ECONOMIC ANALYSIS OF ELECTRIC ENERGY STORAGE

A Thesis by

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I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Electrical Engineering.

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We have read this thesis and recommend its acceptance:

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ABSTRACT

This thesis presents a cost analysis of grid-connected electric energy storage. Various battery energy storage technologies are considered in the analysis. Life-cycle cost analysis is used. The results are presented in term of incremental cost of electricity stored and discharged, in US$/kWh.

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CHAPTER 1

INTRODUCTION

1.1 Background

The definition of energy storage is the storing of some form of energy that can be drawn upon at later time to perform some useful operations. [1] One of the main characteristics of electricity has always been that it can not be efficiently and economically stored in big amounts. Thus, it is necessary to generate electricity instantly when demand occurs. This results in highly demanding and complex electrical system operations, such as balancing supply and demand, and maintaining system security. Various energy storage technologies have been proposed as possible solutions to a number of power system issues. In addition, storage helps to increase value of renewable energy resources.

1.2 Problem Statement

The value of electricity storage is widely known, and there are innumerable applications. However, its cost has prevented high penetrations on electrical systems. These costs are decreasing as technologies improve and new ones are developed. The question to be addressed by this thesis is, "How much does storage add to the cost of a kWh of electric energy?"

The question will be answered through a basic economic analysis of electric energy storage. The capital and operating costs of storage units will be converted to a cost per kWh of energy stored.

1.3 Scope

In order to perform the economic analysis, storage is divided into two categories, which are generation applications and transmission/distribution applications. The discharge power of generation applications ranges from 10MW to 1000MW [2]. For generation applications, the following storage technologies are considered:

- Lead-Acid batteries (LA)
- Valve-Regulated Lead-Acid batteries (VRLA)
- Nickel/Cadmium batteries (NiCd)
- High temperature sodium/sulfur batteries (Na/S)
- Sodium bromide/sodium polysulfide flow batteries (Regenesys®)

For transmission/distribution applications, the discharge power range from 100kW to 2000kW [2]. The following storage technologies are examined in the category of transmission/distribution applications:

- Lead-Acid batteries (LA)
- Valve-Regulated Lead-Acid batteries (VRLA)
- Nickel/Cadmium batteries (NiCd)
- Sodium/sulfur batteries (Na/S)
- Zinc/Bromine batteries (Zn/Br)
- Vanadium-redox batteries (V-redox)

1.4 System Descriptions

Storage is connected to a power system bus as shown in Figure 1-1. The storage system consists of a power conversion system (PCS) and energy storage units. The PCS is a power electronic system that converts energy from ac to dc for the storage units, and converts energy from dc to ac to release electricity to the power system.

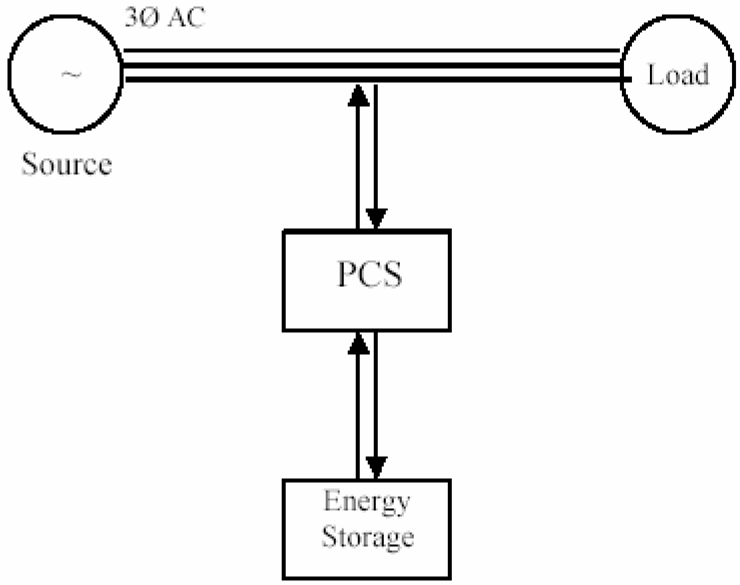

Fig. 1-1 An energy storage system connected to a power system bus [2]

1.5 Thesis Overview

Chapter 2 gives detailed information on applications and technologies of energy storage. Chapter 3 defines the variables and methodology for calculating the cost of electricity. Chapter 4 describes the storage systems to be studied and shows the analysis results. Chapter 5 presents conclusions and future work.

Table 1-1 lists and defines many of the variables that appear in subsequent chapters.

TABLE 1-1

LIST OF VARIABLES

VARIABLE	DEFINITION
A	Annual amount of replacement cost (US$/kWh)
AC	Annualized capital cost (US$/y)
AEP	Annual energy production (kWh/y)
ARC	Annual replacement cost (US$/y)
BOP	Total cost for balance of plant (US$)
BOPU	Unit cost for balance of plant (US$/kWh)
C	Number of charge/discharge cycles in life of storage
COE	Cost of electricity (US$/kWh)
CRF	Capital recovery factor
D	Annual operating days (days/y)
eff	Efficiency
F	Future amount of replacement cost (US$/kWh)
H_o	Length of each discharge cycle (h)
i_r	Annual interest rate (%)
n	Number of discharge cycles per day
OM_f	Fixed operation and maintenance cost (US$/kW-y)
OMC	Annual fixed operation and maintenance cost (US$/y)
P	Rated power output of energy storage (kW)
PCS	Total cost for power electronic (US$)
PCSU	Unit cost for power electronic (US$/kW)

r	Replacement period (y)
SUC	Total cost for storage units (US$)
SUCU	Unit cost for storage units (US$/kWh)
TCC	Total capital cost (US$)
y	Lifetime of energy storage (y)

CHAPTER 2

APPLICATIONS AND TECHNOLOGIES

2.1 Applications

In this chapter, the applications of storage in three characterizes are summarized: generation, transmission and distribution (T&D) and utilization (end-users or customers).

2.1.1 Generation Applications

Enhance generation capacity

When connected to the power grid, storage can effectively increase overall generating capacity by discharging at peak times. This results in deferral of investment in new generating equipment, and decreases the need to upgrade generation systems.

Electricity Price Arbitrages

Electricity price arbitrage is the method of buying low-price electricity during off-peak periods to charge storage, and selling the electricity later on by discharging storage during on-peak periods when the price of electricity is high [3]. This buy low/sell high application focuses mainly on the profitability of storage.

Ancillary Services

The Federal Energy Regulatory Commission (FERC) defines ancillary services as "those services necessary to support the delivery of electricity from seller to purchaser while maintaining the integrity and reliability of power systems" [3]. Storage can supply some ancillary services:

Spinning reserve: Spinning reserve is the generating capacity of the generating units that are running (on-line) and can respond within 10 minutes after receiving a command from the system operator to supply power in cases of power outage [3].

Supplemental Reserve (Non-Spinning Reserve): Supplemental reserve is the generating capacity of the generating units that are not running (off-line) and can respond within 10 to 30 minutes after receiving a command from the system operator [3].

Regulation: Storage can be used to increase or decrease energy to balance supply and demand in real-time.

Load Following: Electric load is constantly changing. Storage can effectively follow load changes and provide energy to meet the hour-to-hour, daily, weekly and seasonal load variations.

Black Start: After a blackout, storage alone can re-energize parts of the electrical system [3].

Other Ancillary Services: In addition, storage can provide other ancillary services such as voltage support, replacement reserve, and capacity [4].

Load Leveling

During a low demand period, low-priced energy is used to charge storage. Storage discharges later on during a high demand period when the price of electricity is high. This results in the improvement of load factor, and delays construction of new generating units [5].

Support of Renewables

Renewable generators cannot effectively follow loads. Storage improves values of renewables by reducing their output fluctuations [5]. Renewable energy generated off-peak can also be stored and used on-peak. This leads to reductions of conventional fuel use and other environmental benefits.

2.1.2 Transmission and Distribution Applications

Peak Shaving

Figure 2-1 indicates how energy storage can shave peak demand [4]. Storage is charged during the off-peak times. It then discharges to the system during peak times.

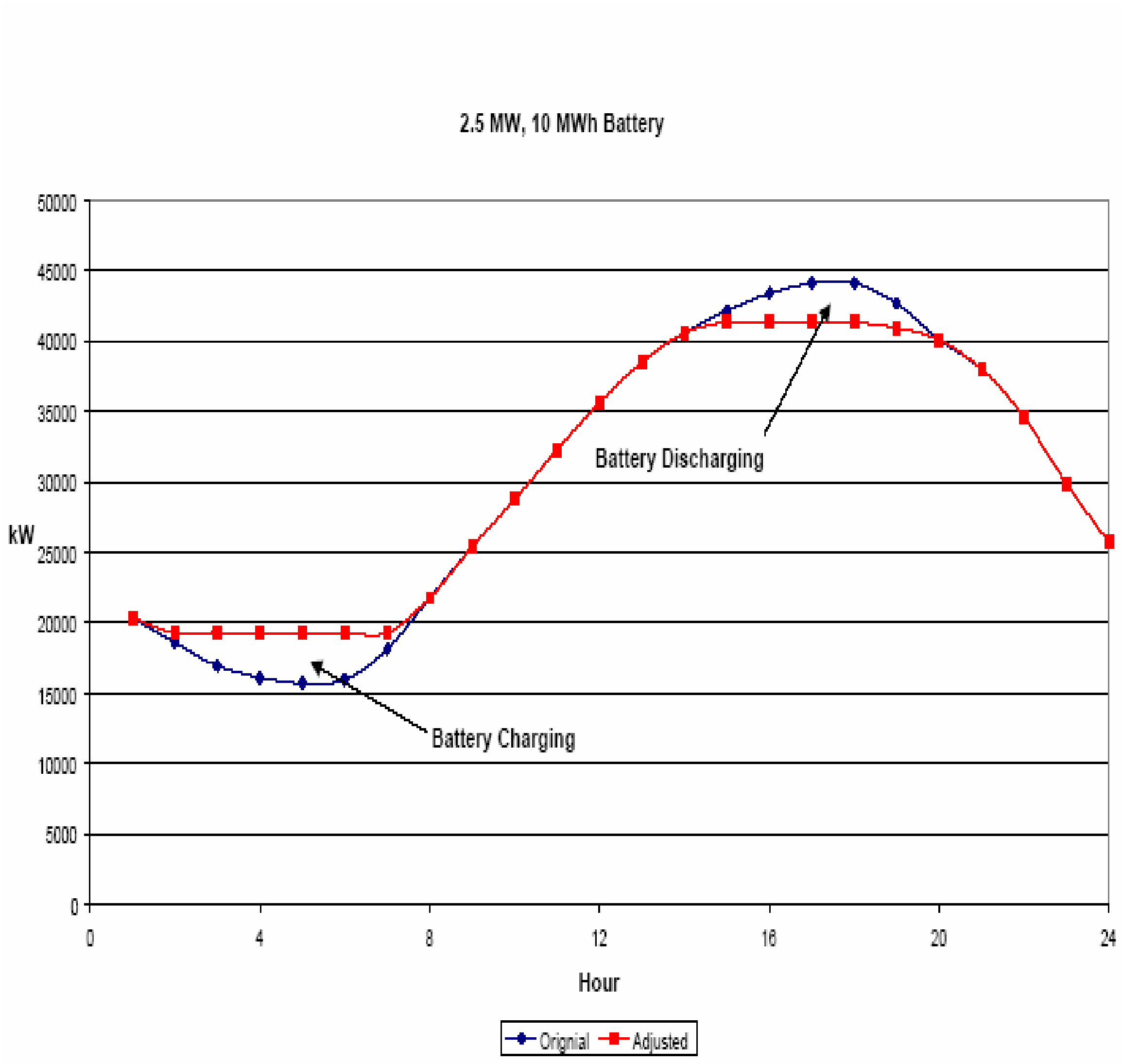

Fig. 2-1: Sample Peak Shaving Operation [4].

Transmission Support

Storage can improve transmission and distribution system performance by reducing system disturbances [3]. Storage enhances load carrying capacity and, thus, improves transmission stability. Storage also reduces under frequency load shedding that occurs during disturbances [3].

Deferral of Transmission and Distribution upgrade

Storage can discharge to transmission or distribution loads during peak times. Reducing the peak loads can delay an investment in new transmission and distribution lines and equipment, in much the same way it can defer generation additions.

Supplemental power supply to distribution system

During peak times, some transmission lines may reach their capacity limits. Storage is then used as a supplemental power supply to provide energy to serve loads of distribution systems supplied by those lines. This also reduces I^2R losses of the transmission lines [4].

2.1.3 End-user Applications

Power Quality

Storage can improve power quality by reducing harmonic distortion and reducing voltage sags, swells, surges, and outages. In this case, storage acts as a power conditioner or uninterruptible power supply. Storage rectifiers will charge using electric power of almost any quality. Storage inverters can then discharge very high quality power to sensitive loads.

Service reliability

During power outages, storage can provide energy to critical loads. It can also allow an orderly shutdown of loads according to process priorities [3].

2.2 Technologies

The batteries analyzed in this thesis are electrochemical devices that store electrical energy in the form of chemical energy and then convert that chemical energy back to electricity. Rechargeable batteries, also called secondary batteries, and flow batteries, are commonly used as energy storage.

Figure 2-2 shows the concept of a rechargeable battery. In the discharge mode, ions flow through a porous separator in the electrolyte between the positive and negative electrodes. This causes electrons to flow through the external load, from the negative to the positive electrode. In the charge mode, this process is reversed. An external supply forces electrons into the negative electrode, charging the battery.

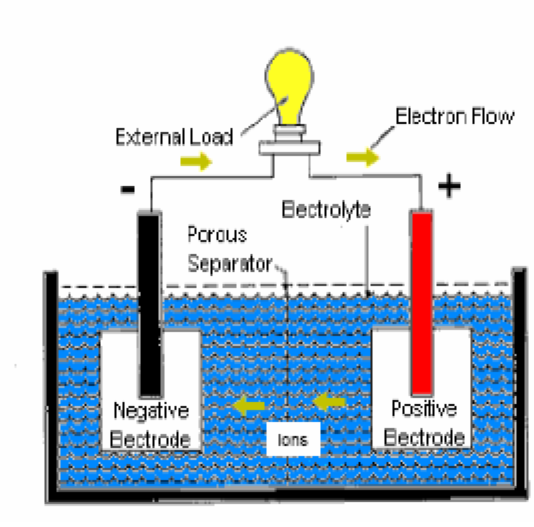

Fig.2-2: Rechargeable Battery in Discharge Mode [2]

2.2.1 Lead-Acid batteries and Valve Regulated Lead-Acid Batteries (LA & VRLA)

Lead-acid is the oldest and the most widely used rechargeable battery. Low cost and high voltage per cell are the advantages of this battery. It is used in the automotive field and in electrical substations for backup power.

The electrodes of a lead-acid battery, as shown in Figure 2-2, are lead, and the electrolyte is sulfuric acid. The sulfuric acid, combining with the lead electrodes, produces lead sulphate on both plates. The battery is fully discharged when both electrodes are fully sulphated [6].

2.2.2 Nickel/Cadmium (NiCd)

Nickel/Cadmium is also a rechargeable battery, which has good temperature characteristics. However, the Nickel/Cadmium battery cost is high compared to lead-acid batteries. The battery contains nickel hydroxide as a positive active material and cadmium hydroxide as a negative material [6]. Potassium hydroxide is used as the electrolyte [6].

2.2.3 Sodium/Sulfur (Na/S)

The Sodium/Sulfur battery employs liquid sulfur as the positive electrode, and liquid sodium as the negative electrode [6]. Sodium combines with sulfur to form sodium polysulfide (Na2S4).

Figure 2-3 illustrates the principle of Na/S batteries. When the battery discharges, electron flow to the circuit, while positive sodium ions flow through electrolyte. The electron flow generates about 2 V, as show in Figure 2-3.

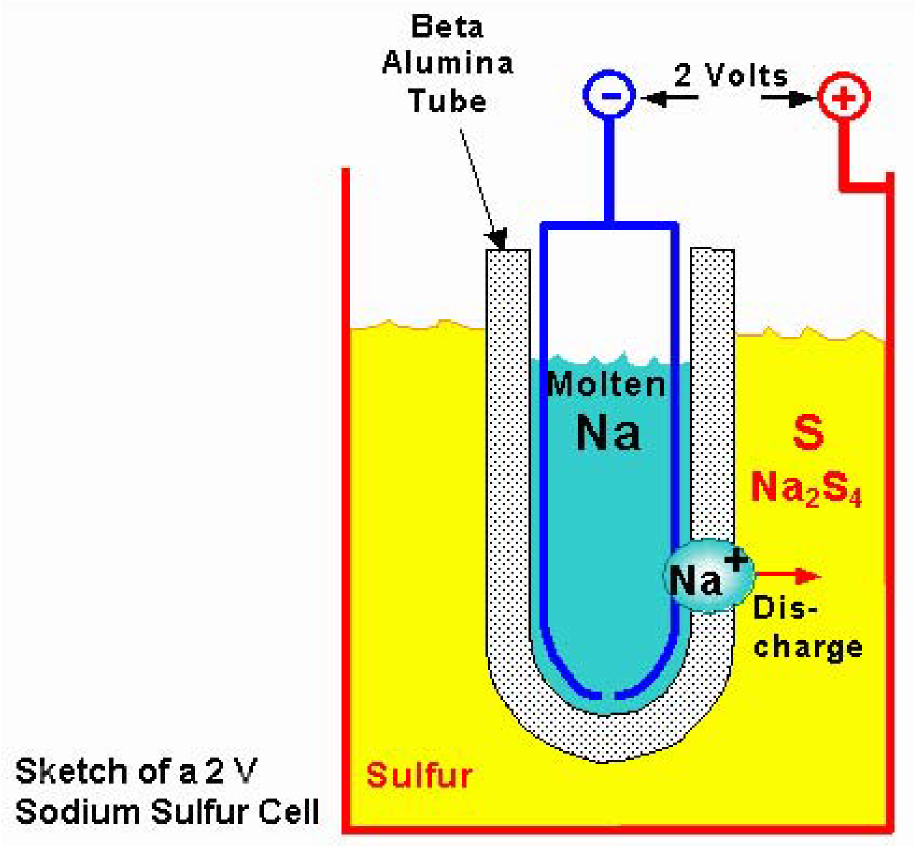

Fig.2-3: Sodium Sulfur Battery [7]

2.2.4 Sodium bromide/sodium polysulfide flow batteries (Regenesys®)

The sodium bromide/sodium polysulfide flow batteries, formerly marketed under the Regenesys® tradename, employ sodium bromide and sodium polysulfide as the active materials. The electrolytes flow through a half cell that produce about 1.5 V [7].

The chemical reaction occurs between two electrolytes that are separated into two tanks. The electrolytes are pumped to regenerative fuel cell modules. An ion-selective membrane in the fuel cell allows only positive sodium ions to pass through [7].

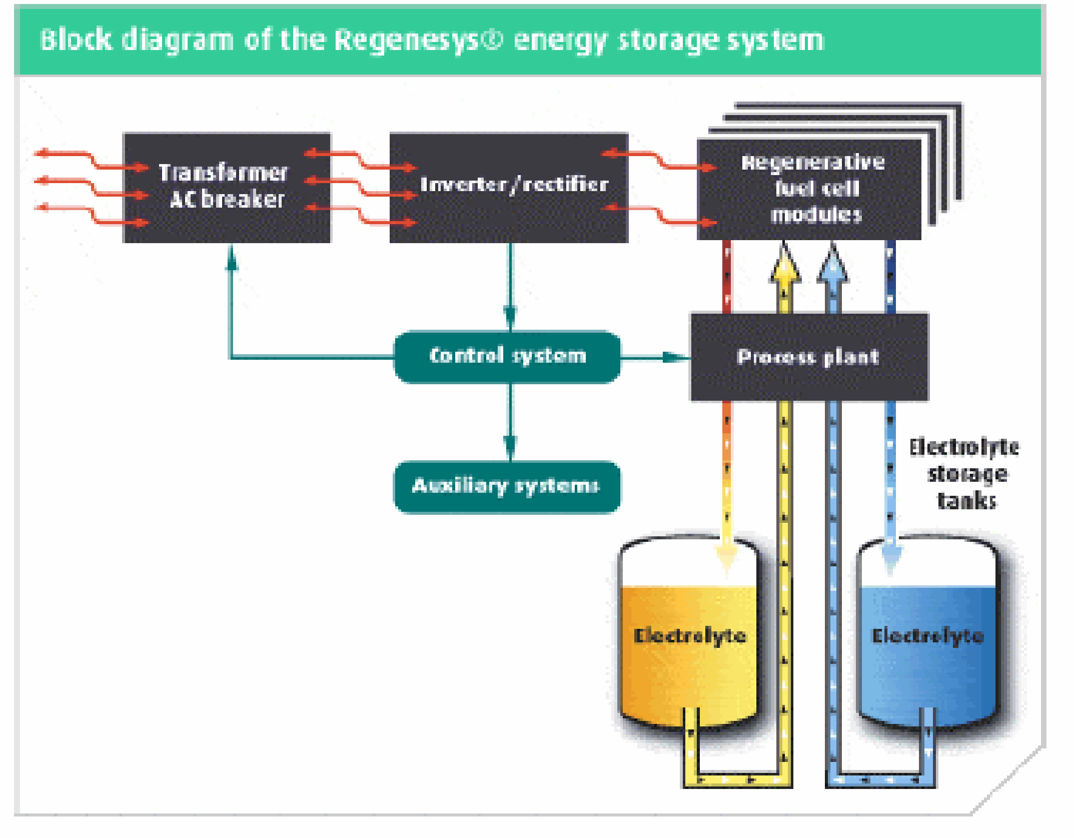

Fig.2-4: Sodium Bromide/Sodium Polysulfide Flow Battery [2]

2.2.5 Zinc/Bromine batteries (Zn/Br)

First developed by Exxon in the early 1970's, the zinc/bromine battery works by combining zinc and bromine to generate a voltage during discharging, and replating zinc on the electrode during charging. The process is shown in Fig. 2-5.

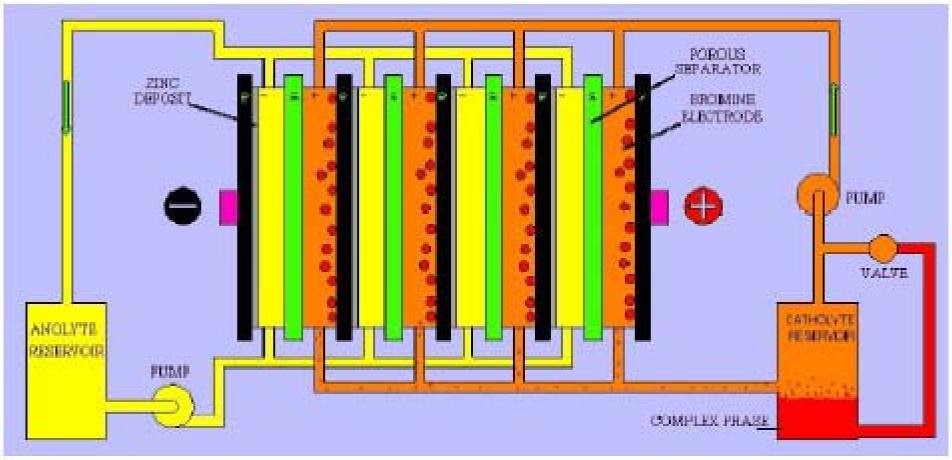

Fig. 2-5: Zinc/Bromine Battery [2]

2.26 Vanadium-Redox batteries (V-redox)

First pioneered by the University of New South Wales, Vanadium-Redox is one of the most promising flow batteries. A typical battery is shown in Fig. 2-6. The system contains two electrolyte tanks, two pumps and active vanadium. Vanadium ions are a medium to move electrons in and out. The vanadium exists in two different oxidation states in the electrolyte. The V2+/V3+ state is located in the negative electrolyte, and V4+/V5+ is in the positive.

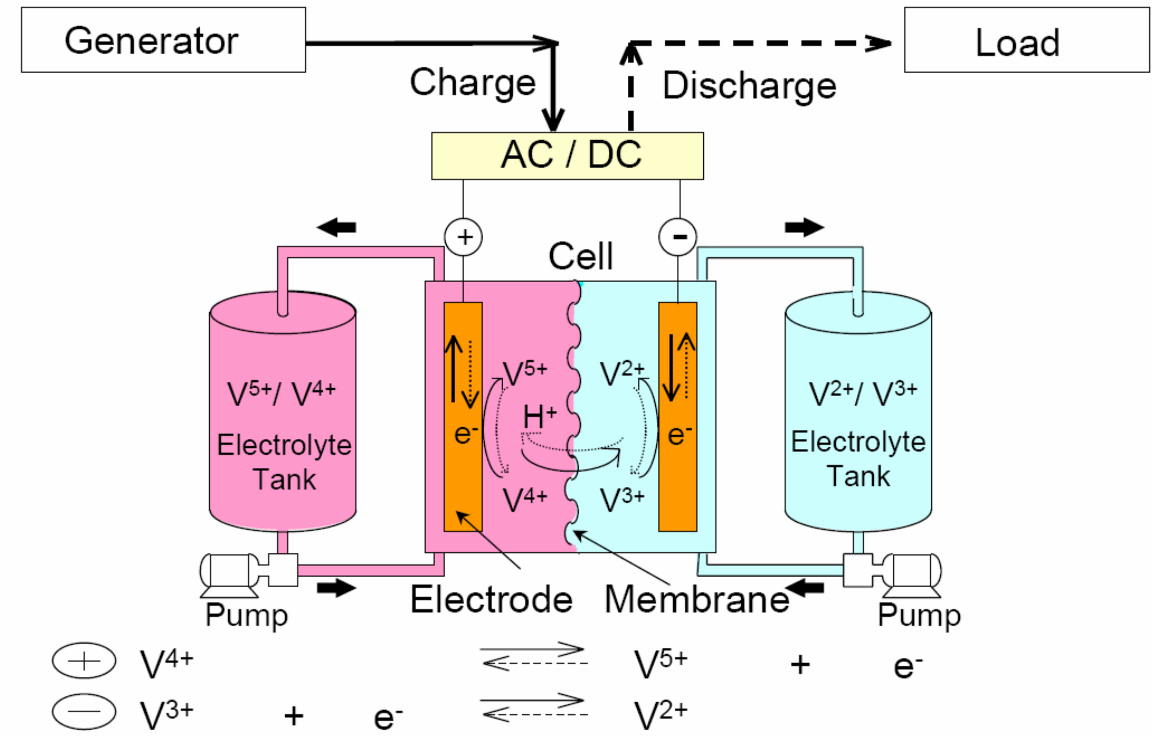

Fig. 2-6: Typical Vanadium –Redox battery [8]

CHAPTER 3

CALCULATION OF COST OF ELECTRICITY

3.1 Methodology

The approach taken in this thesis is to estimate the cost added to each kWh of electricity by the storage system. This will allow comparison of electricity cost, in US$/kWh, of electricity that is stored after generation with electricity that is used immediately. This is done through a life cycle cost analysis.

The annual cost consists of annualized capital cost, annualized replacement cost, and annual operation and maintenance cost. Cost of electricity can be calculated by dividing the total annual cost by the total energy discharged annually from storage system.

The total energy discharged annually will be referred to as annual energy production (AEP), which can be written as follows:

$$AEP = P \times n \times H_o \times D \tag{3-1}$$

where P is rated power output (kW), n is number of charge/discharge cycles per day, H_o is the length of each discharge cycle (h), and D is the number of days the storage is operated each year.

The annual fixed operation and maintenance cost (OMC) is

$$OMC = OM_f \times P \tag{3-2}$$

where OM_f is the fixed operation and maintenance cost per rated kW of storage (US$/kW).

The total capital cost for the energy storage plant consists of three components, which are the total cost of the power electronic system, the total cost for storage units, and the total cost for the balance of plant.

The total cost for the power electronic system is

$$PCS = PCSU \times P \tag{3-3}$$

where $PCSU$ is the unit cost for the power electronic system in US$/kW.

The total cost for storage units can be obtained by

$$SUC = \frac{SUCU \times P \times H_o}{eff} \tag{3-4}$$

where $SUCU$ is the unit cost for the storage units (US$/kWh) and eff is the efficiency of the system:

$$eff = \frac{energy\_(kWh)\_out\_during\_disch\arg e}{energy\_(kWh)\_in\_during\_ch\arg e} \tag{3-5}$$

The total cost for the balance of plant is

$$BOP = BOPU \times P \tag{3-6}$$

where $BOPU$ is the unit cost for the balance of plant (US$/kWh).

The total capital cost (TCC), which is the sum of the total costs for the power conversion system, storage units, and balance of plant, can be written as follows.

$$TCC = PCS + SUC + BOP \tag{3-7}$$

The annualized capital cost (AC) can be written as follows:

$$AC = TCC \times CRF \tag{3-8}$$

CRF is the capital recovery factor [9]:

$$CRF = \frac{((i_r(1+i_r)^y)}{((1+i_r)^y - 1)} \tag{3-9}$$

where i_r is the annual interest rate to finance the storage plant, and y is the life of the plant in years.

When batteries are used as the storage unit, they may have to be replaced one or more times during the life of the plant. This cost is annualized (US$/kWh):

$$A = F[(1+i_r)^{-r} + (1+i_r)^{-2r} + ...]CRF \tag{3-10}$$

where F is future battery replacement cost (US$/kWh) and r is the replacement period (y). The number of terms in the factor of the above equation is equal to the number of replacements during the life of the plant. Thus the equation shown is for batteries being replaced twice during the plant life.

The replacement period r can be calculated as follows.

$$r = \frac{C}{n \times D} \tag{3-11}$$

where C is number of charge/discharge cycles in the battery life.

The annual replacement cost is:

$$ARC = \frac{A \times P \times H_o}{eff} \tag{3-12}$$

The cost of added to electricity stored is:

$$COE = \frac{(AC + OMC + ARC)}{(P \times n \times H_o \times D)} \tag{3-13}$$

This cost is independent of the cost of electricity used to charge the storage.

3.1.2 Variables and Settings

Table 3-1 presents inputs and outputs of the calculations presented in section 3.1.1. Table 3-2 summarizes the numerical values for the parameters used in the analysis of COE for generation applications. Table 3-3 summarizes the parameters used for the numerical values for the calculation of COE in transmission/distribution applications.

TABLE 3-1

INPUTS AND OUTPUTS OF THE CALCULATIONS

INPUTS	**OUTPUTS**
Rated output (kW)	Rated energy capacity (kWh)
Number of discharge cycles per day	Rated storage capacity (kWh)
Length of each discharge cycle (h)	Capital recovery factor
Annual operating days (days/y)	Replacement period (y)
Unit cost for power electronic (US$/kW)	Total cost for power electronic (US$)
Unit cost for storage units (US$/kWh)	Total cost for storage units (US$)
Unit cost for balance of plant (US$/kWh)	Total cost for balance of plant (US$)
Efficiency	Annual capital cost (US$/y)
Interest rate (%)	Annual fixed O&M cost (US$/y)
Fixed operation and maintenance cost (US$/kW-y)	Annual replacement cost (US$/y)
Future amount of replacement cost (US$/kWh)	Annual energy production (kWh/y)
Number of charge/discharge operation cycles in life	Cost of Electricity (US$/kWh)

.

TABLE 3-2

PARAMETERS USED FOR COE STUDY [2]

(GENERATION APPLICATIONS)

PARAMETERS	**LA**	**VRLA**	**NiCd**	**Na/S**	**Regenesys®**
Efficiency	0.75	0.75	0.65	0.7	0.65
Unit cost for power electronic (US$/kW)	125	125	125	150	275
Unit cost for storage units (US$/kWh)	150	200	600	250	100
Unit cost for balance of plant (US$/kWh)	150	150	150	50	50
Fixed O&M cost (US$/kW-y)	15	5	5	20	15
Future amount of replacement cost (US$/kWh)	150	200	600	230	US$150/kW
Number of charge/discharge cycles in life	1500	1500	3000	2500	2500

TABLE 3-3

PARAMETERS USED FOR COE STUDY [2]

(TRANSMISSION/DISTRIBUTION APPLICATIONS)

PARAMETERS	**LA**	**VRLA**	**NiCd**	**Na/S**	**Zn/Br**	**V-redox**
Efficiency	0.75	0.75	0.65	0.7	0.6	0.7
Unit cost for power electronic (US$/kW)	175	175	175	150	175	175
Unit cost for storage units (US$/kWh)	150	200	600	250	400	600
Unit cost for balance of plant (US$/kWh)	50	50	50	0	0	30
Fixed O&M cost (US$/kW)	15	5	25	20	20	20
Future amount of replacement cost (US$/kWh)	150	200	600	230	100	600
Number of charge/discharge cycles in life	1500	1500	3000	2500	2000	3000

CHAPTER 4

ANALYSIS RESULTS

4.1 Case Studies

4.1.1 Operating Assumptions

4.1.1.1 Number of charge/discharge cycles per day

The operating assumption is that storage charges and discharges one time per day for generation applications. For transmission and distribution applications, both one and two charge/discharge cycles per day are considered.

4.1.1.2 Annual Operating Days (days per year)

As a base case, the system operates 250 days per year, which is approximately the number of weekdays minus holidays in a year. Systems designed to operate only during peak use seasons are assumed to operate 100 days per year. These are also investigated and compared with those designed to operate 250 days per year.

4.1.1.3 Length of discharge cycle (h)

The length of the discharge cycle depends on the application. In this study, 8 h [2] is applied for generation applications (10-1000 MW) while 4 h [2] is the discharge time for transmission and distribution applications (100 kW-2.5 MW).

4.1.2 Economic Assumptions

For economic assumptions, this study assumes that the annual interest rate is 8.76%, as was assumed in an earlier study by Sandia Laboratories [4]. Inflation and escalation rate are not considered in this analysis.

4.1.3 Case Studies

Ten case studies are performed to acquire the cost added to stored electricity

(COE) and annual costs. Six cases are generation applications, while four are systems designed for transmission and distribution. The case studies are:

Case 1: Generation applications, 10MW, 80MWh, 250 discharge cycles per year

Case 2: Generation applications, 10MW, 80MWh, 100 discharge cycles per year

Case 3: Generation applications, 25MW, 200MWh, 250 discharge cycles per year

Case 4: Generation applications, 25MW, 200MWh, 100 discharge cycles per year

Case 5: Generation applications, 200MW, 1600MWh, 250 discharge cycles per year

Case 6: Generation applications, 200MW, 1600MWh, 100 discharge cycles per year

Case 7: Transmission and Distribution applications, 2.5MW, 10MWh, 250 discharge cycles per year (discharge once per day, 250 days per year)

Case 8: Transmission and Distribution applications, 2.5MW, 10MWh, 500 discharge cycles per year (discharge twice per day, 250 days per year)

Case 9: Transmission and Distribution applications, 2.5MW, 10MWh, 100 discharge cycles per year (discharge once per day, 100 days per year)

Case 10: Transmission and Distribution applications, 2.5MW, 10MWh, 200 discharge cycles per year (discharge twice per day, 100 days per year)

4.2 Results

4.2.1 Cost Added to Electricity Stored

The length of each discharge cycle, system energy capacity, and the number of discharge cycles per year are each varied in the analysis. The cost added to stored electricity (COE) is plotted vs. each of these variables. The results are presented graphically in Figure 4-1 through 4-24.

The graphs of COE vs. discharge time show, for a given system design in power capacity and annual days of use, the cost added to a kWh of electricity by storing it. The graphs show that as the length of discharge time increases, the cost per unit of energy stored decreases. This is because the power electronic cost is a function only of power capacity and is thus constant, regardless of energy capacity. Total installed cost for the system increases as discharge time increases, because more storage units are needed to provide the additional kWh of storage.

For a system design with fixed power capacity and annual operating cycles, the graphs of COE vs. storage capacity (kWh) also show the cost added to a kWh of electricity by storing it. The graphs indicate that the cost per unit of energy stored decreases as storage capacity increases. The power electronic and operation and maintenance costs are determined only by power capacity, so they do not vary with energy capacity. Total energy stored and discharged annually increases as energy capacity increases, which causes the cost per unit of electricity to decrease. Total installed cost for the system, however, increases as energy capacity increases, because of cost of additional storage units.

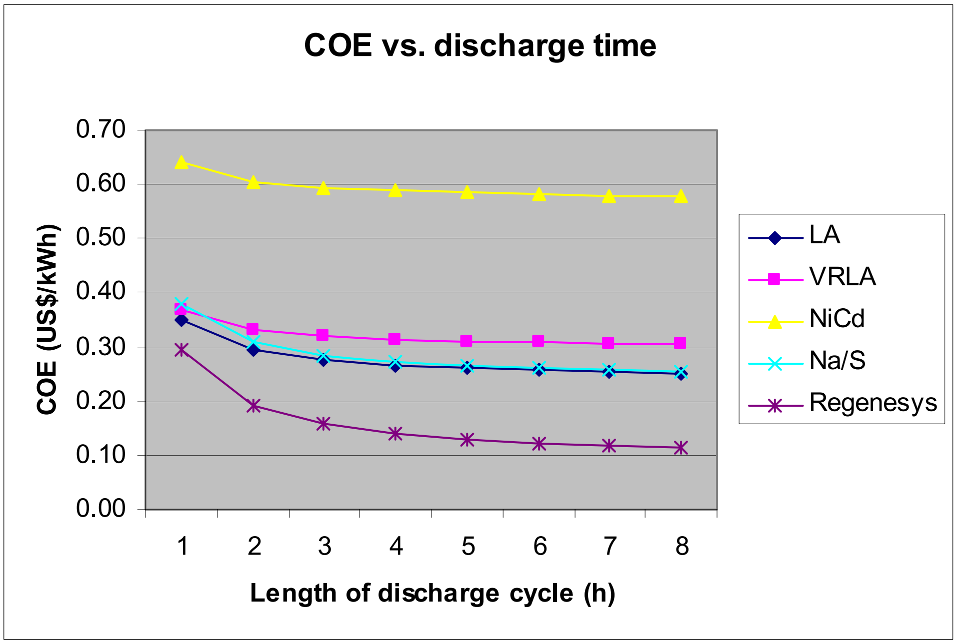

Fig. 4-1: COE vs. length of discharge cycle, Case 1, 10MW, 250 cycles/year.

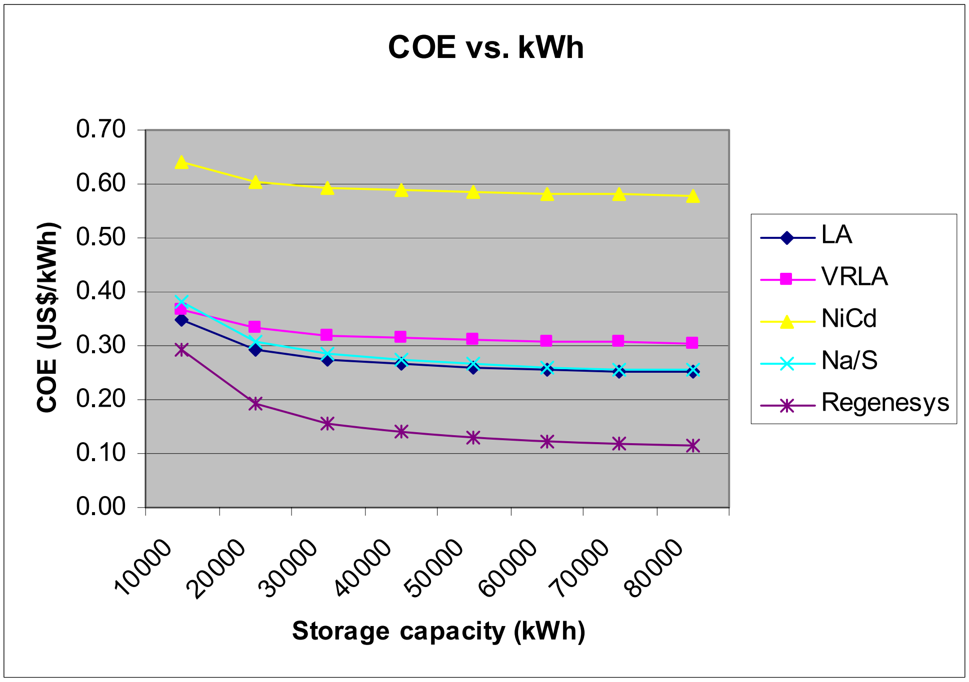

Fig. 4-2: COE vs. storage capacity (kWh), Case 1, 10MW, 250 cycles/year.

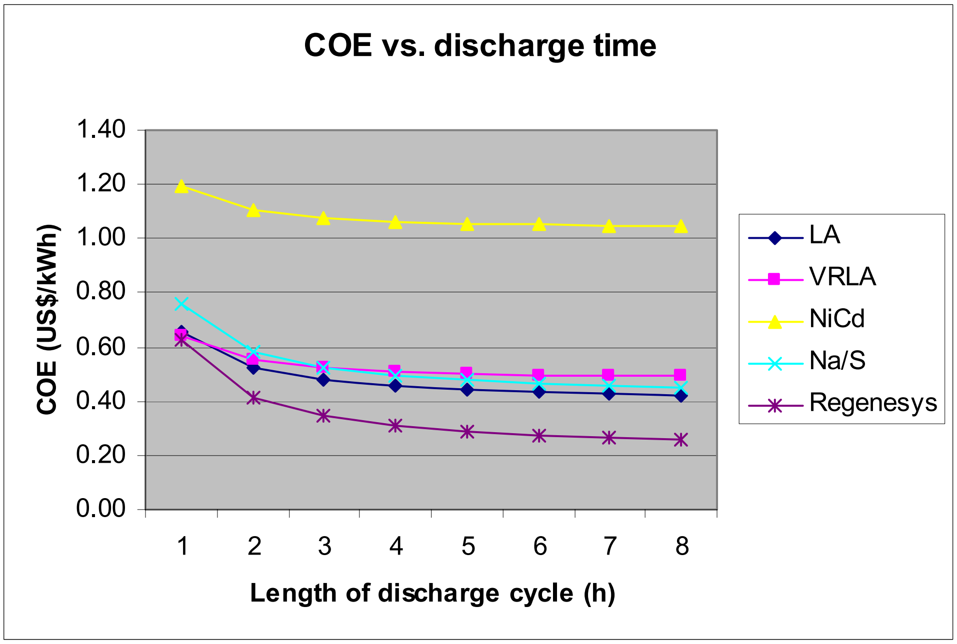

Fig. 4-3: COE vs. length of discharge cycle, Case 2, 10MW, 100 cycles/year.

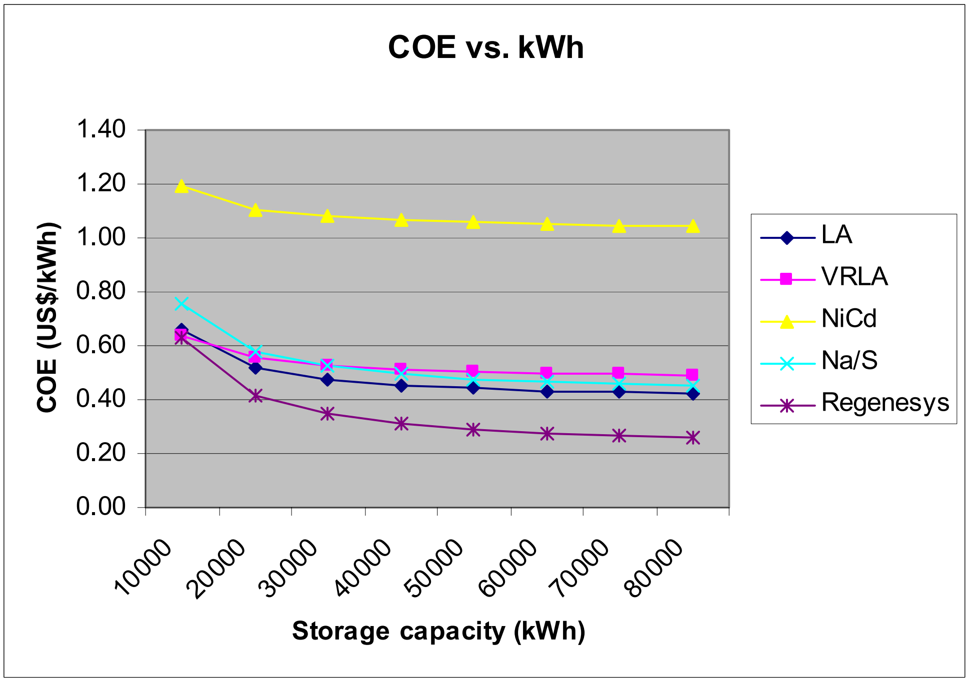

Fig. 4-4: COE vs. storage capacity (kWh), Case 2, 10MW, 100 cycles/year.

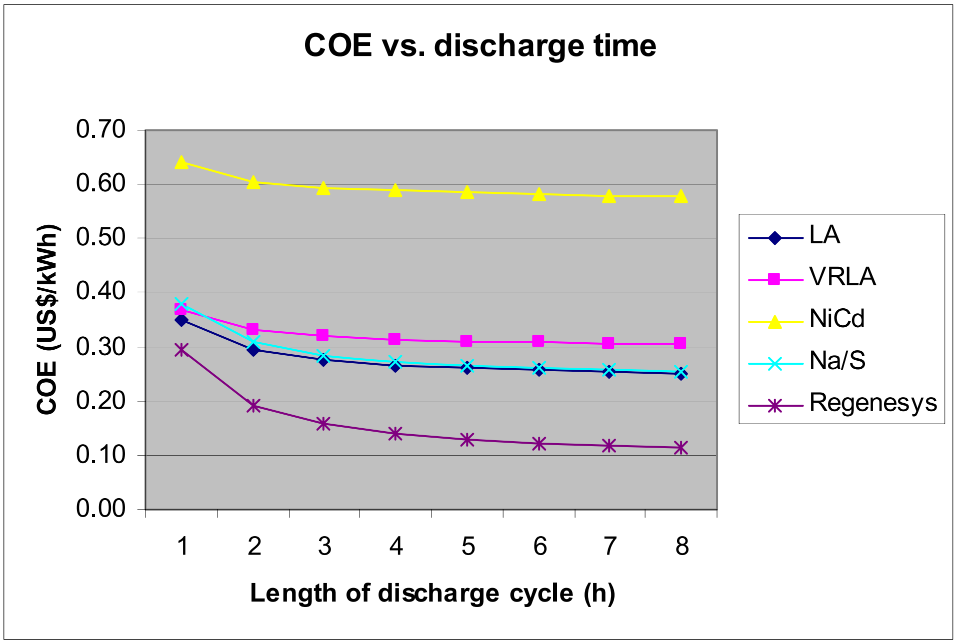

Fig. 4-5: COE vs. length of discharge cycle, Case 3, 25MW, 250 cycles/year.

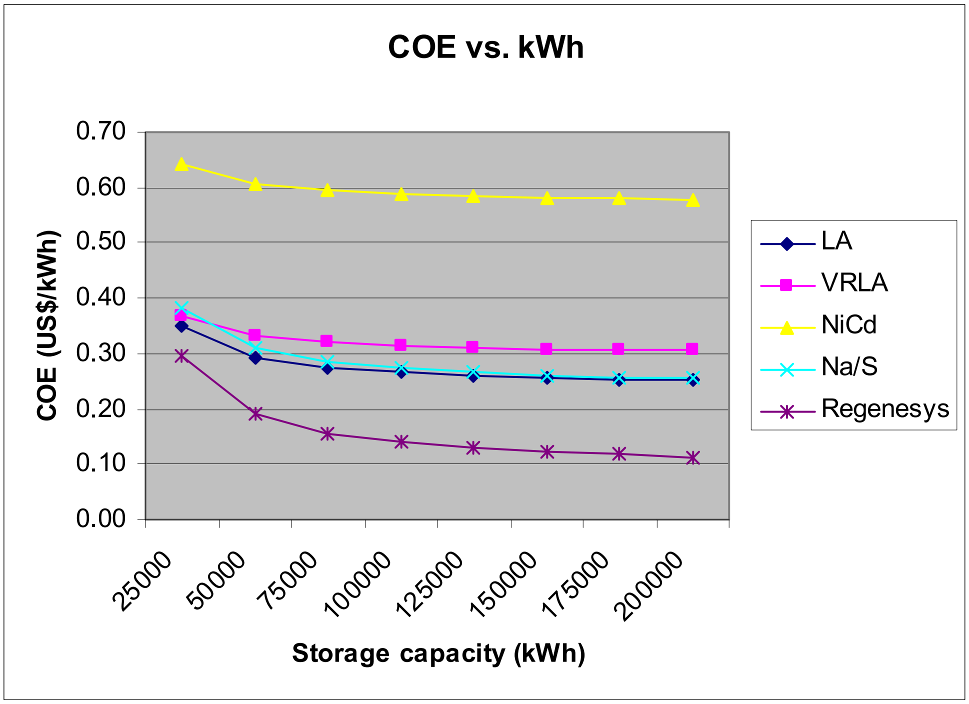

Fig. 4-6: COE vs. storage capacity (kWh), Case 3, 25MW, 250 cycles/year.

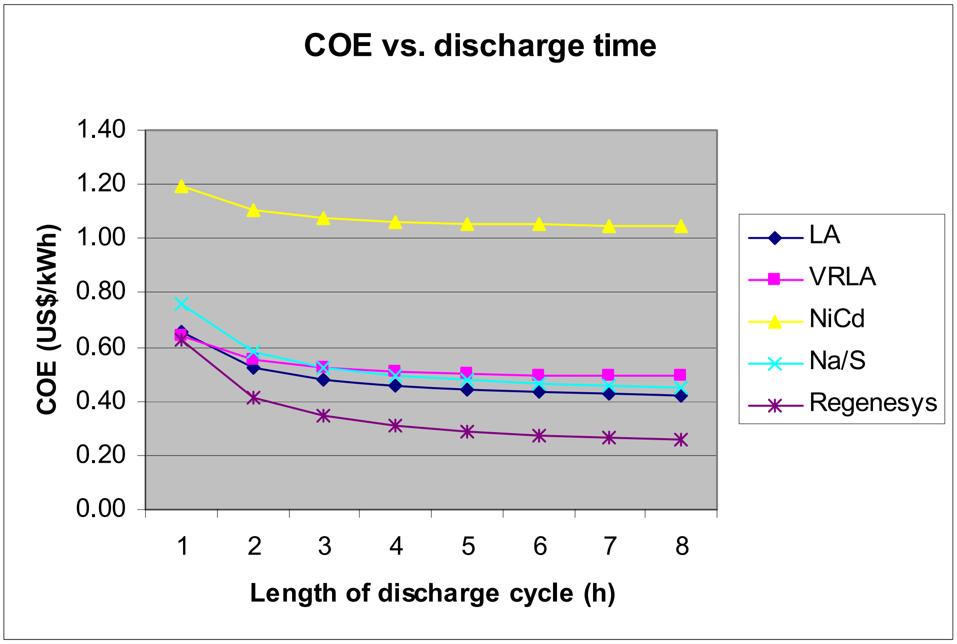

Fig. 4-7: COE vs. length of discharge cycle, Case 4, 25MW, 100 cycles/year.

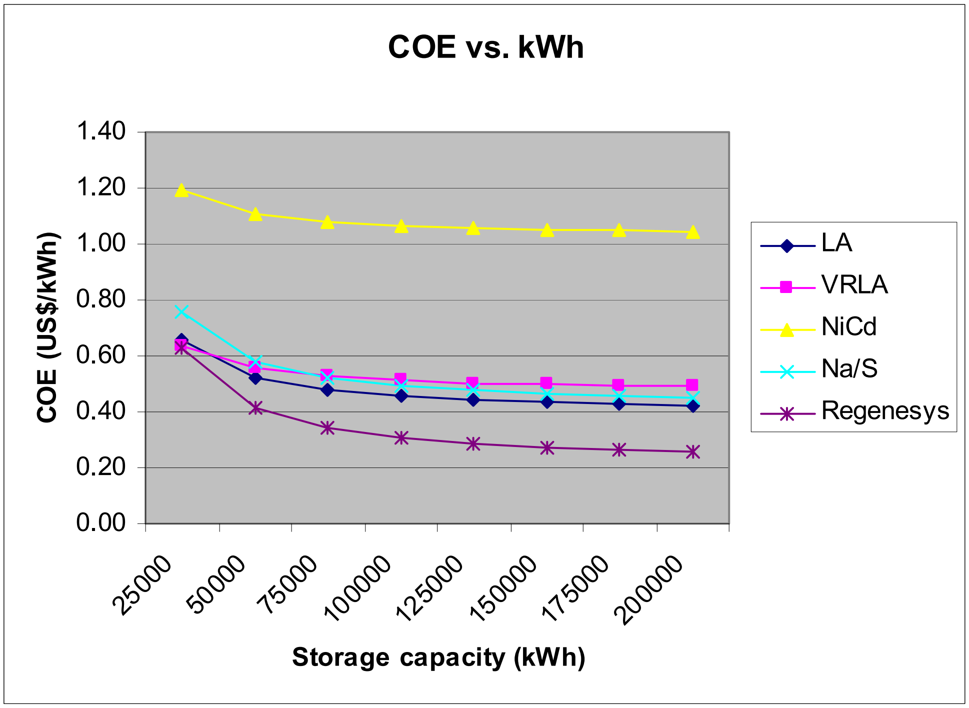

Fig. 4-8: COE vs. storage capacity (kWh), Case 4, 25MW, 100 cycles/year.

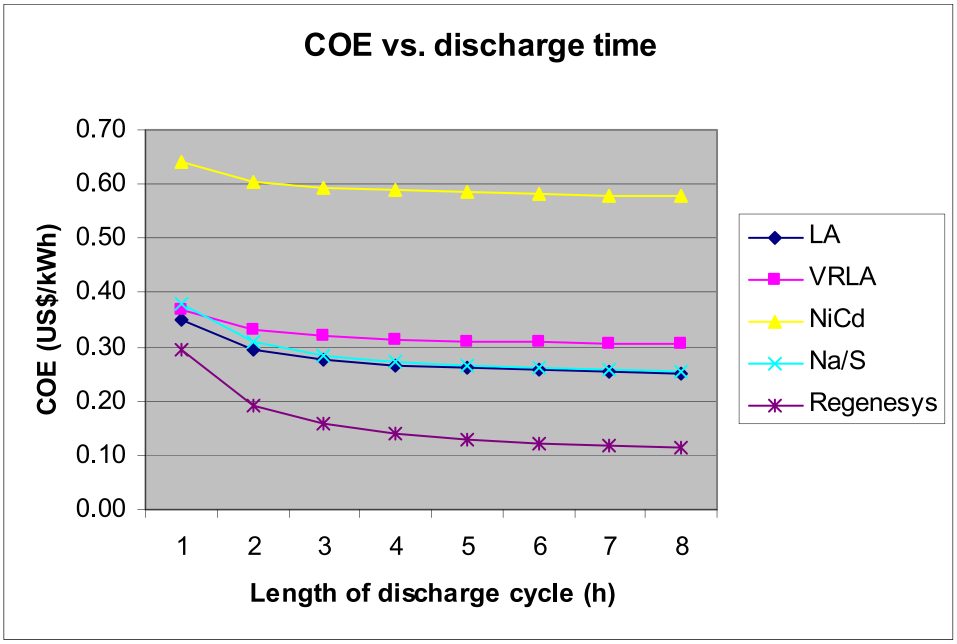

Fig. 4-9: COE vs. length of discharge cycle, Case 5, 200MW, 250 cycles/year.

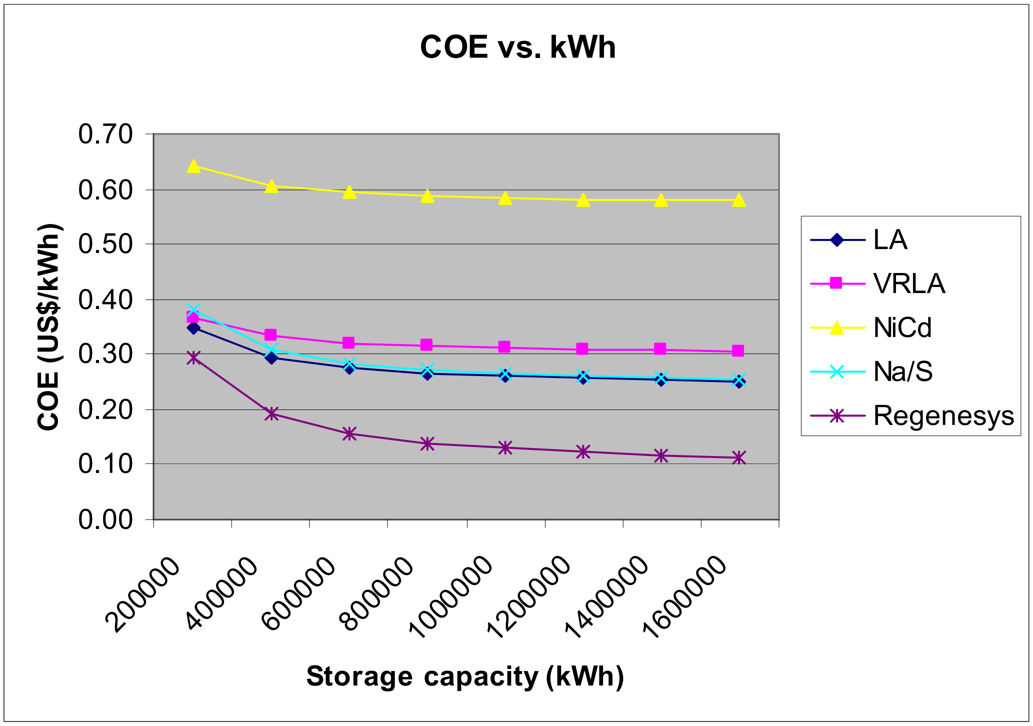

Fig. 4-10: COE vs. storage capacity (kWh), Case 5, 200MW, 250 cycles/year.

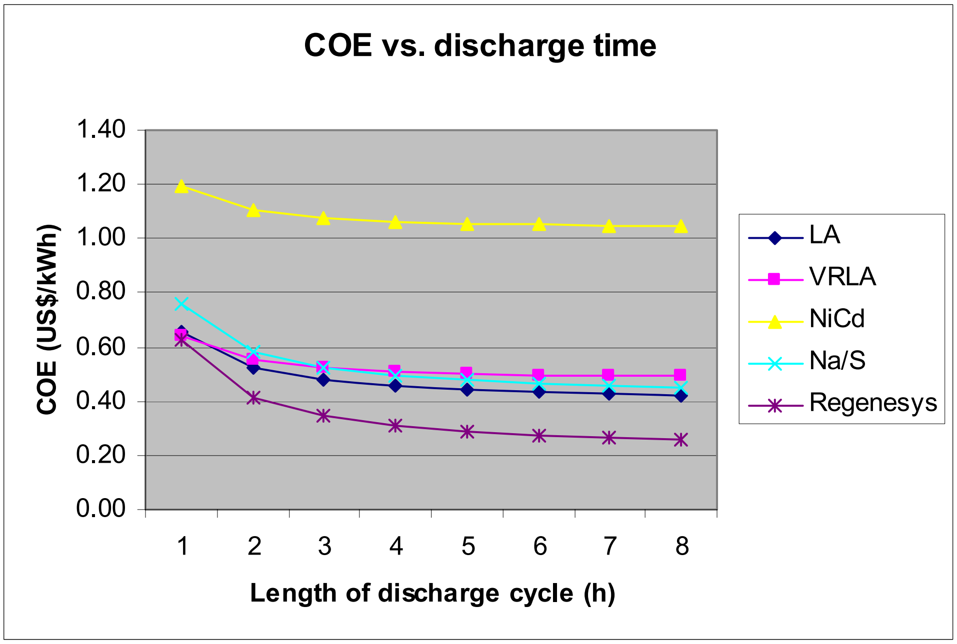

Fig. 4-11: COE vs. length of discharge cycle, Case 6, 200MW, 100 cycles/year.

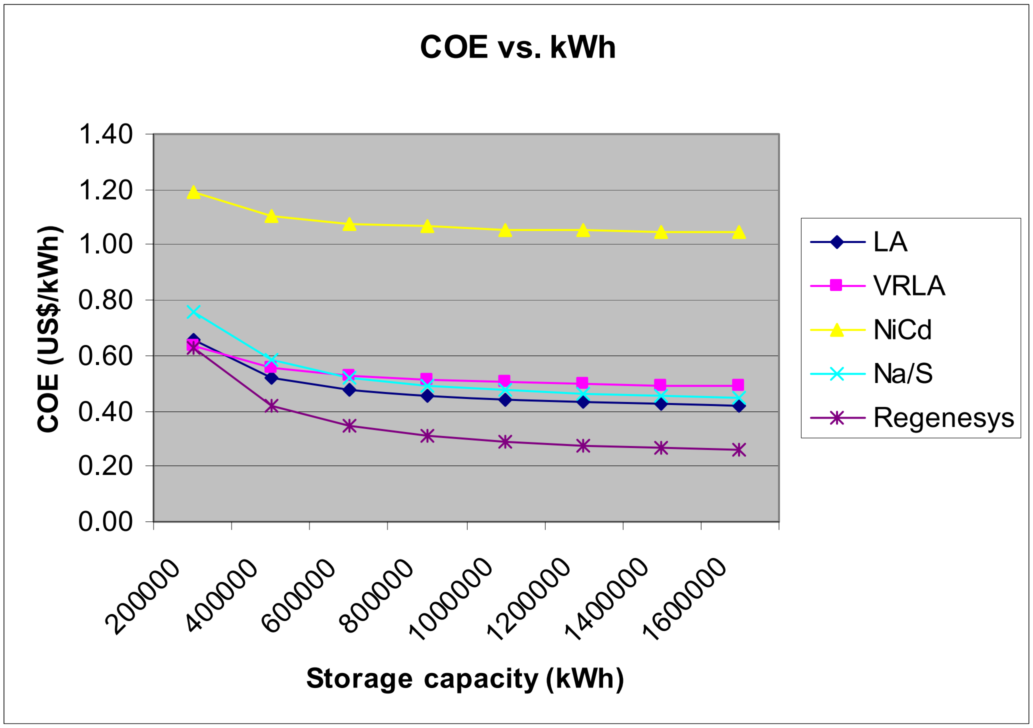

Fig. 4-12: COE vs. storage capacity (kWh), Case 6, 200MW, 100 cycles/year

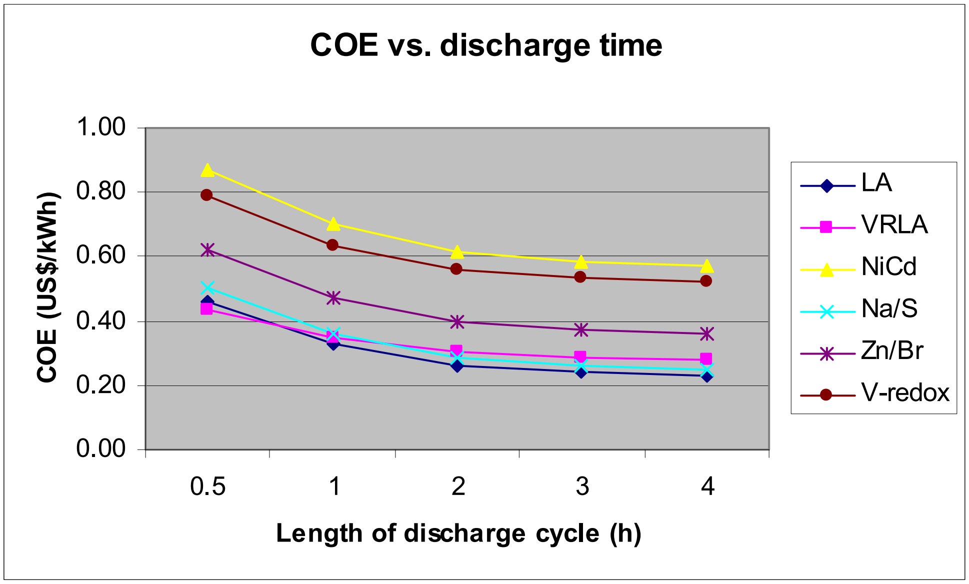

Fig. 4-13: COE vs. length of discharge cycle, Case 7, 2.5MW, 250 cycles/year.

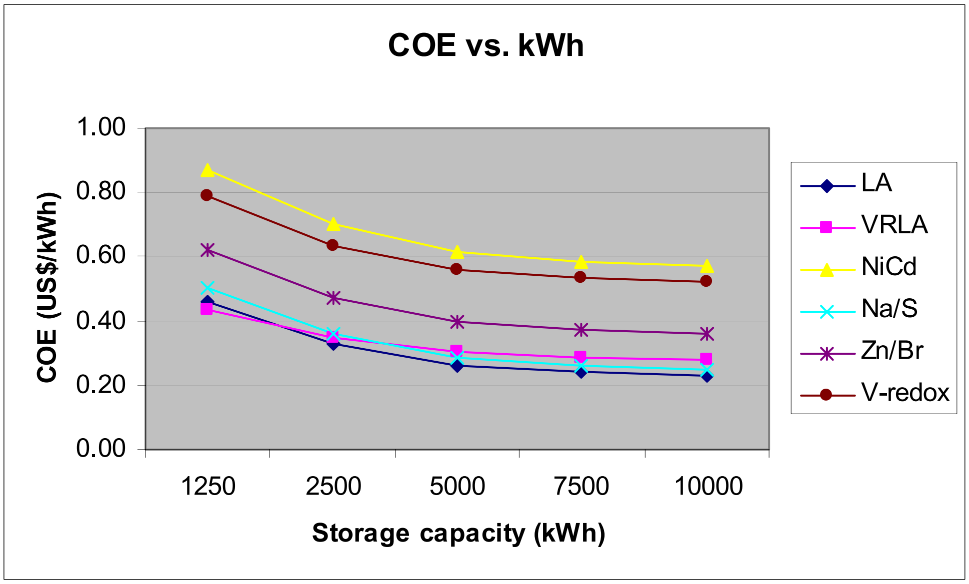

Fig. 4-14: COE vs. storage capacity (kWh), Case 7, 2.5MW, 250 cycles/year

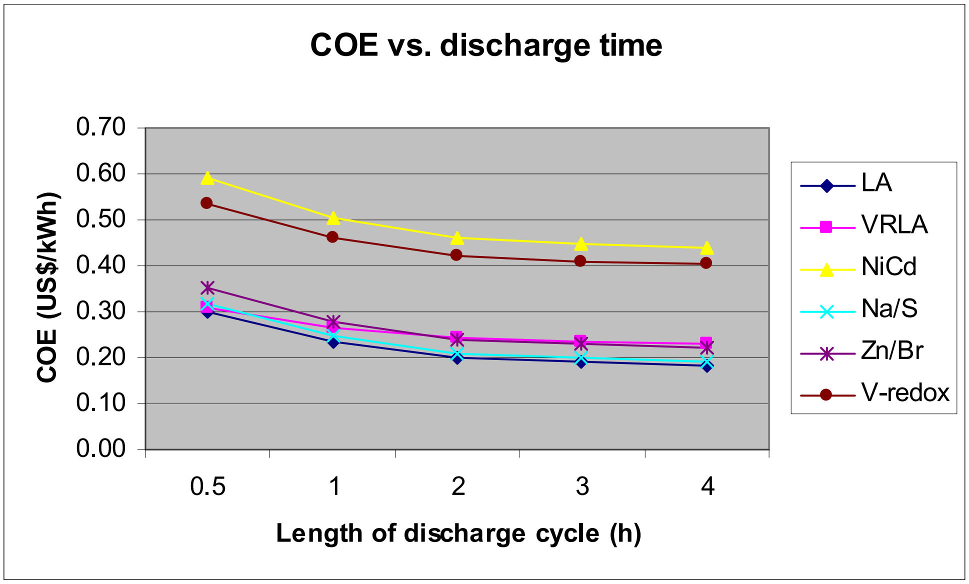

Fig. 4-15: COE vs. length of discharge cycle, Case 8, 2.5MW, 500 cycles/year.

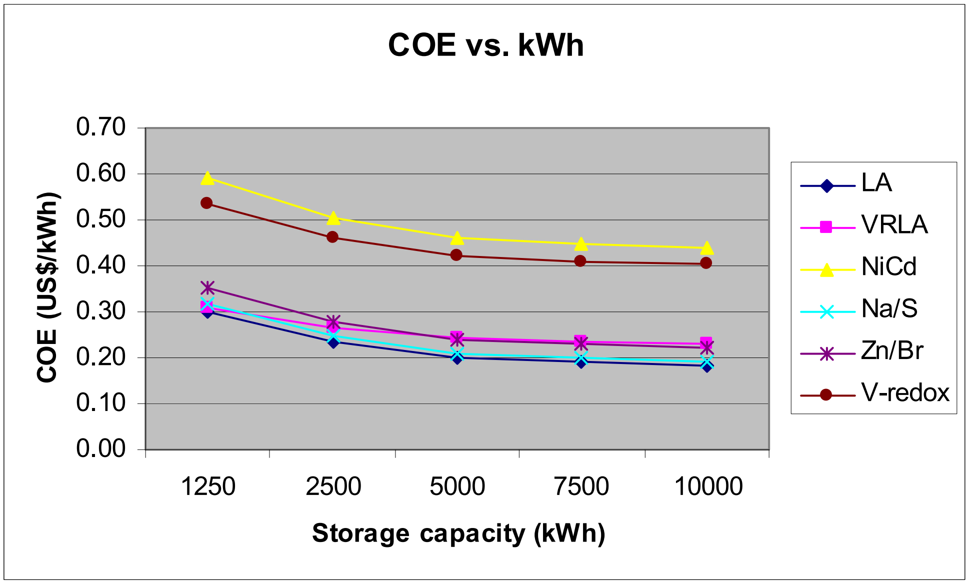

Fig. 4-16: COE vs. storage capacity (kWh), Case 8, 2.5MW, 500 cycles/year

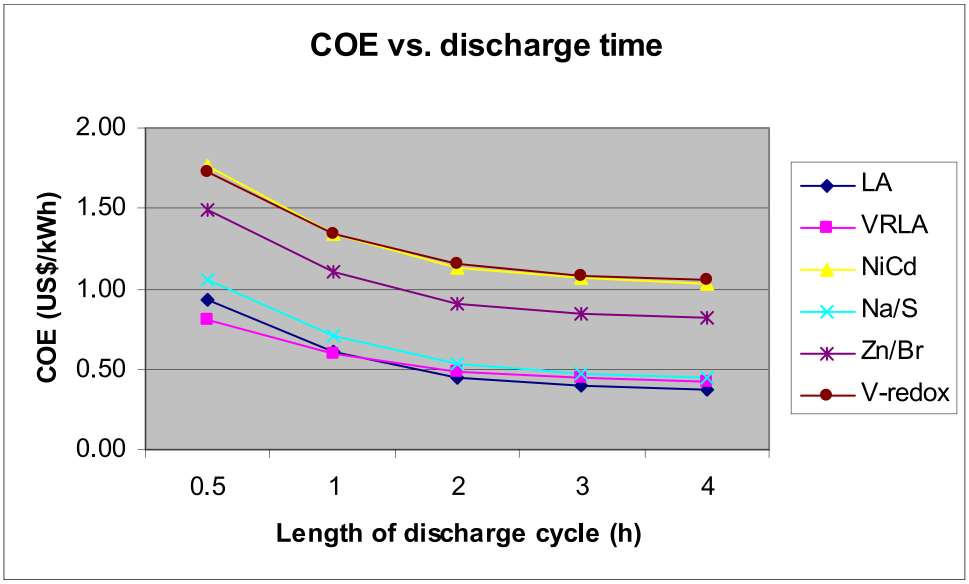

Fig. 4-17: COE vs. length of discharge cycle, Case 9, 2.5MW, 100 cycles/year.

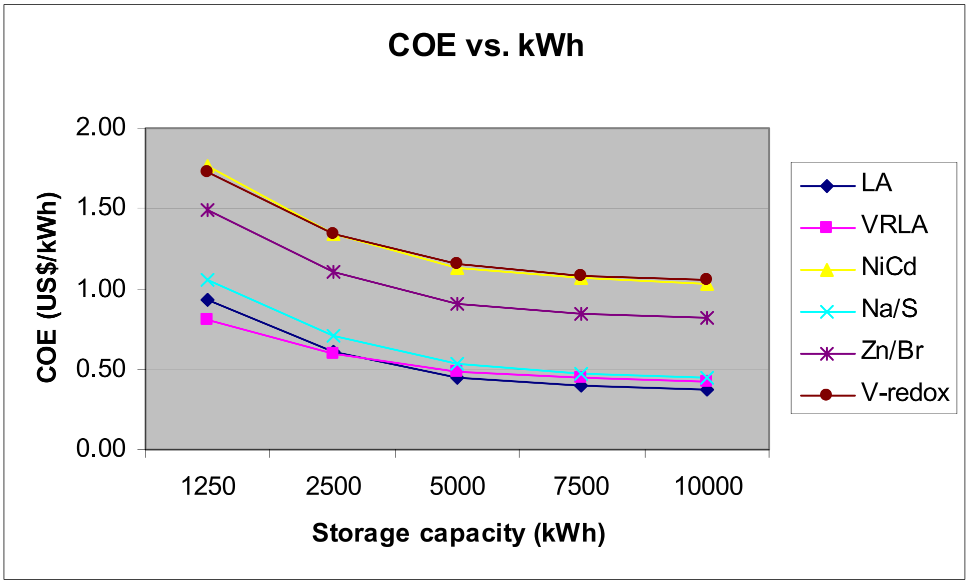

Fig. 4-18: COE vs. storage capacity (kWh), Case 9, 2.5MW, 100 cycles/year

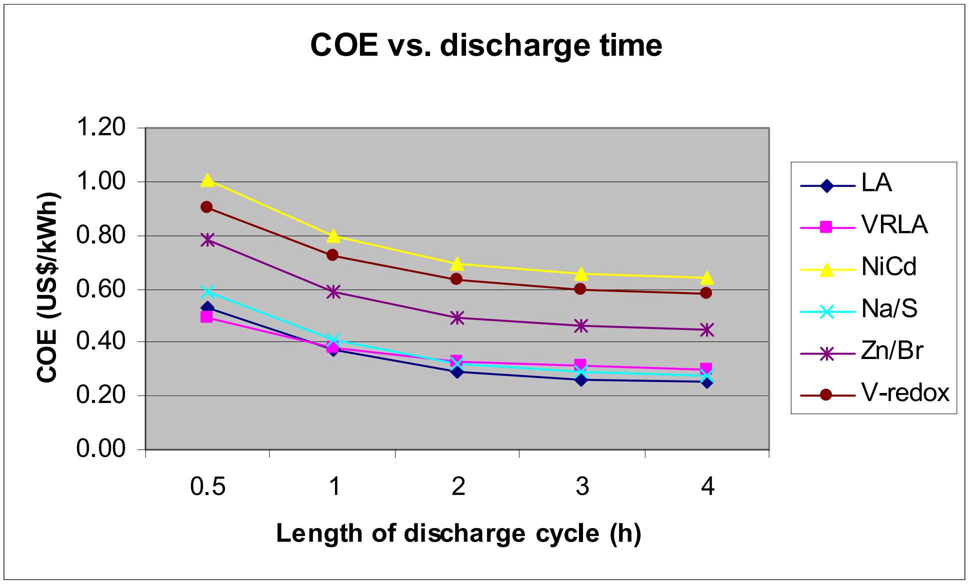

Fig. 4-19: COE vs. Length of discharge cycle, Case 10, 2.5MW, 200 cycles/year.

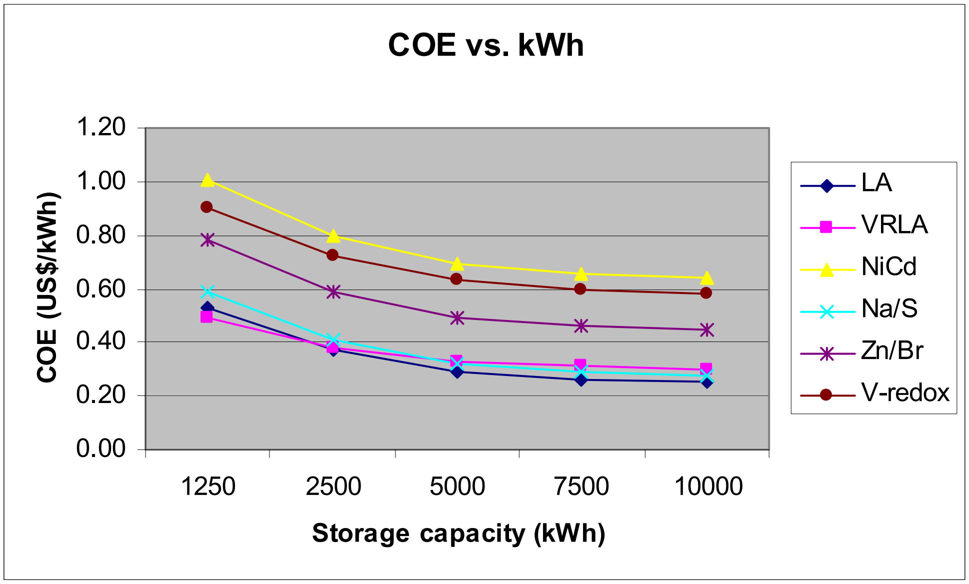

Fig. 4-20: COE vs. storage capacity (kWh), Case 10, 2.5MW, 200 cycles/year

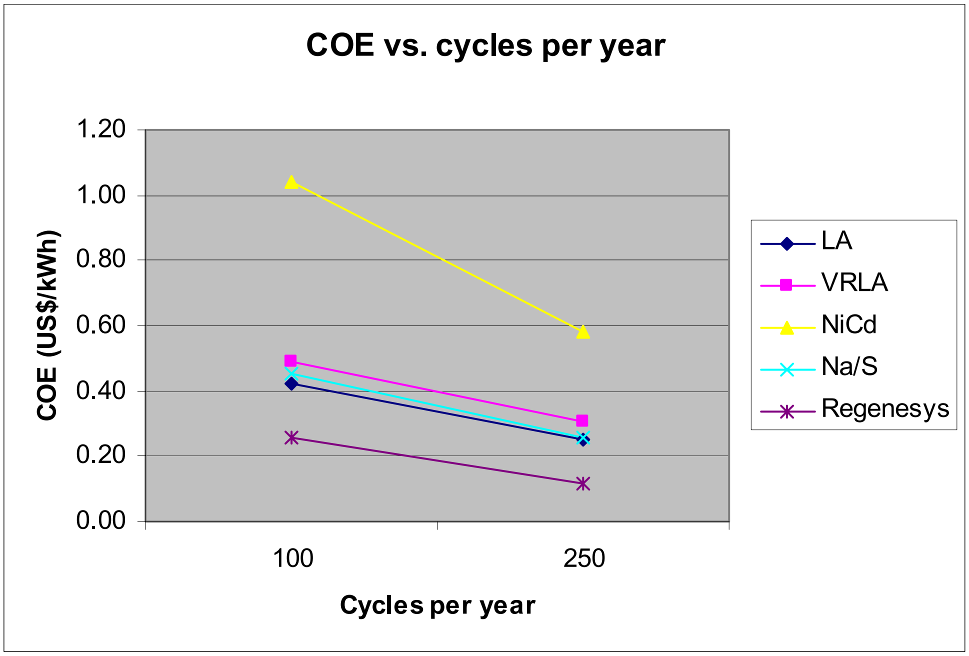

Fig. 4-21: COE vs. cycles per year, 10MW, 80MWh

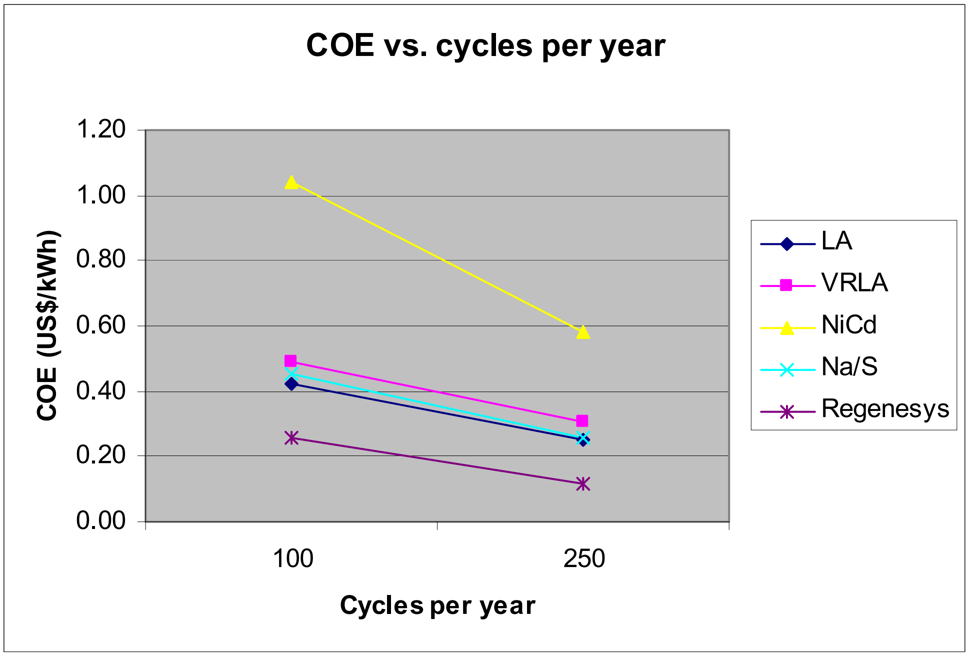

Fig. 4-22: COE vs. cycles per year, 25MW, 200MWh

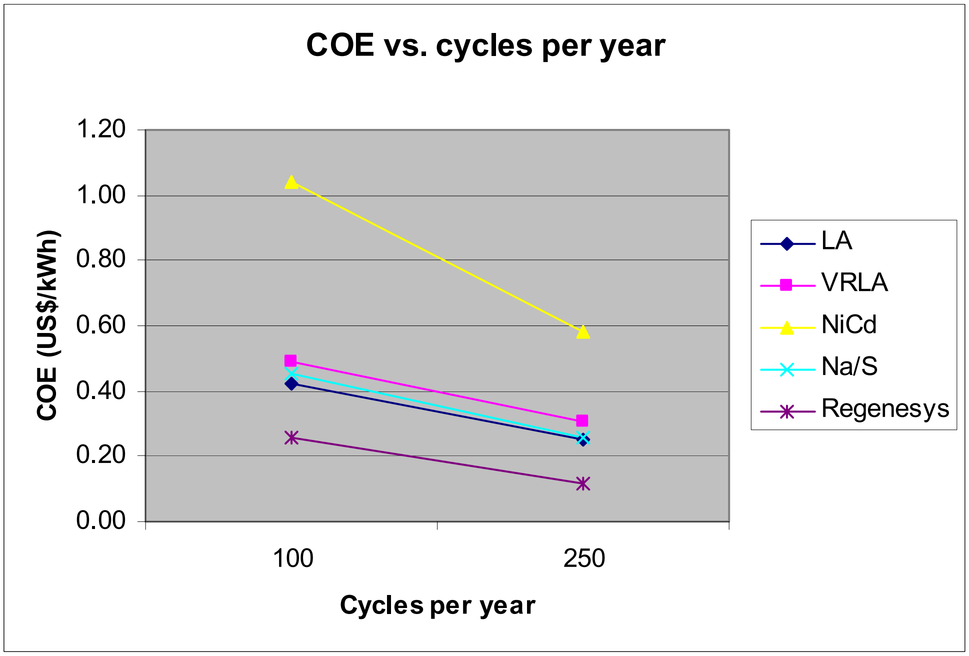

Fig. 4-23: COE vs. cycles per year, 200MW, 1600MWh

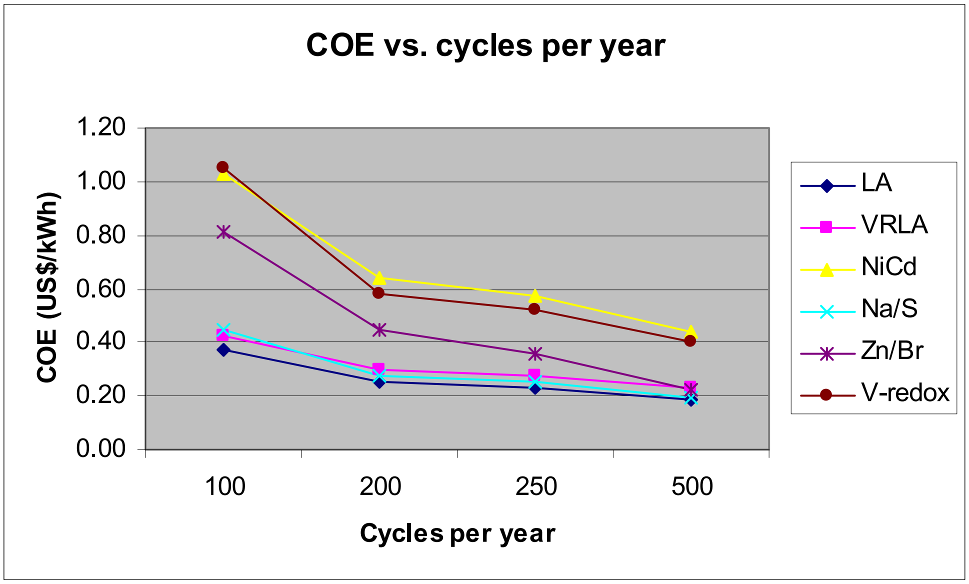

Fig. 4-24: COE vs. cycles per year, 2.5MW, 10MWh

4.2.2 Annual costs

The annualized costs for each study case are presented in figure 24 through 35. The annual capital cost, operation and maintenance cost and replacement costs are also shown in the plots. The annual costs for generation applications are calculated assuming an eight h discharge time. For transmission and distribution applications, the calculation of annual costs is based on four h discharge time.

The graphs of annual costs show the components of the costs for each storage technology, for a system designed for a certain power capacity and annual days of use. The graphs indicate that as system power capacity increases, annual cost increases. This is due to increased capital cost for the additional capacity. According to the graphs, the capital cost is the most significant component of annual costs.

The graphs also show that as cycles per year increase, the annual replacement cost increases. This is due to the life of storage units being defined by total cycles. The annual replacement cost is a significant cost when operating cycles per year increases.

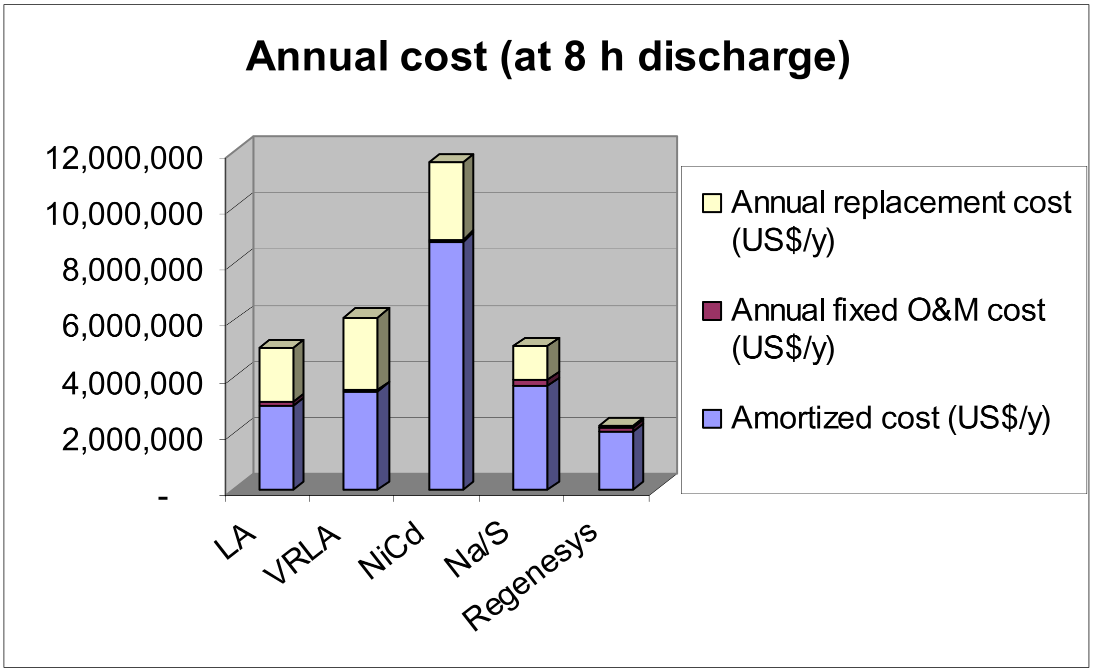

Fig. 4-25: Annual cost of storage, Case 1, 10MW, 80MWh, 250 cycles/year.

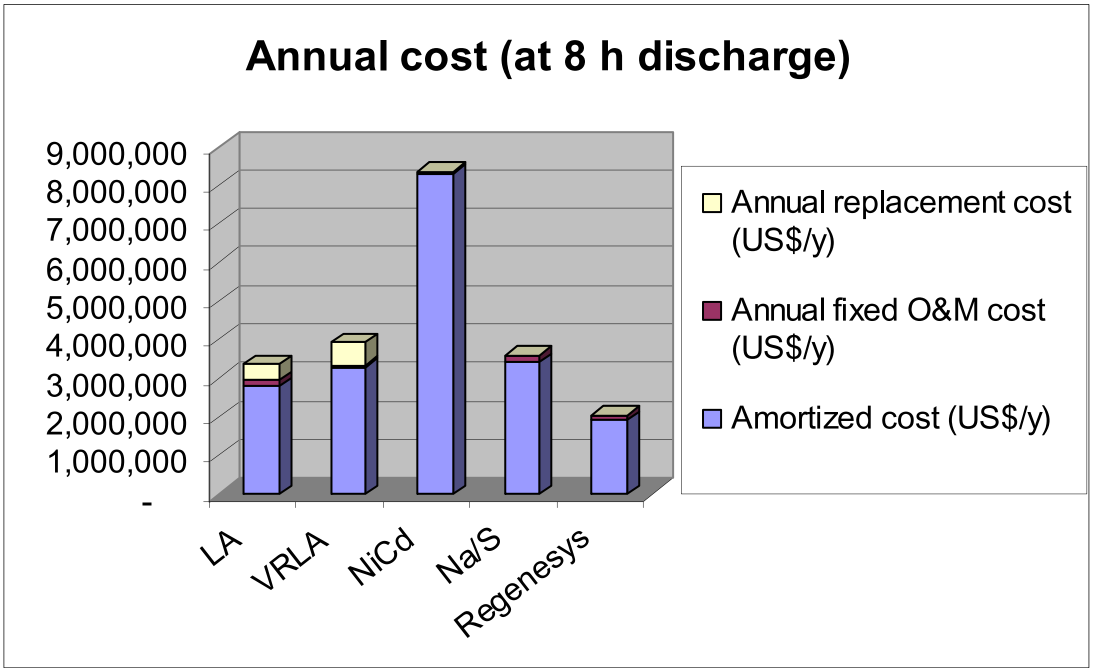

Fig. 4-26: Annual costs of storage, Case 2, 10MW, 80MWh, 100 cycles/year.

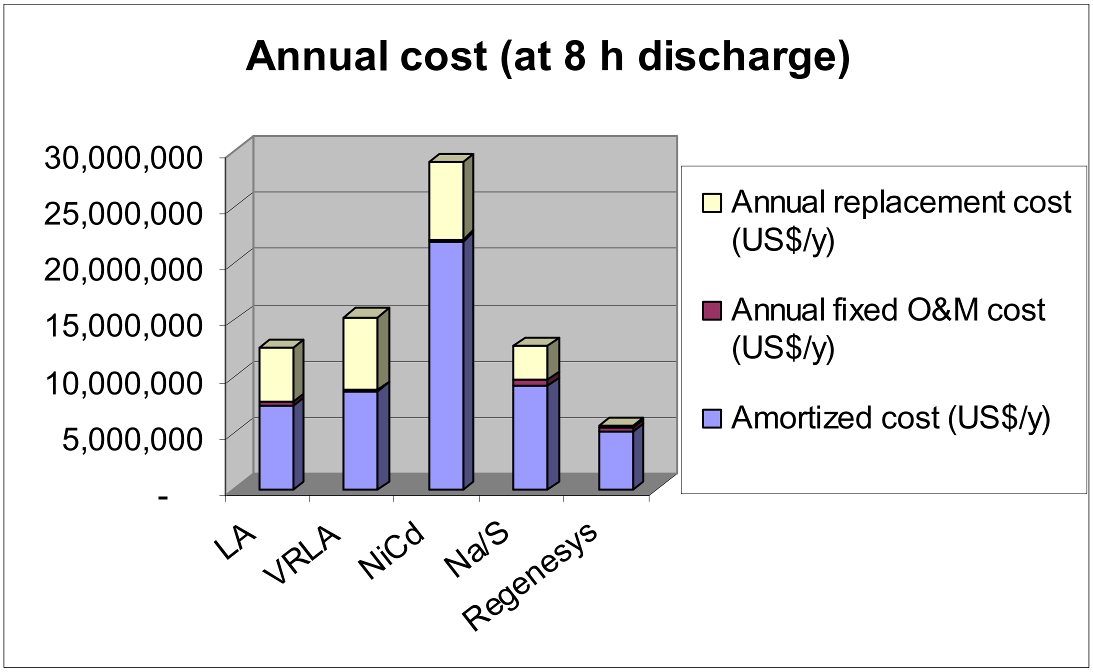

Fig. 4-27: Annual costs of storage, Case 3, 25MW, 200MWh, 250 cycles/year.

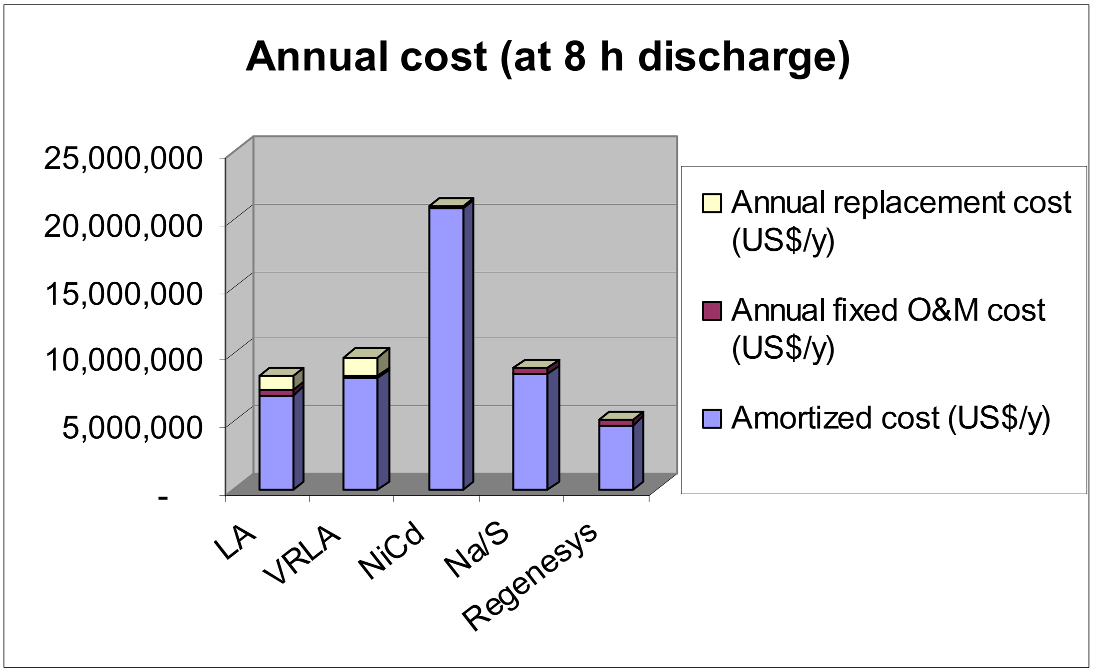

Fig. 4-28: Annual costs of storage, Case 4, 25MW, 200MWh, 100 cycles/year.

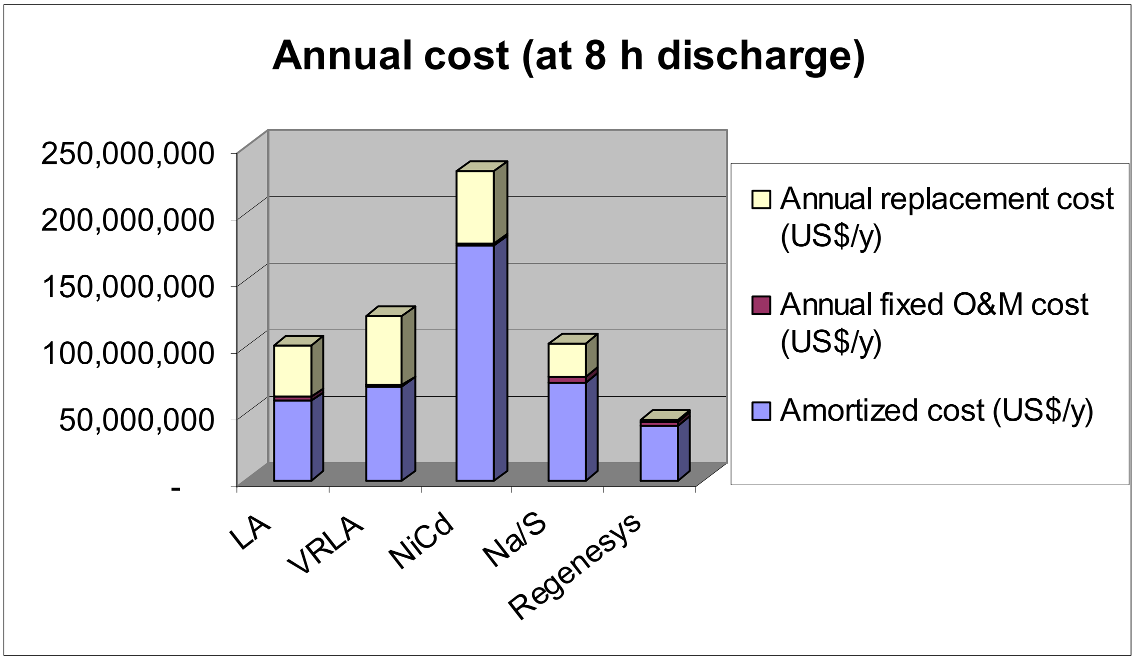

Fig. 4-29: Annual costs of storage, Case 5, 200MW, 1600MWh, 250 cycles/year.

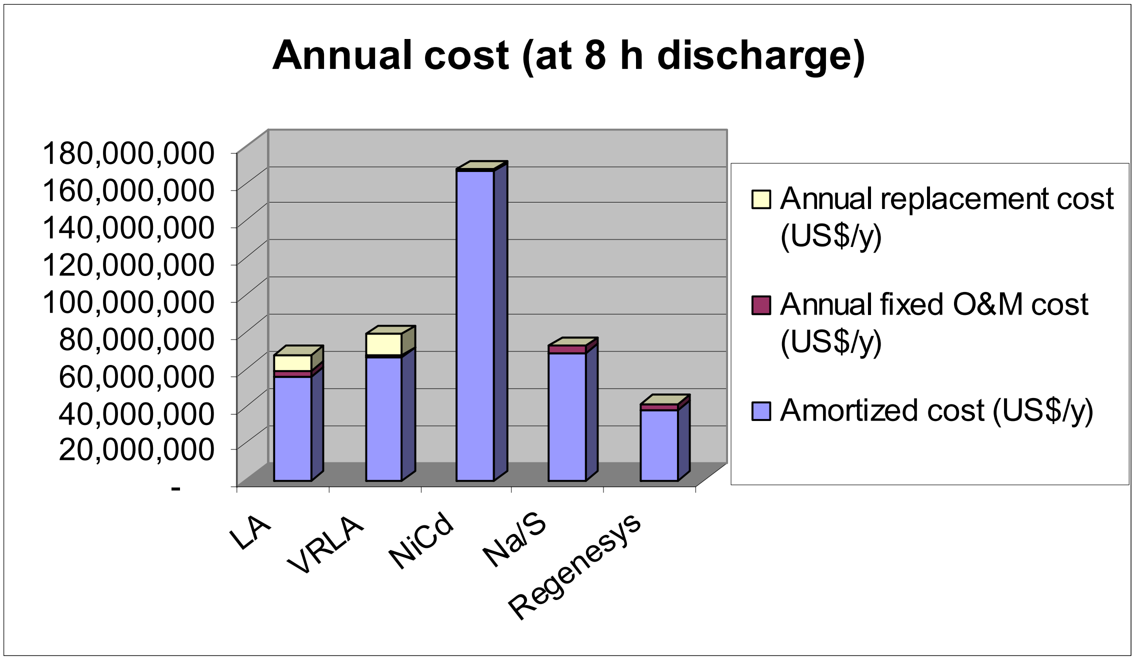

Fig. 4-30: Annual costs of storage, Case 6, 200MW, 1600MWh, 100 cycles/year.

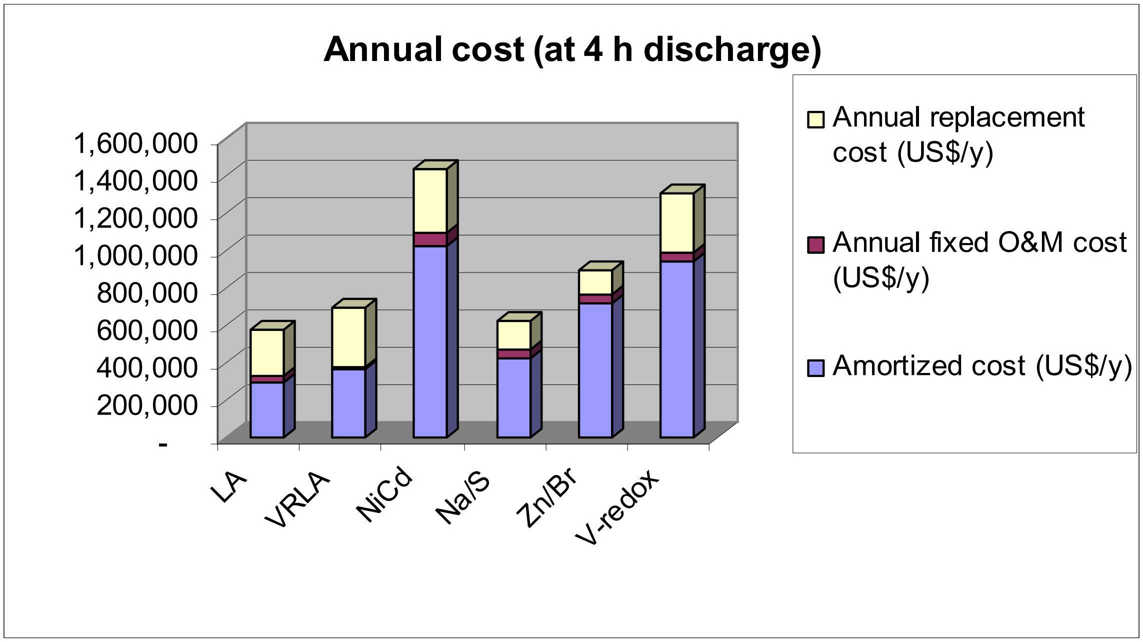

Fig. 4-31: Annual costs of storage, Case 7, 2.5MW, 10MWh, 250 cycles/year.

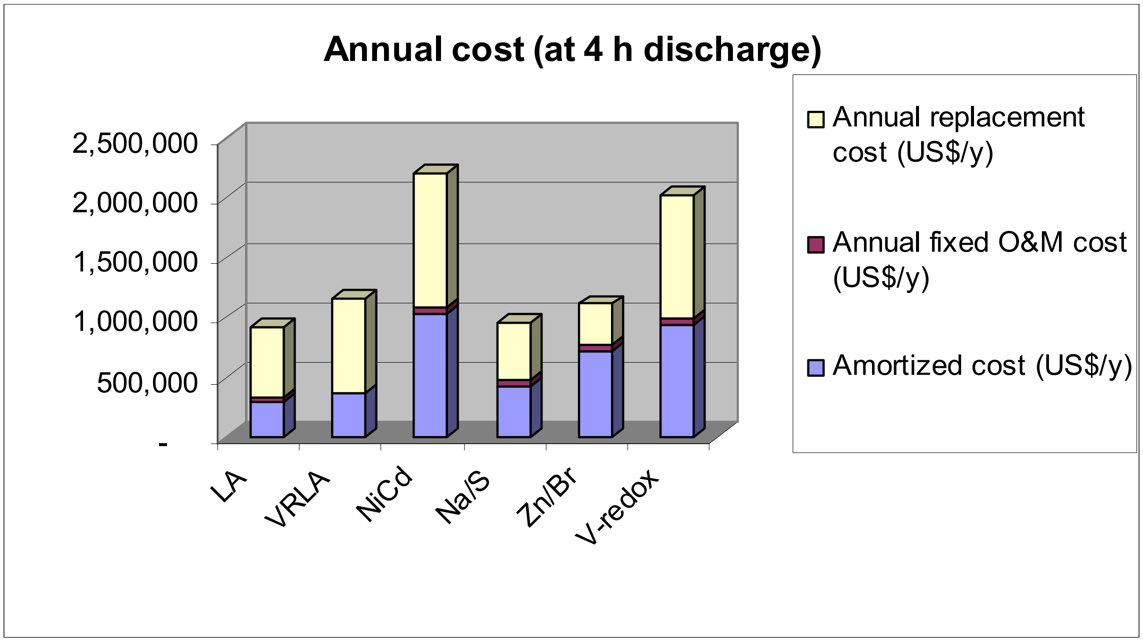

Fig. 4-32: Annual costs of storage, Case 8, 2.5MW, 10MWh, 500 cycles/year.

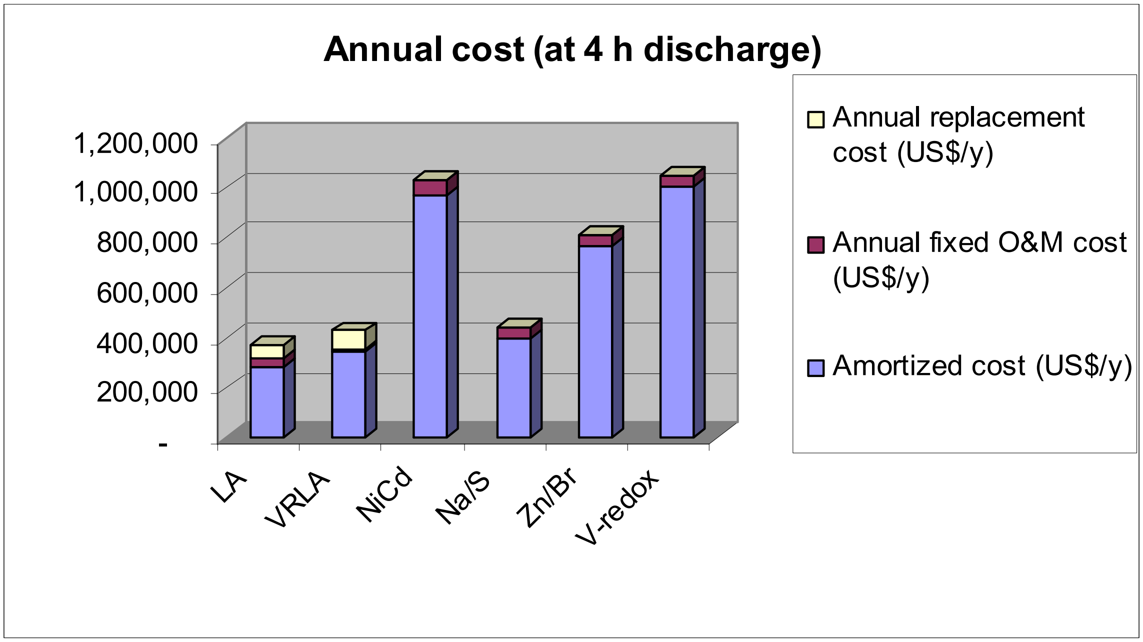

Fig. 4-33: Annual costs of storage, Case 9, 2.5MW, 10MWh, 100 cycles/year.

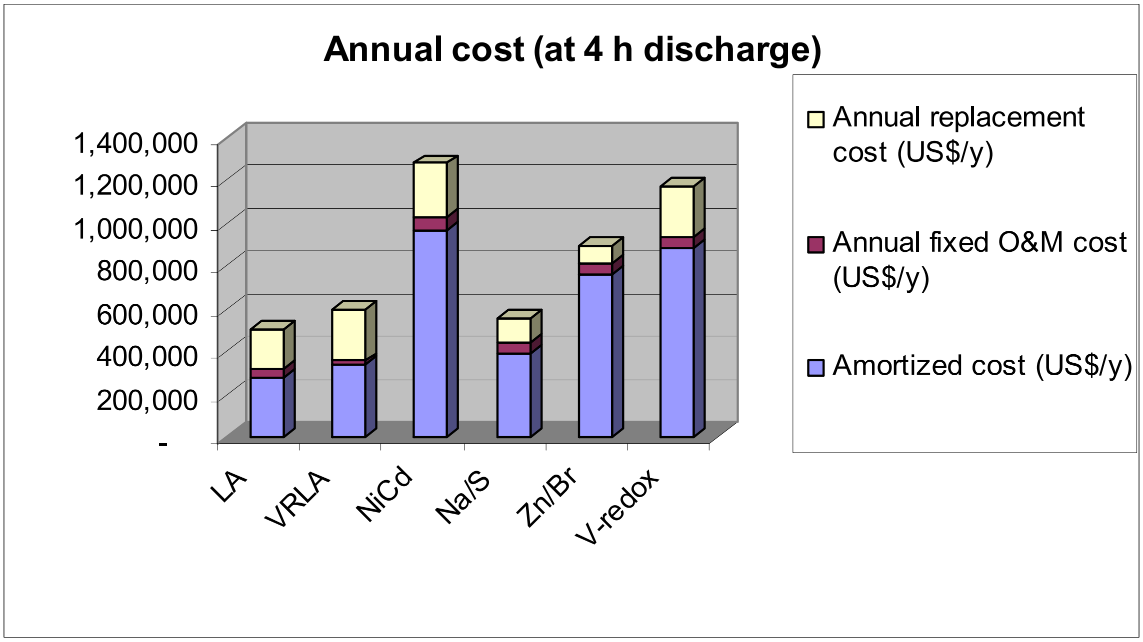

Fig. 4-34: Annual costs of storage, Case 10, 2.5MW, 10MWh, 200 cycles/year.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

The section 4 graphs show that a battery storage system designed to operate 250 d/y with an 8 h charge/discharge cycle add about US$ 0.10 to US$ 0.30 to the cost of electricity. A system that charges and discharges twice a day on a 4 h cycle adds about US$ 0.20 to US$ 0.40. With North American wholesale electricity prices now in the range of 0.05 – 0.16 US$/kWh [10], it appears that battery energy storage will more than double the wholesale cost of electricity, which will be difficult to justify for most applications at current battery prices.

Similarly, a system designed to operate only during peak seasons, 100 d/y, on one 8 h cycle, adds about US$ 0.25 to US$ 0.50 to each kWh stored. A system that charges and discharges twice a day on a 4 h cycle adds about US$ 0.25 to US$ 0.60 to each kWh stored.

From the comparison with wholesale electricity prices, it appears that the cost of electricity storage systems needs to drop by 50% or more of its present cost, before it will be useful for widespread load-leveling use. Additional cost of energy, however, is only one component of the economic justification for storage. Other issues, such as deferral of transmission and generation facilities, must be considered in a complete economic analysis. Market design, and how markets will treat stored energy, must also be considered. These will be included in future work.

This thesis has also produced a tool that will calculate COE for any energy storage system based on the Section 3 design parameters. The tool is in the form of a spreadsheet. Examples of the form are included in Appendix A.

It is clear that some parameters have highly affected on the cost of electricity (COE). Parameters of operating condition such as number of discharge cycle per day and operating days per year are important factors that lead to variation of COE.

The replacement period have a crucial impact on replacement costs. A designer of the storage should make sure the replacement period is proportional to the life of the storage that is based on life of power electronic (power conversion system) and balance of plant.

According to the results, operation and maintenance cost is the least significant component when compared with capital cost and replacement cost.

In this study, the most cost effective technology of studied technologies for generation applications is sodium bromide/sodium polysulfide flow batteries. For transmission and distributions, the most cost effective technology is Lead-Acid batteries.

However when costs of storage are reduced, storage will play an important rule in solving many problems in electrical power systems including those of utilities, end-users and renewable energy resources. Clearly, profits can be made from storage in many applications.

5.2 Future Works

The future studies should include:

5.2.1 Perform sensitivity analysis to determine the impact of each input variation. Combine this with a study of various control protocols to optimize the section 3 design parameters.

5.2.2 Incorporate additional energy storage technologies such as flywheels, electrochemical capacitors (“super” or “ultra” capacitors) and other battery energy storages in order to determine the most promising storage technologies for each application.

5.2.3 Investigate and update the energy storage technologies including unit cost of storage unit since the development of storage technologies is dramatically progressive.

5.2.4 Consider levelization factor and taxes.

5.2.5 Expand the economic analysis to include the other benefits of electricity storage, and the effects of electricity market design on storage.

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APPENDICES

Appendix A: Spreadsheet

Economic Factors and Operation Assumptions

i_r	Interest rate	0.0876
D	Annual operating days (days per year)	250
n	number of charge/discharge cycles per day	1
Ho	Length of each discharge cycle (h)	8
n*Ho	Total discharge time (h per day)	8
n*D	Number of charge/discharge cycles per year	250

	Parameters	LA	VRLA	NiCd	Na/S	Regenesys
P	Rated output(kW)	10,000	10,000	10,000	10,000	10,000
E	Rated energy capacity(kWh)	80,000	80,000	80,000	80,000	80,000
eff	Efficiency	0.75	0.75	0.65	0.7	0.65
PECU	Unit Cost for Power Electronics (US$/kW)	125	125	125	150	275
PEC	Total Cost for Power Electronics (US$)	1,250,000	1,250,000	1,250,000	1,500,000	2,750,000
SUCU	Unit Cost for Storage (US$/kWh)	150	200	600	250	100
SUC	Total Cost for Storage (US$)	16,000,000	21,333,333	73,846,154	28,571,429	12,307,692
BOPU	Unit Cost for Balance of Plant (US$/kWh)	150	150	150	50	50
BOP	Total Cost for Balance of Plant (US$)	12,000,000	12,000,000	12,000,000	4,000,000	4,000,000
TCC	Total capital cost (US$)	29,250,000	34,583,333	87,096,154	34,071,429	19,057,692
OM_f	Fixed O&M cost(US$/kW-y)	15	5	5	20	15
C	Number of charge/discharge cycles in life	1500	1500	3000	2500	2500
r	Calculated replacement period(y)	6	6	12	10	10
F	Future storage replacement cost (US$/kWh)	150	200	600	230	150
						(US$/kW)
	Rated storage capacity (kWh)	106,667	106,667	123,077	114,286	123,077
AEP	Annual energy production (kWh)	20,000,000	20,000,000	20,000,000	20,000,000	20,000,000
y	Life of Storage System (y)	24	24	24	20	20
CRF	Capital recovery factor	0.10	0.10	0.10	0.11	0.11
A	Annual amount of replacement cost(US$/kWh)	18.04	24.05	22.14	10.69	6.97
AC	Amortized cost (US$/y)	2,956,291	3,495,330	8,802,789	3,668,787	2,052,119
OMC	Annual fixed O&M cost (US$/y)	150,000	50,000	50,000	200,000	150,000
ARC	Annual replacement cost (US$/y)	1,924,117	2,565,489	2,724,701	1,222,250	69,748
COE	Cost of Electricity (US$/kWh)	0.25	0.31	0.58	0.25	0.11