) to find out the total cost, the minimum payback period of BESS system can be calculated by Equation (13):

$$n = \frac{\log\left(1 - \frac{\mathrm{C}_{Total}}{REV} \frac{1-k}{k}\right)}{\log k} \tag{13}$$

4.3. BESS Application Modelling

4.3.1. Electric Energy Time-Shift Model

The spot market of the electric energy in Australia is operated by AEMO. AEMO conducts the spot market through managing the balances between electric generation and consuming. The balances are achieved by AEMO centrally-coordinated dispatch process which contains following activities (AEMO, 2015):

- Managing the bidding
- Scheduling and dispatch of generators
- Determining the spot price
- Measuring electricity use
- Settling the market

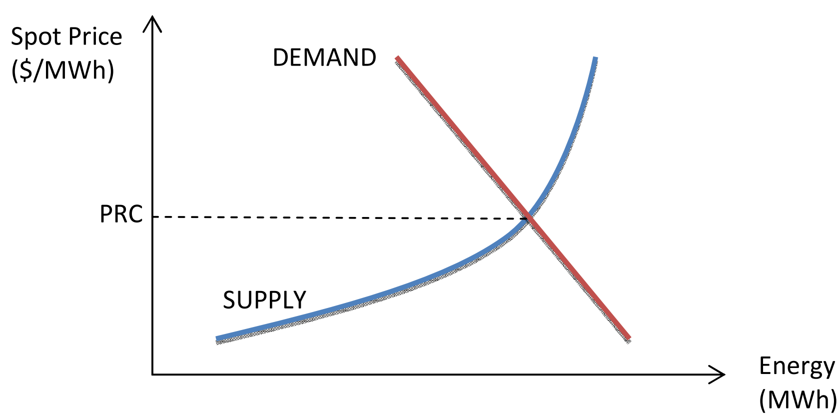


Figure 4-1: Spot Market Supply and Demand Curves

The spot prices differ widely through time to time which reflect the cost of the electricity supply to meet the demand of load. Figure 4-1 shows the market operation between electricity supply and demand. If the price is below point “PRC”, supply will have less volume than the demand. The spot prices will be raised because of the shortage of energy. On the contrast, if the price is above point “PRC”, supply will be greater than the demand. The price will be dropped by over-supplied energy. In both cases, the spot price will be eventually come close to the point “PRC” where the demand and supply are in balance. The spot price, electric capacity and the load demand are correlated. The lower the electricity supply or the higher load demand will cause higher price for electricity.

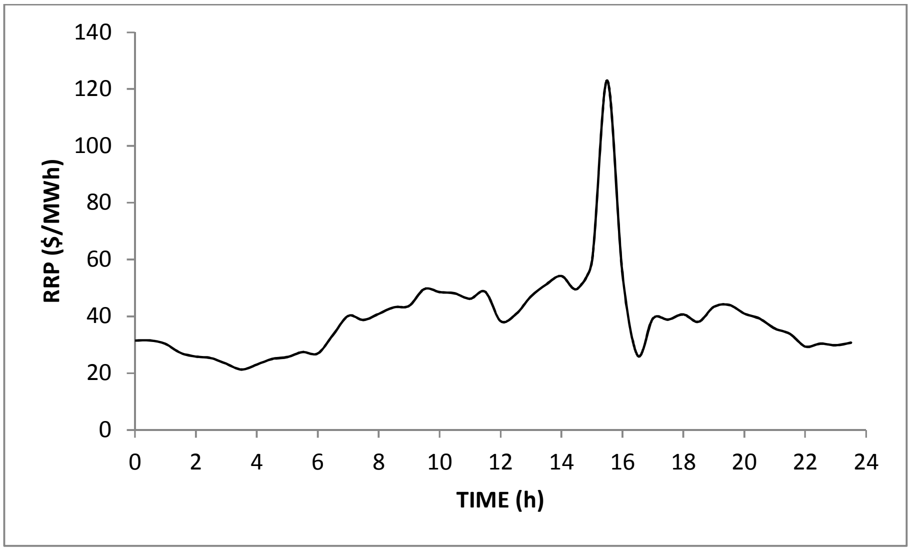


Figure 4-2: A Typical Spot Price Daily Curve

Figure 4-2 shows a typical spot prices curve. In the figure, spot price changes through the day because of the affects from supply and demand. In the graph, the spot price curve varies from day to night and reaches its peak at 3.30pm to $123.00 per MWh. The spot price can reach to a really high value when the weather is under the extreme condition. There is a market price cap for electricity of $13,500/MWh for the (2014-2015) financial year to prevent market exceeds the maximum generation capacities (AEMO, 2015). This price cap will trigger AEMO to start load shedding to keep supply and demand in the system in balance.

For the energy time-shift application, the economic benefits depend on the incremental incomes made by the difference of low energy purchased price and high energy sold price to the grid. The benefits will be significant if the gap between these two prices is high. The economic benefit model can be described using the following parameters:

- Total energy time-shift economic benefit for a day: $D\_REV_{Time-Shift}$
- BESS system energy rating, E_{BESS}
- Spot price for energy discharged at time interval (i) during a day, SP_i
- Discharge C-rating, CR_i

- Spot price for energy charged at time interval (j) during a day, SP_j
- Charge C-rating, CR_j
- The round trip efficiency, η

The daily benefit of energy time-shift application can be calculated by equation (14):

$$
\begin{aligned}
&D\_REV_{Time-Shift} = E_{BESS}\left(\sum \mathrm{CR}_i \times SP_i \times \eta - \sum CR_j \times SP_j\right) \\
&E_{BESS}\sum \mathrm{CR}_i \times \eta \leq \text{ BESS previous energy level} + E_{BESS}\sum CR_j
\end{aligned} \tag{14}
$$

Assume that the BESS system has N charge/discharge cycles during a year and the economic benefits are similar to each year. Uses present worth value factor defined in equation (8). The total life time benefit can be calculated by equation (15):

$$
\begin{aligned}
&REV_{Time-Shift} = PWF \times \sum_{year=1}^{N} D\_REV_{Time-Shift} \\
&\text{Where } N \leq 365 \\
&Unit\_REV_{Time-Shift} = REV_{Time-Shift} / E_{BESS}
\end{aligned} \tag{15}
$$

4.3.2. Feeder Construction Deferral Model

The feeder construction deferral benefit is the financial value associated with using a relatively small amount of storage to defer the feeder upgrade. For a feeder which is rated at 12MVA, Figure 4-2 shows its 15 minute average peak load during a year. The daily peak loads are generally higher during the winter time and some of summer time. But in the spring or autumn season, the load demands are relatively low. The feeder has the highest peak load demand at 12.2MVA which is over the 12MVA feeder rating. But there are only total 60 hours where the loads are over 10MVA during the whole year.

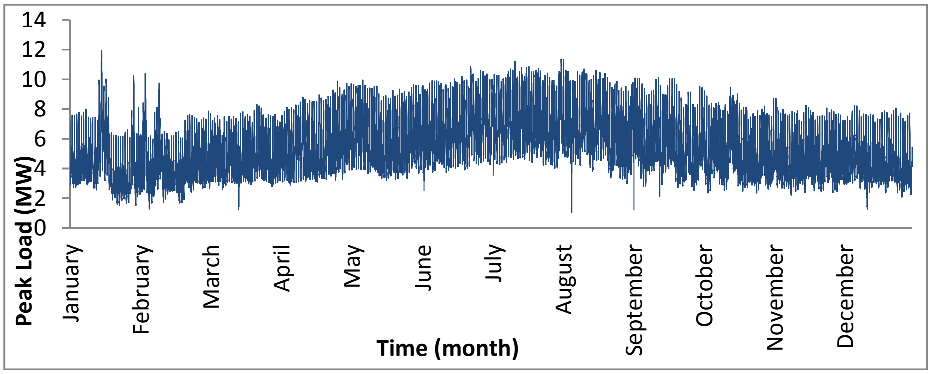


Figure 4-3: A Yearly 3 Phase 15min Average Peak Load Curve

Figure 4-3 shows the maximum load demand curve of a 12MVA feeder of 4% demand growth rate. The demand growth rate varies depending on the lot of criteria such as (EYER, J. and Corey, G., 2010):

- Earlier peak load plus load shape
- Expected load growth & uncertainty
- Storage module sizes availability
- Development in the area
- Weather conditions

The feeder shown in the figure 4-3 will reach its power supply capacity at critical time T1. It means by that time either the feeder capacity needs to be increase or an alternative method needs to be approached. As the load growth rate is 4%, the feeder needs 480kVA increased each year from time T1. If a 2MW BESS system is installed at time T0 and then adds 500kVA incrementally to feeder network each year as shown in the graph, the critical time for the feeder will be delayed to time T2 about 4 years later.

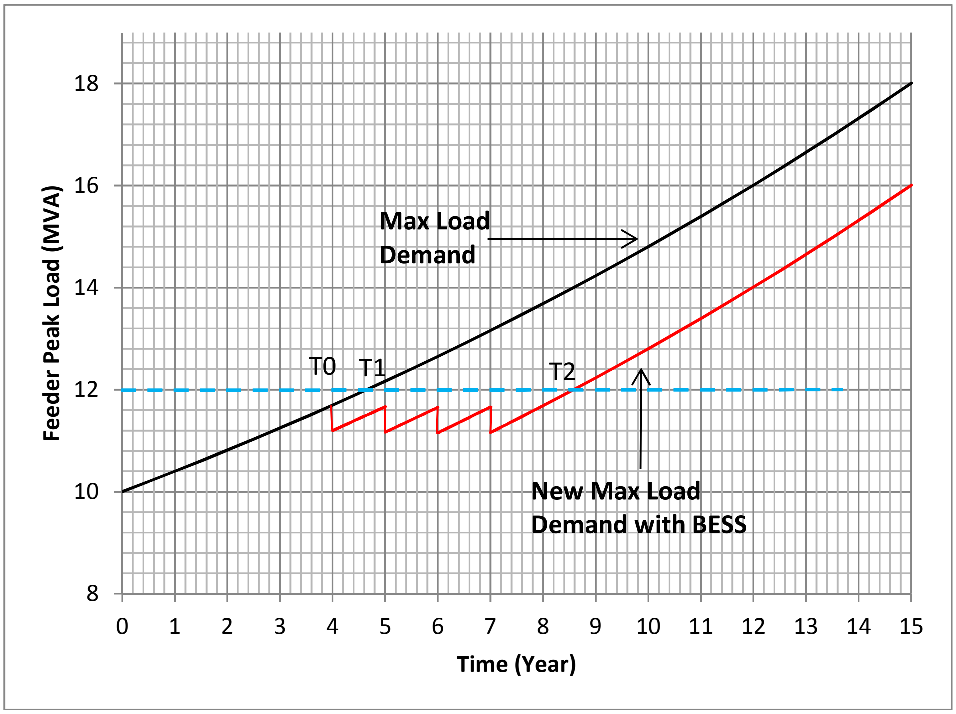


Figure 4-4: Feeder Peak Load Curve Dropped with 2MW BESS Installed

The benefit of installing the BESS system comes from avoiding the investment of the feeder upgrading construction. In general the feeder upgrade size will be in the range of 25%-40% of the total capacity. For example, assume feeder rated at 12MVA will be upgraded extra 3MVA to 15MVA rating which increases 25% feeder capacity. The savings from the construction deferral is the interest rate of the 3MVA investment during the deferral time.

For BESS feeder construction deferral, the one year benefit can be calculated with parameters as following:

- One year construction deferral benefit: $REV_{Deferral}$
- Feeder capacity, S_{Fdr}
- Feeder upgrade factor, r_{Fdr_upgrade}
- Unit price for feeder upgrade cost, $Unit\_Cost_{Fdr}$
- Feeder length, L_{Fdr}
- Load growth factor, r_{Load_growth}
- Interest rate, d
- Battery round trip efficient, η

The equation for one year total benefit is shown as below:

$$REV_{Deferral} = S_{Fdr} \times Unit\_Cost_{Fdr} \times L_{Fdr} \times r_{Fdr\_upgrade} \times d \qquad (16)$$

The optimal BESS storage size used for feeder construction deferral is:

$$S_{Deferral} = S_{Fdr} \times r_{Load\_\mathrm{growth}} \times \eta \qquad (17)$$

Unit benefit from the optimal BESS system:

$$Unit\_REV_{Deferral} = REV_{Deferral} / S_{Deferral} \qquad (18)$$

4.4.Forward Dynamic Programming Approach

4.4.1. Introduction

In this research, a forward dynamic programming algorithm is adopted in order to solve the given problem. Dynamic programming is an optimization method widely used for efficiently solving optimization problems which exhibit the characteristics of overlapping sub problems and optimal substructure. There are two types dynamic programming: forward induction and backward induction (WEB.MIT.EDU). The difference between two types is that forward induction is always to find the best path from certain start point to any other points; backward induction is the opposite to find from certain end point to any other points in the network. For our research, forward dynamic programming is more suitable. The Figure 4-5 shows an example of dynamic programming for finding the least cost path through the network.

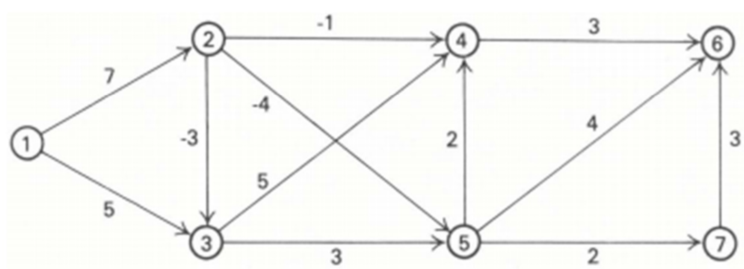


Figure 4-5: An Example of Dynamic Programming for the Least Cost Path (graph from internet)

The essential feature of dynamic programming is to find the best option through multiple stages. Through stage by stage, values of the each part of option are re-calculated and recorded. The iteration will keep running until the optimal solution is found.

In the example, if we want to find the shortest path from node 1 to node 6, then the processes are as below (arrow indicates the movement direction):

Stage 1: M(1, 2) = 7, M(1, 3) = 5→ M(1, 2) = 7, M(1, 3) = 5

Stage 2: M(1, 2, 3) = 4→M(1, 3) = 4

M(1, 2, 4) = 6, M(1, 2, 5) = 3

Stage 3: M(1, 3, 4) = 9, M(1, 3, 5) = 7→ M(1, 2, 5) = 3

Stage 4: M(1, 2, 5, 4) = 5, M(1, 2, 5, 6) = 7, M(1, 2, 5, 7) = 5

→ M(1, 2, 5, 4) = 5, M(1, 2, 5, 7) = 5

Stage 5: M(1, 2, 5, 4, 6) = 8, M(1, 2, 5, 7, 6) = 8, M(1, 2, 5, 6) = 7

So the final solution is 1→2→5→6 which the cost is 7.

4.4.2. Optimal Battery Charging/Discharging Routine

In order to find the optimal battery storage system charging/discharging routine, first let's define a network for battery energy status by time. Assume there are *m* different energy levels at a time point. E_m is the maximum value of the battery energy level where E_1 is the minimum value of the battery energy level.

E_m	E_m	E_m	E_m	E_m	E_m	E_m	E_m	E_m
E_{m-1}	E_{m-1}	E_{m-1}	E_{m-1}	E_{m-1}	E_{m-1}	E_{m-1}	E_{m-1}	E_{m-1}
…	…	…	…	…	…	…	…	…
E_2	E_2	E_2	E_2	E_2	E_2	E_2	E_2	E_2
E_1	E_1	E_1	E_1	E_1	E_1	E_1	E_1	E_1
t_1	t_2	t_3	…	t_i	t_{i+}	…	t_{n-1}	t_n

Figure 4-6: Battery Storage System Charging/Discharge Routine Network

With the defined network, the initiate problem has become to find an optimal path from time point t_1 with the energy level E_s to the time point t_n with the energy level E_d; where $1 \le s \le m; 1 \le d \le m$.

Because time only can move forward continuously, so the battery charging/discharging routine can only move from start point t_1 to end point t_n direction one time point per step. For battery storage system, there will be only three types of procedures during the system operation: battery charging, battery discharging or system standby. Through the time, the movement of the battery storage system status can be described as:

If $j = 1$,

$$E_j \text{ at time point } t_i \rightarrow \begin{cases} E_{j+C1} \text{ at time point } t_{i+1} \text{ - battery charging} \\ E_j \text{ at time point } t_{i+1} \text{ - system standby} \end{cases}$$

If $1 < j < m$,

$$E_j \text{ at time point } t_i \rightarrow \begin{cases} E_{j+C1} \text{ at time point } t_{i+1} \text{ - battery charging} \\ E_j \text{ at time point } t_{i+1} \text{ - system standby} \\ E_{j-C2} \text{ at time point } t_{i+1} \text{ - battery discharging} \end{cases}$$

If $j = m$,

$$E_j \text{ at time point } t_i \rightarrow \begin{cases} E_j \text{ at time point } t_{i+1} \text{ - system standby} \\ E_{j-C2} \text{ at time point } t_{i+1} \text{ - battery discharging} \end{cases}$$

C1 and *C2* are the battery charge and discharge rates.

The costs or benefits bringing through these procedures are assigned as:

When battery is charging, cost for energy purchased from time t_j to t_{i+1} is

$$Mc_i = (E_{j+1} - E_j) \times Spot\_Price_i + Cost_{op} \text{ (\$/MWh)} \tag{19}$$

When battery is discharging, benefit from energy trade from time t_j to t_{i+1} is

$$Me_i = (E_j - E_{j-1}) \times Spot\_Price_i - Cost_{op} \text{ (\$/MWh)} \tag{20}$$

If it is system standby,

$$Mc_i \approx 0 \text{ ; } Me_i \approx 0 \tag{21}$$

The total avenue *M* related to energy purchase shift is:

$$M = \sum Me_k - \sum Mc_l \tag{19}$$

The optimal routine for battery storage system charging/discharging operation is the routine with the maximum avenue *M* which we can use dynamic programming approach to find out.

5. SYSTEM SIMULATION & RESULTS

5.1. Introduction

This chapter shows the simulation results using system modelling methods, which are presented in previous chapter, with the typical datasets. The chapter contains two parts: first part is about using HOMER modelling software to simulate the economic benefits of the applications using DMSP battery energy storage system; Second part is using Matlab programming to achieve the optimal battery operation method presented in previous chapter.

5.2.Simulation using HOMER Modelling

The simulations for DMSP energy time-shift and feeder construction deferral applications are achieved by using HOMER Pro microgrid software by HOMER Energy. HOMER (Hybrid Optimization Model for Multiple Energy Resources) is one of the most popular software for optimizing microgrid design. It has the powerful tools for microgrid simulation, optimization and Sensitivity analysis which show the project's engineering aspects along with its economic aspects (HOMER ENERGY, 2015). But The HOMER has limitation in the simulation of the entire grid. In this research, because whole project is feeder oriented, there are special methods need to be approached to make the software proceeding the correct simulation.

5.2.1. Data Used for HOMER Simulation

The datasets used in the simulation contains two types of data. One type is the spot market information; another type is the load information.

The data of spot market information is required for both simulations of DMSP energy time-shift and feeder construction deferral applications. The data sets used in this research are attained from AEMO free sources. The spot prices are various for the different area, obviously due to the varied local electric generation and load demand conditions. In the research, three typical spot price datasets are chosen to be used in the simulation:

- Case 1: Low active spot market
- Case 2: Medium active spot market
- Case 3: High active spot market

Table 5.1: Three spot price datasets details

	Ave. Price ($/MWh)	Hours When Prices > $100/MWH	Hours When Prices > $200/MWH	Hours When Prices > $1000/MWH	MAX Price ($/MWh)
Case 1	41.62	68.5	23.5	5.5	5972.27
Case 2	48.13	168	58	15	6213.38
Case 3	50.91	97.5	49.5	33.5	13499.00

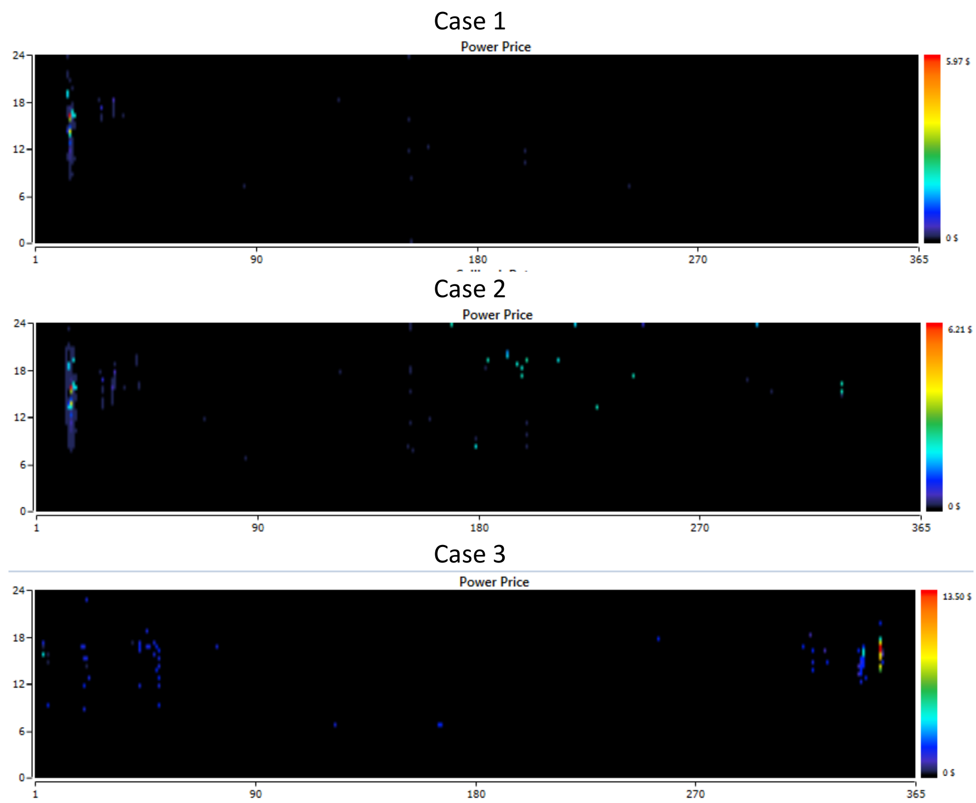


Figure 5-1: Power Price Graphs for Case 1-3

Three datasets all contain information of the whole year 30 minutes average spot prices from 1/1/2014 to 31/12/2014. Table 5.1 lists the average prices, maximum prices and hours through the year to reach certain price levels to show the difference between these three datasets. Figure 5-1 also shows the power price graphs of dataset case 1-3. As shown in the table and graphs, case 1 dataset has the lowest average price and few high price hours during the year. Case 2 dataset's average price is higher than the case 1 data with more hours of high prices during the year. Case 3 dataset has the similar average price compared with case 2 dataset. But case 3 dataset has more hours with higher prices over $1000/MWh with some extremely high prices. The economic benefits of energy time-shift application correlate with the characters of electrical market. In this research, using three different sets of spot prices will gave the comparison results of what and how many benefits the energy time-shift application.

The electric load information is required for DMSP feeder construction deferral application's economic analysis. The load information is using the whole year feeder load database from 1/1/2014 to 31/12/2014. The dataset contains the 15 minute load average power consumed for the studied area as shown in Figure 5-2. The Figure 5-3 below shows the monthly load figures through the whole year time. As we can see from the graph, the load has the relatively higher value during the winter time. But during the summer time the variations of load demands can get enormous mainly because of the extremely weather conditions in summer. The feeder planed capacity is 12MVA. In 2014 the maximum load demand reached 11.93MW active power with 2.63MVAr reactive power which made the apparent power at the time was 12.2MVA which exceeded the feeder rating. So there is definitely requirement for adding more electrical capacity to this feeder through feeder upgrading, or adding other facilities such as generators or energy storage units. To simulation the feeder construction deferral benefits, besides the load datasets used, the spot prices also add into the simulation model to reflect as the grid. In the process , as same as for the energy time-shift application, three difference spot price datasets are used to reflect different grid conditions.

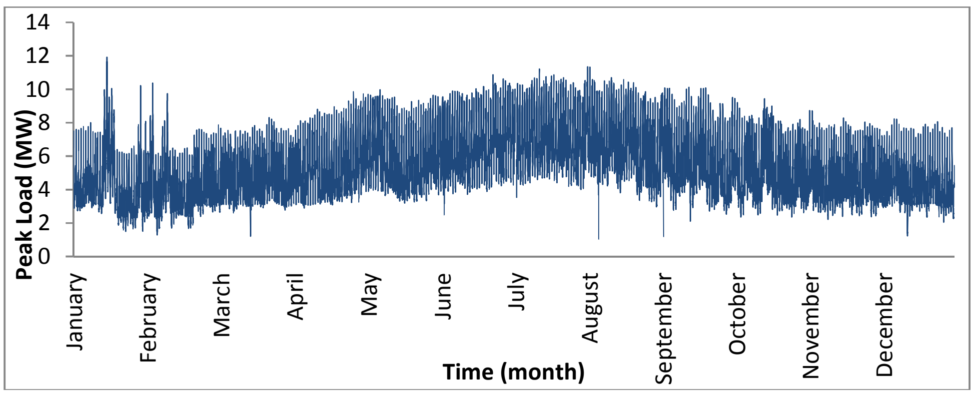


Figure 5-2: Whole Year 15 minutes Average Power Curve

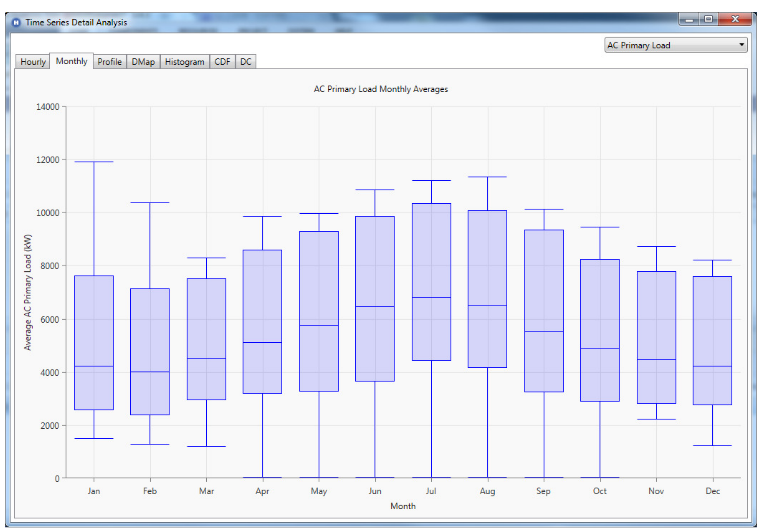


Figure 5-3: Load Monthly Averages

5.2.2. Simulation for Energy Time-Shift

After creating a HOMER file to process the simulation, the schematic needs to be built for the energy time-shift application with essential components and their configurations. HOMER uses the schematic to simulate the application and generate results by net present cost.

The HOMER schematic created for energy time-shift application is shown in Figure 5-4. The project time is set to 30 years.

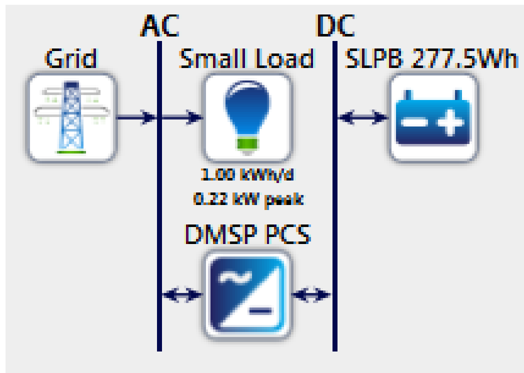


Figure 5-4: Energy Time-Shift Application HOMER Schematic

The schematic has four components along with AC & DC buses. The four components are:

- Grid: The grid component is reflecting the feeder supply to the area. Three spot price datasets were formed into a .txt files and are loaded individually into *Grid* component through the real time rates loading function. Because the DMSP battery system is 2MW which is larger than AEMO's 1MW minimum market attendant requirement, so the system can attend the spot market trading. It is assumed that spot market has the same purchase price and sellback price at the same time. Another type of the configurations is about the costs of the system. Because it is the buy/sell processes that we are monitoring, so there is no extension cost added to grid. The *Grid* also has purchase and selling capacities set to 999999kW which means there are large enough electric volumes for the application simulation.
- A small electrical load: HOMER software has the limitation that won't start the simulation without the load. Even though there is no need to have electrical load in the energy time-shift application, we still add the electrical load component into the

schematic. This load is configured to a very small value so it won't affect to any simulating results.

- Battery system: The DMSP project is using the SLPB Lithium Polymer NMC batteries as the storage medium. The configuration of this type of battery is added to the system library as specified in chapter 3. Basically the battery is set to 3.7V 277.5Wh capacity with 5%-95% SOC and maximum 1C charge/discharge rate. Battery has 7500 life cycles and 94% efficiency. Battery O&M cost is set to $1 per battery. The battery capital and replacement costs are leaved as $0 in this analysis because the research is to find out the benefit from the energy purchasing / selling. The battery system contains 7200 SLPB batteries so the capacity of the battery system is 2MWh.
- Power conversion system: The power conversion system is set as an AC/DC convertor in the schematic. The power conversion system has 2MW rating and 90% efficiency. Same as the battery system, the capital and replacement costs for power conversion system are leaved as $0.

For the application simulation, the discount rate is set to 5.5% due to the current low interest rate. The inflation rate is set to 2%. The load growth rate is set to 4% analysed from historical load data.

With the configuration of the schematic model created, HOMER calculates and provides the simulation results. The Figure 5-5 shows the energy purchased and energy sold volume during the simulation for three apllication cases. As shown in the Figure, energy sold volumes are less than the energy purchased because of the power losses due to the battery system and power conversion system's efficiency. Case 1 has the least volumes of energy purchased and sold which are less than half of case 2 and case 3's volumes. Case 2 has the similar results just a slightly less compared with case 3's figures.

Case 1:

Energy Purchased	Energy Sold
53,395	44,988

Case 2:

Energy Purchased	Energy Sold
115,833	97,957

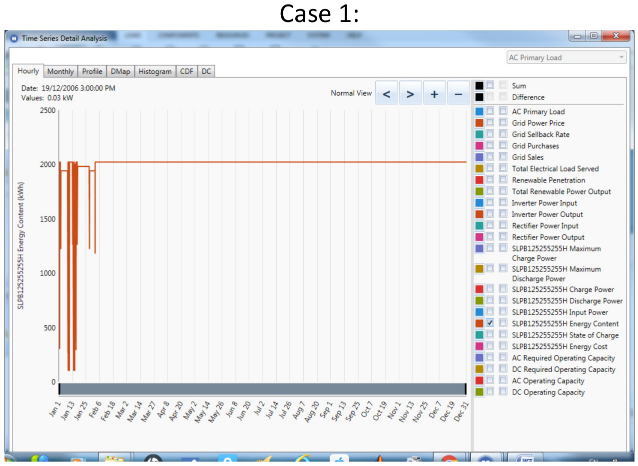
Case 3:

Energy Purchased	Energy Sold
128,031	108,305

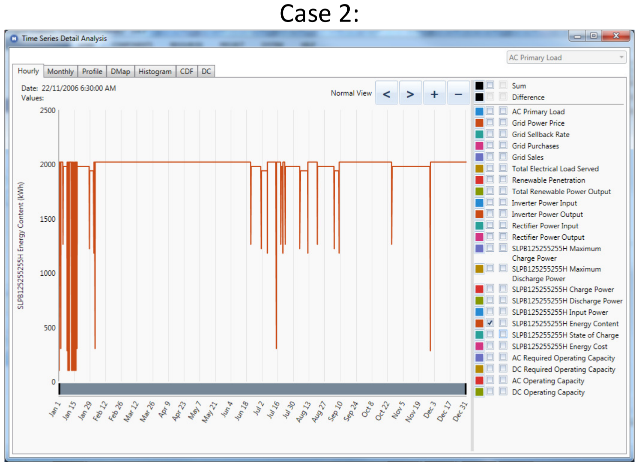
Figure 5-5: Energy Purchased vs. Energy Sold in Application Case 1-3 (kW)

HOMER provides the statistics data for the application simulation. Figure 5-6 shows the energy status of battery system of three cases. Case 1 only has traded in the energy market during the hot summer time. Case 2 has traded more than case 1 during the summer and winter time. Case 3 has traded in the energy market extensively through whole year. With more active electric energy market, the trades are more dynamic.

Case 1:



Case 2:



Case 3:

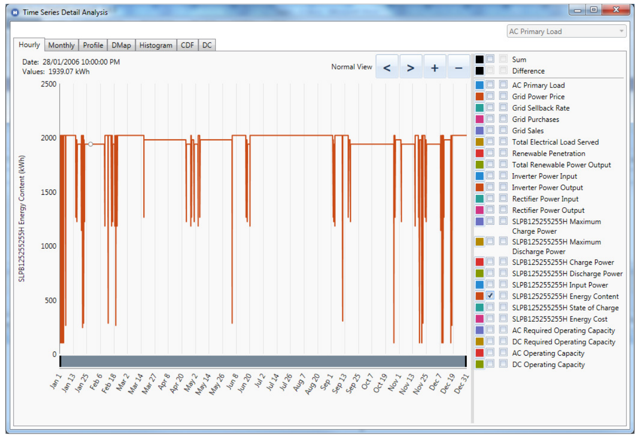


Figure 5-6: Battery System Energy Content Case 1-3

Case 1:

			SLPB 277.5Wh	Grid (kW)	DMSP PCS (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)
			7,280	999,999	2,000	CC	$0.111	$106,148	$5,022

Case 2:

			SLPB 277.5Wh	Grid (kW)	DMSP PCS (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)
			7,280	999,999	2,000	CC	-$0.141	-$292,920	-$13,860

Case 3:

			SLPB 277.5Wh	Grid (kW)	DMSP PCS (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)
			7,280	999,999	2,000	CC	-$1.78	-$4.09M	-$193,343

Figure 5-7: Battery Energy Time-shift Benefits Case 1-3

After the simulation, HOMER provides the analysis results for the application simulation. Figure 5-7 shows the optimazation results of HOMER. From those results, the possible benefits could be found that achieved from the DMSP battery system energy purchasing/selling processes of three cases. For the summary, case 1 needs to cost about $5000 per year to keep the operation of energy energy purchasing/selling processes due to the operation and maintenanse costs. The results are stimulating compared with case 2 and case 3 figures. Even case2 and case 3 has similar trading volues, the results from the simulations are quite different. Case 2 has the potiential benefits of $13,860 per year which is the net present value of about $300,000 lift time. Case 3 has the potiential benefits of $193,343 per year which is the net present value of about $4.09M lift time. The difference between case 2 and case 3 is caused by the high average spot price and relatatively low peak prices of case 2. For case 3, if assume the capital investment of the battery energy storage system is 2 million dollars in total, it can easily get the investment paid back throught the energy time-shift application.

From the simulations, it shows that the characters of the electrical energy market decide how many benefits will be delivered through the BESS energy time-shift applications. It is a must to study thoroughly of the local energy market before add energy time-shift applications into it. Australia has less populations and business not as active as in Europe or United States. So the electrical market is not as active as in those areas. For example, in United States, the average hours above the price $100/MWh are about 900 hours per year (EYER, J. and Corey, G., 2010). Compared with it, in Australia, even the active market like case 3 has less than 100 hours per year over the price of $100MWh. With the economic development in the country, there will be load demand requested. That is when the application of BESS energy time-shift gets more potential.

5.2.3. Simulation for Feeder Construction Deferral

Similar to the simulation of energy time-shift application, HOMER file and HOMER schematic need to be built for the feeder construction deferral application. Because within HOMER software there is no option for adding two types of grid components for comparison, the research has to build another feeder upgrading model first for simulating the feeder construction upgrade model.

The HOMER schematic created for feeder upgrading model is shown in Figure 5-8. The purpose of setting up this model is to find out what the net present cost is for the feeder with feeder upgrading option. Unlike the energy time-shift application using 30 years project time; this model is set the project time to 5 years because a 2MW battery system is about deferring 12MVA feeder for about 4 years.

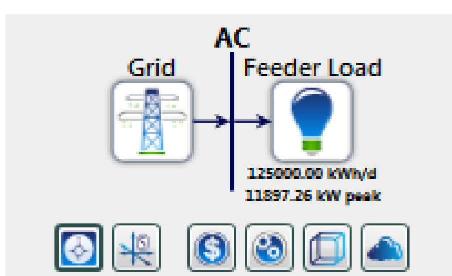


Figure 5-8: Feeder Upgrading HOMER Schematic

The schematic has simply two components along with AC bus. The two components are:

- Grid: *Grid* component is reflecting the feeder supply. Similar to the energy time-shift application, three spot price datasets are loaded individually into *Grid* component through the real time rates loading function for comparison analysis. The *Grid* has set to hold 999999kW selling capacity which means there are large enough grid abilities to purchase energy from battery system. With the original Grid rating of 12MW and 25% feeder upgrading ratio, the *Grid* purchasing capacity is set to 15MW with an extra construction cost. The construction cost uses the construction unit rate $410/kW (WILLIS, H. L. and Scott, W. G., 2000) and add in as an extension cost to the schematic. In total the construction cost is about $1.55M.
- Feeder load: The feeder load is described in section 5.2.1 shown in Figures 5-2 & 5-3. A feeder load component is created by loading our feeder load demand dataset into HOMER. The load dataset still needs to be formed in a single column .txt file. HOMER will load the file and determine the time intervals. In our case, the time interval is 15 minutes.

After the model calculation through HOMER, for each type of spot price market, we get the summery costs of the extended feeder. Figure 5-9 shows the feeder operation cost with feeder extension option for individual cases. For case 1, the feeder operation cost is $12.5 M (NPC); where for case 2 it is $14.6M (NPC) and for case 3 it is $44.9M (NPC).

Case 1:

	Grid (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)
	15,000	CC	$0.0608	$12.5M	$2.43M	$1.55M

Case 2:

	Grid (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)
	15,000	CC	$0.0708	$14.6M	$2.88M	$1.55M

Case 3:

	Grid (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)
	15,000	CC	$0.0588	$12.1M	$2.34M	$1.55M

Figure 5-9: Upgraded Feeder Cost Summary Case 1-3

Besides the feeder upgrading model, another model needs to be built for the simulation for the feeder construction deferral application. This model needs to demonstrate the installation of battery energy storage system to defer the feeder upgrade construction.

The HOMER schematic created for feeder construction deferral model is shown in Figure 5-10. The purpose of setting up this model is to find out what the net present operation cost is for the feeder with BESS system installed. Project time for this model is also set to 5 years.

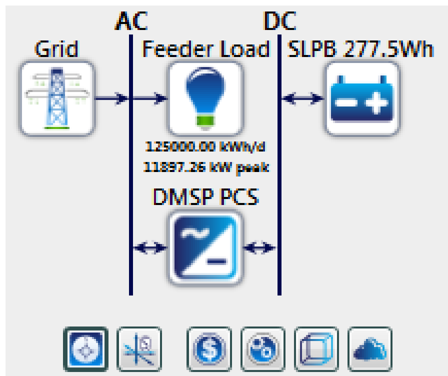


Figure 5-10: Feeder Construction Deferral HOMER Schematic

The schematic has four components along with AC & DC buses. The four components are:

- Grid: The grid component is set similar to the feeder upgrading model but with 12MW purchasing capacity and 999999kW selling capacity with no upgrading cost. It is reflecting the current existing feeder supply to the area. Three spot price datasets were formed into a .txt files and are loaded individually into *Grid* component through the real time rates loading function.
- Feeder load: The feeder load component is set up as same as in the feeder upgrade model.
- Battery system: The Battery system is set up similarly to the one in the energy time-shift model. O&M cost is set to $0.8 per battery. The battery capital and replacement costs are both set to $100 per battery in this analysis.
- Power conversion system: The power conversion system is set up similarly to the one in the energy time-shift model. O&M cost is set to $3 per kW. The power conversion capital and replacement costs are both set to $300 per kW in this analysis.

In the feeder construction deferral model, for battery system and power conversion system, the simulation also set up a range of search space for sensitivity analysis. The battery system is set from 0 to full size 2MW with the interval of 500kW. The power conversion system is also set to same range. Figure 5-11 shows the search space range. The purpose of this setting is to find out the optimal size of battery system to defer the feeder construction for DMSP project.

DMSP PCS Capacity (kW)	Grid Purchase Capac (kW)	SLPB 277.5Wh Strings (#)
0	12000	0
500		14
1000		28
1500		42
2000		56

Figure 5-11: Feeder Construction Deferral Model Search Space Setting

After the model calculation through HOMER, for each type of spot price market, we get the summery costs of the feeder with BESS system installed. The HOMER simulation results for three cases are shown in the Figure 5-12. It shows that with BESS system installed the feeder operation cost could be cut enormously. For case 1, the feeder operation cost is $11.1M (NPC); where for case 2 it is $13.1M (NPC) and for case 3 it is $10.1M (NPC). The Figure 5-12 also shows that for case 1 and 2 HOMER chooses 500MW BESS system as the optimal options; but for case 3 HOMER chooses 2000MW BESS system as the optimal option. It is because only case 3 project has the energy time-shift and feeder construction deferral application running together.

Case 1:

			SLPB 277.5Wh	Grid (kW)	DMSP PCS (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)
			1,820	12,000	500	CC	$0.0536	$11.1M	$2.37M	$332,000

Case 2:

			SLPB 277.5Wh	Grid (kW)	DMSP PCS (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)
			1,820	12,000	500	CC	$0.0636	$13.1M	$2.83M	$332,000

Case 3:

			SLPB 277.5Wh	Grid (kW)	DMSP PCS (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)
			7,280	12,000	2,000	CC	$0.0488	$10.1M	$1.93M	$1.33M

Figure 5-12: Feeder Construction Deferral Cost Summary Case 1-3

Table 5.2 summarizes the economic benefits from feeder construction deferral application for three different spot markets.

Table 5.2: Feeder Construction Deferral Cost Comparison Case 1-3

	Option 1: Upgrade feeder (NPC)	Option 2: Using BESS defer feeder construction (NPC)	Cost difference between two options (NPC)
Case 1	$12.5M	$11.1	$1.4M
Case 2	$14.6M	$13.1	$1.5M
Case 3	$12.1M	$10.1	$2.0M

As shown in the table, no matter the market is active or inactive; the economic benefits are all have enormous value from $1.4M to $2M with 5 years' time. It indicates the huge potentials of BESS system installed on the feeder with the load demand reaching the feeder's supply capacity.

5.2.4. Some Further Investigations

The BESS system hasn't been applied widely in Australia. The current price for the battery and control system are on the high levels. With the previous experiences of the prices of solar panels, the prices for BESS system will be dropped down in the future. Paper (NYKVIST, B. and Nilsson, M., 2014) indicates that the battery price will be dropped 14% annually and will be the half prices in 2020 compared to the current prices.

The research made a further simulation with the half costs for BESS system. The simulation results are summarized in Table 5.3. Compared with Table 5.2 and Table 5.3, with the half prices of BESS system, the benefits don't change much except the case 3 project. It indicates that the price cut of BESS system will not affect the economic benefits from feeder construction deferral applications but will increase the economic benefits from energy time-shift applications.

Table 5.3: Feeder Construction Deferral Cost Comparison Case 1-3 with Half BESS Costs

	Option 1: Upgrade feeder (NPC)	Option 2: Using BESS defer feeder construction (NPC)	Cost difference between two options (NPC)
Case 1	$12.5M	$11.0M	$1.5M
Case 2	$14.6M	$13.1M	$1.5M
Case 3	$12.1M	$9.95M	$2.15M

The round trip efficiency is an important element in the analysis of BESS system benefit. It seems that the higher round trip efficiency the more economic benefits will be gain. To further investigate its affections to BESS system, different battery round trip efficiencies have been set to the HOMER model shown in Figure 5-4. HOMER model uses the same load and spot price data and simulates the economic benefits for each setup. The results are presented in Figure 5-4.

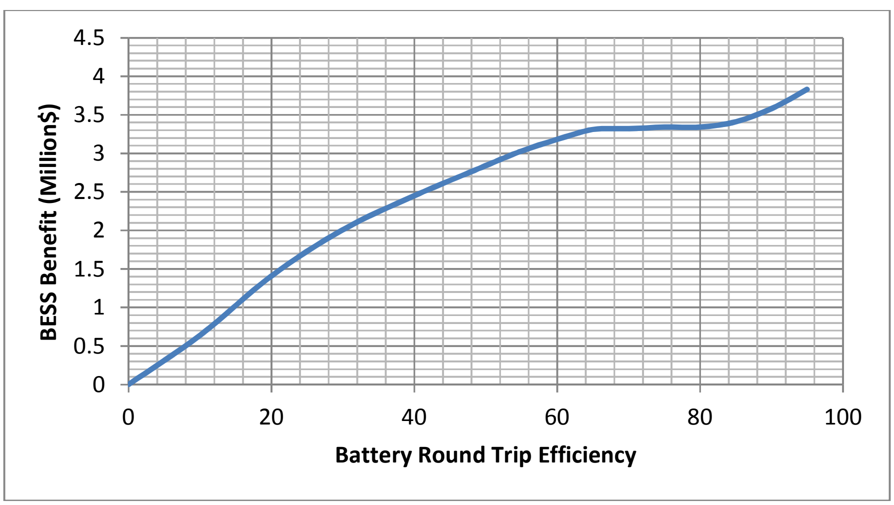


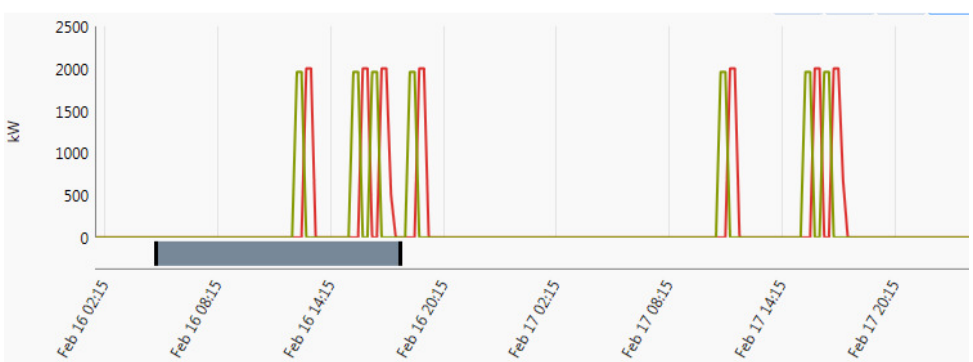
Figure 5-13: Battery Round Trip Efficiency vs. Battery Benefit

With the simulation results, it can be said that that the higher round trip efficiency will bring more economic benefits. But the results also approve the relationship between the efficiency and benefit is nonlinear. From 80% efficiency upward, the BESS system benefits increase rapidly. Below 65% efficiency the BESS system benefits drop sharply. The interesting thing from the simulation results is that between 65% and 80% round trip efficiency, BESS system benefits are in the similar level. That means two systems, one with 65% efficiency, another one with 80% efficiency and obviously much more expensive, could bring the similar benefits. So it is important to look at the battery round trip efficiency when chooses the battery medium for BESS system.

5.3.Optimal Battery Control Method

This section will present simulation results from the optimal battery charge/ discharge routine by using forward dynamic programming algorithm.

Previous section describes the electrical application simulations in HOMER software. HOMER enhances in application simulation and optimization. But it doesn't provide efficient tools and functions for users to find an optimal operation schedule. For simulating battery energy storage system (BESS) processes, HOMER calculates the average energy cost for the BESS system. This average cost will be used as the set point for the energy trading. Once the energy spot price is under the set point, BESS system will start charging energy to store energy if it has enough energy storage space. On the other hand, once the energy spot price is over the set point, BESS system will start discharging energy and sell stored energy to the market which will make some profits from it. Because of this reason, we always can see that BESS system charges right after the battery discharged in the HOMER simulations as shown in Figure 5-13. The advantage of this method is the simplicity of the control process. But because of the battery always charges or discharge at the early available points so the economic profits are not the best can be achieved. Also HOMER didn't provide users many controls of their BESS system of the different durations or charge/discharge rates.



Red – Charging   Green - Discharging

Figure 5-14: HOMER Battery Charge/Discharge Routine (16/02/2014-17/02/2014)

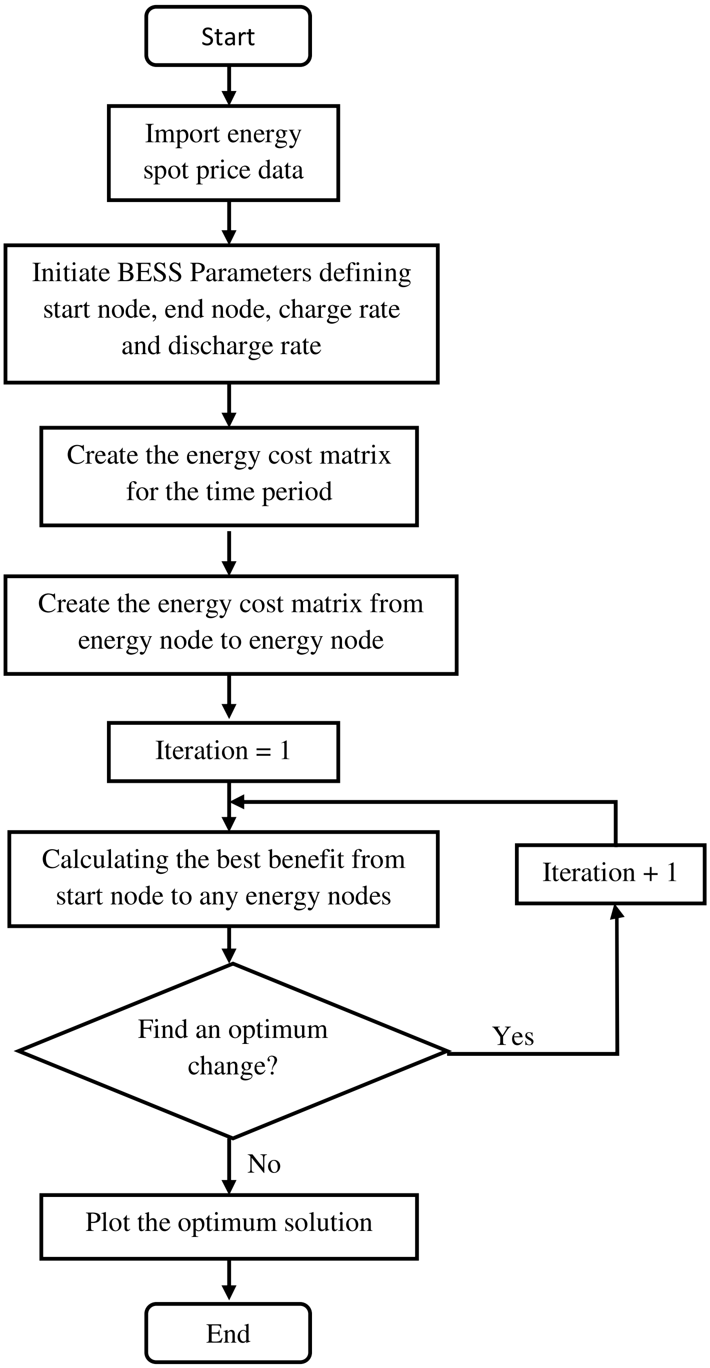


Figure 5-15: Flow Chart for the Optimal Battery Control Scheme

The optimal battery control scheme introduced in this section provides an approach to achieve the maximum economic benefits. It uses the electric energy pricing data to create an optimal charge/discharge plan for BESS system over a period of time. In the plan, it will indicate the time when battery is charged or discharge and by what rates of charge and discharge. The control scheme is used the forward dynamic programming algorithm programmed by MATLAB. The flow chat of the program is shown in Figure 5-14.

The simulation for the optimal battery control scheme is under the assumption of having the spot prices forecasted. It is also assumed that energy market has efficient capacity for energy selling and purchasing. The simulation uses the same spot price data as used for previous HOMER simulation which results are shown in the Figure 5-13. The Figure 5-15 shows the spot price data during the 48 hour time period from 16/02/2014 to 17/02/2014 which is the same time period used for HOMER simulation as Figure 5-13 shown. The dataset has the resolution of 30 minutes time steps. The maximum spot price during this time period is \$2021.13 per MWh where the minimum price is \$39.10 per MWh.

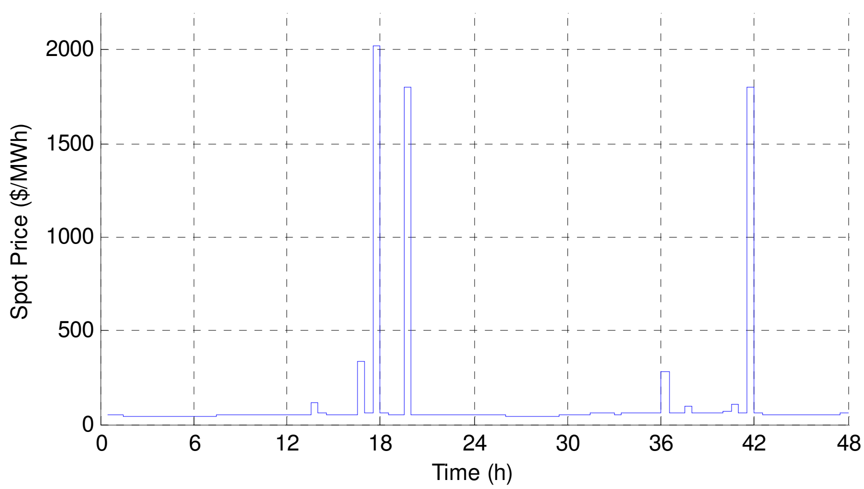


Figure 5-16: Spot Prices Data from 16/02/2014 to 17/02/2014

In the simulation, DMSP BESS system has been set to have five energy input/output options: two discharge rates C1 or C0.5; two charge rates C1 or C0.5 and standby where the maximum charge/discharge power rate is 2MW for C1. The total capacity of BESS system is set to 2MWh. The battery round trip efficiency is set to 95%. The battery O&M cost is set to \$20 per MWh

Before simulation users can also define the energy storage levels at the start time and end time of the simulation. There is a parameter input dialog as show in Figure 5-16 provided with the program so users can setup different scenarios for simulation. The default values are set to 2MWh energy level at the beginning of the simulation; 2MWh energy level at the end; C0.5 charge rate and C1 discharge rate.

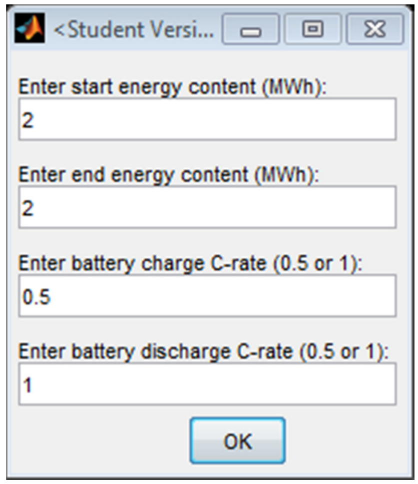


Figure 5-17: Parameter Input Dialog for Optimal Battery Control

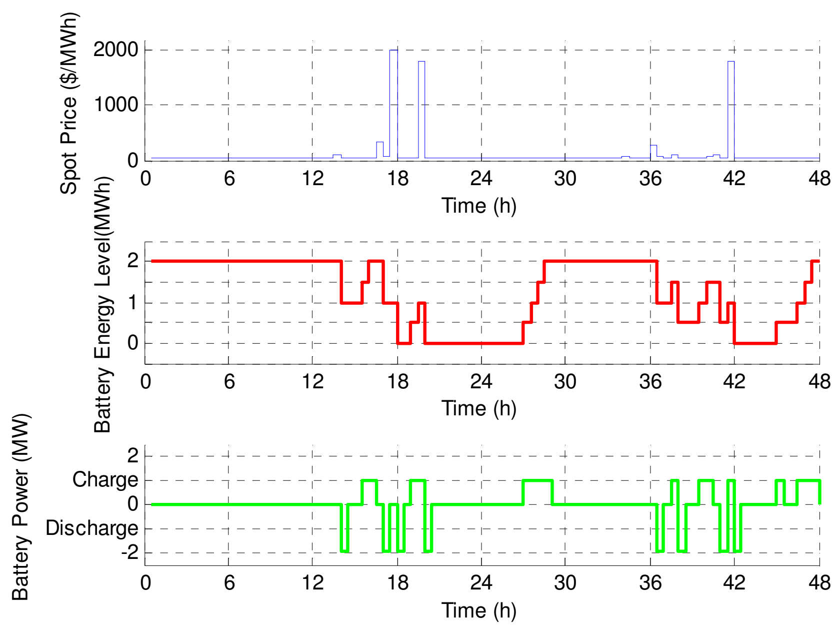


Figure 5-18: Simulation Results of Optimal BESS control Scheme

Running the simulation program, we can get the results shown in Figure 5-17.

From the simulation the net economic benefit is in total $5650.5 gained from the BESS system energy trading during this 48 hour period. Compared with HOMER simulation results shown in Figure 5-13, the discharge periods of BESS system are similar. But the BESS system charge periods are different because the optimal battery control scheme is able the find the lowest cost charge time.

Table 5.4 shows the BESS system economic benefits with the different system settings. The simulation results show that the discharge rate is the main aspect that affects the BESS benefits in our case. The spot prices are correlated with load demand through the time. But with few moments the spot market will have price spikes which are much higher than the normal price. If the BESS system can sell energy storages at those times then the considerable benefits will be made.

Table 5.4: BESS Economic Benefits with Different System Settings

	C0.5 Charge rate C0.5 Discharge rate	C0.5 Charge rate C1 Discharge rate	C1 Charge rate C1 Discharge rate
2MWh Energy Start 2MWh Energy end	$2839.6	$5650.5	$5654.7
2MWh Energy Start 0MWh Energy end	$2963.2	$5774.2	$5776.7
0MWh Energy Start 2MWh Energy end	$2741.2	$5552.2	$5556.4
0MWh Energy Start 0MWh Energy end	$2864.8	$5675.8	$5678.4

The optimal battery control scheme uses the forward dynamic programming model to form an approach to find an optimum BESS operation strategy. With the spot market data predicated, this approach can give the users indication of when and how the BESS system operates. It can assist to setup BESS system operation profile. This battery control scheme can be applied to longer time period with more charge/ discharge power level options which will make the strategy more accurate.

6. Conclusion

6.1. Conclusions

This thesis has introduced the effects of battery energy storage system (BESS) on the distribution network. BESS system as a technology newly applied in Australia has attracted a lot of attentions from not only the utility companies but also retailors and the demand side customers. Will the BESS system makes profits is always the first question to be asked.

One of the aims of the thesis is to justify the economic feasibility of BESS system. After introduced the BESS system characteristics and their impacts on the distribution network, variable applications of BESS system are presented. Two major types of applications are further explored in the document: energy time-shift application and feeder construction deferral application. For both applications, system models have been created to quantify the economic benefits. With the energy economic data and distribution load data, the application system models are achieved in simulation tools and produced simulation results which demonstrate the benefits can be obtained by both applications with various conditions.

For energy time-shift application, the benefits come from the BESS system activities of buying energy at low price and selling energy at high price. The simulating system model is the function of spot prices, battery energy rating, battery charge/ discharge rates and round trip efficiency. With the simulation setup in three different energy market environments, the result indicates that energy market characteristics determine the economic feasibility of this type application. With the high battery capital costs and O&M costs, the BESS system only can get payback in the very active energy market in Australia. With medium active energy markets, the energy time-shift application should be combined with other applications to gain profit. For low active energy markets, the energy time-shift application should not be considered. This type application can have more potentials with the electrical prices raised (market gets more active) or the BESS system cost dropped.

For feeder construction deferral application, the potential benefits come from using relatively small investment on BESS system to defer the large amount of investment on feeder construction. The system model is described as a function of feeder capacity, feeder upgrade factor, feeder load growth rate, feeder length, BESS round-trip efficiency, BESS system capacity and interest rate. HOMER has simulated costs for both options: feeder with construction; or feeder with BESS system installed. With the HOMER simulation results, it shows that the feeder construction deferral will have significant benefits if the investment for feeder upgrade is large. The result also shows that the size of BESS system should be considered carefully and correlated with the feeder construction costs. System oversize will not bring extra benefits but the extra system investment. Simulation also indicates that the battery round trip efficiency has nonlinear relationship with the application benefit potentials. 80% battery round trip efficiency is the turning point for earning large returns from energy time-shift application.

The optimal battery control method provides a valuable mean to deliver battery charge/discharge operation strategy with the most benefits gained. With the methodology, battery charge/discharge operation strategy manages to charge at the lower energy cost time and discharge at high energy cost time. The optimal battery control program provides user interface to change parameters of simulation. Through the use of this program, better understanding can be achieved.

The results of the economic analysis performed with real data from the Australian electricity market and distribution network show the economic feasibility of DMSP BESS system. The feeder construction deferral application has significant potentials in the distribution area. The energy time-shift application also can bring large payback if the application site has been chosen correctly.

6.2.Suggestions for Future Works

There are future researches and works can be done in the following fields:

1. The simulation in this research is under the assumption of having the energy market and load information predicated. One of the further research areas is to find out the models for the load demand predication and spot price forecasting.

2. As we can see in the paper, in order to make profits, BESS system sometimes needs to have multiple applications running together. As the energy storage system installed on the distribution feeder, there are some other applications will fit well with the energy time-shift and feeder construction deferral applications. These applications include the voltage support and frequency support application which bring more reliability to the distribution network. The island mode application is another application worth the further research works.

3. For the BESS system grid into the network, protection is another area to work with. The research area can be covered such as how the BESS system will affect the network protection settings, or how to protect the BESS

system from fault condition, or what the setting should be for the island mode.

4. Once the DMSP project completed, the testing results needs to be collected and checked with the simulating results. From the comparison, the simulation can be further adjusted to closely reflect the real situation.

APPENDIX A: ENG4111/4112 Research Project Specification

For: Jennifer Jiang

Topic: Demand Management Storage Project (DMSP) - An Application of Grid Scale Energy Storage Systems

Supervisor: A/Prof Tony Ahfock

Anil Singh, Powercor Australia

Enrolment: ENG4111 – semester 1, 2015

ENG4112 – semester 2, 2015

Sponsorship: Powercor Australia

Project Aim: This research is to examine current demand management storage system, validate both cost and benefit of deep discharge storage services, review the system modelling and grid connection compliance, specify the system hardware and control functionality and provide the optimal control scheme for the system operation.

Programme:

1) Review the current existing grid scale energy storage systems and deep discharge storage technologies. Identify the application of storage services for a range of network constraints, in particular the ability to target peak demand.
2) Investigate the current distribution network condition. Then to establish and specify the storage system which includes battery ESS (Energy Storage System) heart, inverter, transformer and protection equipment.
3) Analyse the storage system effects on the distribution network by using microgrid simulation software HOMER.
4) Summarise the benefits of the demand management storage system.
5) Define the optimal battery control scheme.

As time permits:

6) Exam the testing results. Identify if the demand management storage system is a suitable solution for this particular case.

APPENDIX B: OPTIMAL BATTERY CONTROL MATLAB CODE

```
% This is the main file to find an optimal battery charge/discharge routine
%
% The program uses dynamic programming method to find the optimal path
% of battery charge/discharge with the most benefits by energy trading.
%
% This program is part of final year research for BENG degree
% Course ENG4111/ENG4112
%
% The program is written in Matlab by
% Student: Jennifer Jiang
% Student number: 0061035128
%
% -----------------------------------------------------------------------


% Start the program with clearing all variables and figure view
%
% -----------------------------------------------------------------------

clc;
clear all;
close all;

% -----------------------------------------------------------------------


% Import data from prepared .txt file
% The file contains the data of 30min average spot prices
% Data inputs to array SpotPrice
%
% -----------------------------------------------------------------------

SpotPrice =
importdata('D:\Jennifer_USQ\ENG4111\matlab\DATA\Spot_Price.txt');

% -----------------------------------------------------------------------


% Diagrams for entering parameters for this program
% Parameters entered through dialogue and transfered to variables
%
% EngStart: start energy content
% EngEND: end energy content
% RateCh: battery charge C-rate
% RateDisch: battery charge C-rate
%
```

```
% ----------------------------------------------------------------------

prompt = {'Enter start energy content (MWh):',...
        'Enter end energy content (MWh):',...
        'Enter battery charge C-rate (0.5 or 1):',...
        'Enter battery discharge C-rate (0.5 or 1):'};
dlg_title = 'Input parameters for battery charge/discharge';
num_lines = 1;
def = {'2','2','0.5','1'};
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='tex';
answer = inputdlg(prompt,dlg_title,num_lines,def);
[c1, c2, c3, c4] = answer{1:4};
EngStart = str2double(c1);
EngEnd = str2double(c2);
RateCh = c3;
RateDisch = c4;

% ----------------------------------------------------------------------



% Create array - BattEng
% Relecting the five energy status at each half hour time point
% Status: 0MW, 0.5MWh, 1MWh, 1.5MWh, 2MWh
%
% ----------------------------------------------------------------------
[num, n] = size(SpotPrice);
BattEng = zeros(5,num);
for i = 2:5
   for j = 1 : num
      BattEng(i,j) = i*0.5;
   end
end
% ----------------------------------------------------------------------



% Call Function CostEnergy
% This function is calculating the energy cost/income from battery
% charge/discharge for each time point with one energy movement
% including: charge, discharge or standby
%
% Inputs: battery energy matrix, spot price matrix
% Output: Energy cost matrix
%
% ----------------------------------------------------------------------

EngCost = CostEnergy(BattEng, SpotPrice, RateCh, RateDisch);
```

```
% -----------------------------------------------------------------------


% Call Function DynProg
% This is the function that will perform the dynamic programing approach.
% The method is using iteration to find the best battery routine with
% maximum benefits.
%
% Inputs: Energy cost matrix, Energy start state, time points
% Output: node to node energy cost matrix
%       predecessor node matrix
%
% -----------------------------------------------------------------------

[StageEngCost, PredNode] = DynProg(EngCost, EngStart, num);

% -----------------------------------------------------------------------


% Call Function DynProg
% This function traces back the PredNode to find the optimal battery route.
%
%
% Inputs: node to node energy cost matrix, predecessor node matrix
%       energy start state, energy end state, time points
% Output: optimal route matrix
%       total income figure
%
% -----------------------------------------------------------------------

[OptimalRoute, TotalIncome] = FindRoute(StageEngCost, PredNode, EngStart,
EngEnd, num);

% -----------------------------------------------------------------------


% Call Function DynProg
% This function traces back the PredNode to find the optimal battery route.
%
%
% Inputs: node to node energy cost matrix, predecessor node matrix
%       energy start state, energy end state, time points
% Output: optimal route matrix
%       total income figure
%
% -----------------------------------------------------------------------

[TimeBatt, EngContent, Power] = BatteryRoute(BattEng, OptimalRoute);

% -----------------------------------------------------------------------
```

```
%Plot the spot price graph
subplot(3,1,1);
grid;
hold on;
stairs(SpotPrice);
xlim([0 96]);
ylim([0 2200]);
xlabel('Time (h)');
ylabel('Spot Price ($/MWh)');
set(gca,'XTick',0:12:96)
set(gca,'XTickLabel',{'0','6','12','18','24','30','36','42','48'});

%Plot the energy content graph
subplot(3,1,2)
grid on;
hold on;
axis([0 num -1 5]);
stairs(TimeBatt, EngContent, 'r', 'LineWidth', 2)
xlim([0 96]);
set(gca,'XTick',0:12:num)
set(gca,'XTickLabel',{'0','6','12','18','24','30','36','42','48'});
set(gca,'YTick',-1:1:6)
set(gca,'YTickLabel',{'','0','','1','','2',''});
xlim([0 num]);
xlabel('Time (h)');
ylabel('Battery Energy Level(MWh)');


%Plot the power level graph
subplot(3,1,3)
grid on;
hold on;
axis([0 num -2.5 2.5]);
stairs(TimeBatt, Power, 'g', 'LineWidth', 2)
set(gca,'XTick',0:12:num)
set(gca,'XTickLabel',{'0','6','12','18','24','30','36','42','48'});
set(gca,'YTick',-2:1:2)
set(gca,'YTickLabel',{'-2','-1','0','1','2'});
xlim([0 num]);
xlabel('Time (h)');
ylabel('Battery Power (MW)');
```

```
function EngCost = CostEnergy(BattEng, SpotPrice, RateCh, RateDisch)

% This is the function to create a energy transition matrix.
%
% Matrix BattEng(5, n)as energy status of the battery system, with matrix
% SpotPrice as spot prices by time, the cost can be found from
% one time point to its surrounding time points
%
% Numbering each element in the energy status matrix BattEng(5,n)as nodes:
%
%  4n+1 4n+2 4n+3 4n+4 4n+5 ... 5n
%  3n+1 3n+2 3n+3 3n+4 3n+5 ... 4n
%  2n+1 2n+2 2n+3 2n+4 2n+5 ... 3n
%   n+1  n+2  n+3  n+4  n+5 ... 2n
%    1    2    3    4    5 ...  n
%
% EngCost(TO_NODE, FROM_NODE): transition cost from FROM_NODE to
TO_NODE
% Its value is ranging from 0 to inf. The matrix size is (5xn,5xn).
%
% From one node, the energy movement rules are:
% Charge: 0.5MWh up or 1MWh up if the C-rate is C1. Time to next 0.5h.
% Discharge: 0.5MW down or 1MW down if the C-rate is C1. Time to next 0.5h.
% Standby: no change. Time to next 0.5h.
%
% ----------------------------------------------------------------------


% Pre-set matrix EngCost
%
% ----------------------------------------------------------------------

[m, n] = size(BattEng);
EngCost = -inf * ones(m * n);

% ----------------------------------------------------------------------

% Define the paramenters
%
% ----------------------------------------------------------------------

Rate1 = 0.5;
Rate2 = 1;
Ef = 0.85;
OpCost = 20;
t = 0.5;

% ----------------------------------------------------------------------


% Calculate the cost can be found from one time point to its
```

```
% surrounding time points.
%
% ------------------------------------------------------------------------

for P_Eng = 1 : m
   for P_Time = 1 : n
      FROM_NODE = (P_Eng - 1) * n + P_Time;

      % Battery standby
      if P_Time < n
         r = P_Eng ;
         c = P_Time + 1;
         TO_NODE = (r - 1) * n + c;
         EngCost(TO_NODE, FROM_NODE) = 0;
      end

      % Battery charging 0.5MW avaiable for both C0.5 and C1 rates
      if P_Time < n && P_Eng < m
         r = P_Eng + 1;
         c = P_Time + 1;
         TO_NODE = (r - 1) * n + c;
         EngCost(TO_NODE, FROM_NODE) = max(-inf,...
                    -Rate1*SpotPrice(P_Time)-Rate1*t*OpCost);
      end

      % Battery charging 1MWh only avaiable for C1 rates
      if RateCh == '1'
        if P_Time < n && P_Eng < m-1
          r = P_Eng + 2;
          c = P_Time + 1;
          TO_NODE = (r - 1) * n + c;
          EngCost(TO_NODE, FROM_NODE) = max(-inf,...
                    -Rate2*SpotPrice(P_Time)-Rate2*t*OpCost);
        end
      end

      % Battery discharging 0.5MW avaiable for both C0.5 and C1 rates
      if P_Time < n && P_Eng > 1
         r = P_Eng - 1;
         c = P_Time + 1;
         TO_NODE = (r - 1) * n + c;
         EngCost(TO_NODE, FROM_NODE) = max(-inf,...
                    Rate1*Ef*SpotPrice(P_Time)-Rate1*t*OpCost);
      end

       % Battery discharging 1MWh only avaiable for C1 rates
       if RateDisch == '1'
         if P_Time < n && P_Eng > 2
           r = P_Eng - 2;
           c = P_Time + 1;
           TO_NODE = (r - 1) * n + c;
```

```
            EngCost(TO_NODE, FROM_NODE) = max(-inf,...
                     Rate2*Ef*SpotPrice(P_Time)-Rate2*t*OpCost);
          end
        end

        % For calculating purpose, set the cost of the time node to
        % itself to 0.
        EngCost(FROM_NODE, FROM_NODE) = 0;

    end
end
```

```
function [StageEngCost, PredNode] = DynProg(EngCost, EngStart, num)

% This is the function that will perform the dynamic programing approach.
% The method is using iteration to find the best battery routine with
% maximum benefits.
%
% Assume we have n number of nodes. EngCost matrix is the energy cost
% matrix with dimension of 5n x 5n(square matrix).
% EngCost(TO_NODE, FROM_NODE)shows energy cost from FROM_NODE to
TO_NODE.
%
% Within each iteration:
% StageEngCost will store the cost from START_NODE to each node.
% StageEngCost(i) = current stage cost from START_NODE to node i.
%
% PredNode will store parent/predecessor node of each node for every stage.
% PredNode(i, j): parent of node i during stage j.
%
% -----------------------------------------------------------------------


% Set related parameters
%
% -----------------------------------------------------------------------

MAX_Iteration = 1000;  % Maximum iteration loops
START_NODE = EngStart / 0.5 * num + 1; % count start node number from
                               % start energy state
% -----------------------------------------------------------------------


% Initiate StageEngCost & PredNode matrix
% Dynamic programming starts from START_NODE
%
% -----------------------------------------------------------------------

[m, n] = size(EngCost);
StageEngCost = - ones(1, m) * inf;
StageEngCost(START_NODE) = 0;
PredNode = zeros(m, MAX_Iteration);

% -----------------------------------------------------------------------



% Iteration stages
% Find available connection from any energy-time nodes to any energy-time
% nodes, keep the gain from energy trading as high as possible
%
% -----------------------------------------------------------------------
```

```
for stage = 1 : MAX_Iteration

  PrevEngCost = StageEngCost;
  StageEngCost = -ones(1, m) * inf;

  % Calculating the energy cost from node to node
  % Once there are more benefits from the new route
  % The new route will replace the old one
  %
  for FORM_NODE = 1 : m
    for TO_NODE = 1 : m
      aij = EngCost(TO_NODE, FORM_NODE);
      dj = aij + PrevEngCost(FORM_NODE);
      if dj > StageEngCost(TO_NODE)
        StageEngCost(TO_NODE) = dj;
        PredNode(TO_NODE, stage) = FORM_NODE;
      end
    end
  end

  % Terminate the iteration once there is no more better route can be
  % found
  %
  if (StageEngCost == PrevEngCost)
    break;
  end
end

PredNode = PredNode(:, 1:stage); % resize the matrix
```

```
function [OptimalRoute, TotalIncome] =
FindRoute(StageEngCost, PredNode, EngStart, EngEnd, num)

% This function traces back the PredNode to find the optimal
battery route.
%
% -----------------------------------------------------------
--------------



stage = size(PredNode, 2);  % find stage numbers
START_NODE = EngStart / 0.5 * num + 1; % find start node
END_NODE = (EngEnd / 0.5 + 1)* num; % find end node

node = END_NODE; % route finding start fron END_NODE

index = 2;

% route finding start fron END_NODE, trace back to START_NODE
%
% -----------------------------------------------------------
--------------

while (1)
    OptimalRoute(index - 1) = node;
    node = PredNode(OptimalRoute(index-1), stage - index +
1);
    if node == START_NODE
        OptimalRoute(index) = START_NODE;
        break;
    end
    index = index + 1;
end

% -----------------------------------------------------------
--------------


OptimalRoute = fliplr(OptimalRoute); % revise the route


TotalIncome = StageEngCost(END_NODE); % find the total income
from battery

end
```

```
function [TimeBatt, EngContent, Power] = BatteryRoute(BattEng, OptimalRoute)

% Create visualization of the battery routine
% Convert energy cotent back the node number to time base
% Calculate power level
%
% ------------------------------------------------------------------------

[m, n] = size(BattEng);
L_BattRoute = length(OptimalRoute);
Ef = 0.85;

TimeBatt = zeros(1, L_BattRoute);
EngContent = zeros(1, L_BattRoute);
Power = zeros(1, L_BattRoute);

for i = 1 : L_BattRoute
   TimeBatt(i) = mod(OptimalRoute(i) - 1, n) + 1;
   EngContent(i) = abs((OptimalRoute(i) - 1 - mod(OptimalRoute(i) - 1, n))/n) + 1;
end

Power(1) = 0;
for i = 2:L_BattRoute
   Power(i) = (EngContent(i) - EngContent(i-1));
   if Power(i)<0
     Power(i) = Power(i) * Ef;
   end
end

EngContent = EngContent - 1;
```

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