Evaluation of Flow Battery Technology: An Assessment of Technical and Economic Feasibility

by

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Abstract:

Energy storage has been a topic of recent political discussions. There is interest in utilizing energy storage technologies to improve the emissions and "green" the environment. Many of the energy storage technologies have been around for many decades; however, there is often little research done into the analysis of the economic and technical feasibility of these technologies. This study aims to assess the feasibility of flow batteries for both large and small scale energy storage applications.

Applications for larger scale storage must meet the price point set out by utilities of \$1000/kW all inclusive. Additionally, getting prices below \$200/kWh is important in order to have a technology be likely to receive attention and interest from utilities and larger companies. This study breaks down the cost of the Zinc Bromine flow battery in order to assess the current cost and predictions for the future.

In addition to assessing the cost, this study analyses the performance of the Zinc Bromine battery and determines for which applications and markets the Zinc Bromine battery is best suited.

Supervisor: Professor Donald R. Sadoway

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CONTENTS

ACKNOWLEDGEMENTS **5**

CONTENTS **7**

LIST OF FIGURES **9**

CHAPTER 1 – INTRODUCTION **10**

1.1 MOTIVATION FOR RESEARCH 11

CHAPTER 2 – TECHNOLOGY INTRODUCTION **14**

2.2 REDOX FLOW BATTERIES 15
2.2.1 True Redox Flow Batteries *17*
2.2.2 Hybrid Redox Flow Batteries *17*
2.3 REDOX COUPLES 17
2.4 FLOW BATTERY CHEMISTRIES 19
2.4.1 Zinc Bromine Chemistry *19*
2.4.2 Vanadium Vanadium Chemistry *19*
2.4.3 Iron Chromium Chemistry *20*
2.4.4 Polysulfide Bromide Chemistry *21*
2.4.5 Zinc Chlorine Chemistry *21*
2.4.6 Vanadium Bromine Chemistry *22*

CHAPTER 3 – ZINC BROMINE BATTERY **23**

3.1 CELL COMPONENTS 23
3.1.1 Electrolyte *24*
3.1.2 Electrode *25*
3.1.3 Membrane Separator *26*
3.1.4 Pumps and Flow Meters *27*
3.1.5 Pipes *28*
3.1.6 Frame *30*
3.1.7 End-Plates *31*
3.2 PERFORMANCE CHARACTERISTICS 31
3.2.1 Current Density *32*
3.2.2 Energy Density *33*
3.2.3 Efficiency *33*
3.2.4 Lab Testing *34*
3.3 BATTERY SYSTEMS 35
3.3.1 Cell Stacks *36*
3.3.2 System Size *36*
3.4 CHALLENGES OF TECHNOLOGY 37
3.5 HEALTH AND ENVIRONMENTAL IMPACT 38
3.6 TECHNOLOGY SUMMARY 40

CHAPTER 4 – COST EVALUATION **42**

4.1 ZINC BROMINE COST MODEL 42
4.1.1 Assumptions *43*
4.2 COMPONENT COST 44
4.2.1 Electrolyte *44*
4.2.2 Tank *44*
4.2.3 Electrode *45*
4.2.4 Membrane *46*
4.2.5 Pumps and Flow Meters *47*
4.2.6 Pipes *48*
4.2.7 Frame *49*

4.3 LABOR COST 49
4.4 OVERHEAD COST 49
4.5 TRANSPORTATION COST 50
4.6 ADDITIONAL COSTS 50
4.6.1 Inverter *51*
4.6.2 Power Electronics *52*
4.6.3 Control System *52*
4.7 MODEL OF 1MW BATTERY SYSTEM 52
4.7.1 Breakdown of Cost *53*
4.7.2 Key Cost Drivers *55*
4.8 POWER CAPACITY VARIATION 56
4.9 ENERGY CAPACITY VARIATION 57
4.10 SENSITIVITY ANALYSIS 60
4.11 COST SUMMARY 61

CHAPTER 5 – APPLICATIONS AND MARKETS 62

5.1 SMALL-SCALE APPLICATIONS 63
5.1.1 Off-Grid and Micro-Grid Support *63*
5.1.2 Lawnmower and Golf Carts *64*
5.1.3 Electric Wheelchairs, Trams and Scooters *67*
5.2 LARGE-SCALE APPLICATIONS 68
5.2.1 Wholesale Electricity Markets *68*
5.2.2 Renewable Energy Stabilization *72*

CHAPTER 6 – COMPETING TECHNOLOGIES 75

6.1 COMPARISON OF TECHNOLOGIES 75

CHAPTER 7 – INTELLECTUAL PROPERTY 78

7.1 PATENTS 78
7.1.1 Zinc Bromine Electrolyte Patents *79*
7.1.2 Zinc Bromine Device Patents *80*
7.1.3 Important Flow Battery Patents *81*
7.2 COMPETITORS IN SPACE 81
7.2.1 Zinc Bromine Battery Companies *81*
7.2.2 Other Redox Flow Battery Companies *82*

CHAPTER 8 – TECHNOLOGY ROADMAP 85

8.1 PROOF OF TECHNOLOGY 85
8.2 FUTURE PROJECTIONS 86

CHAPTER 9 – CONCLUSION 88

REFERENCES 89

APPENDIX 91

COST MODEL FOR A 100KW/3HR ZINC BROMINE BATTERY SYSTEM 91

LIST OF FIGURES

FIGURE 2.1: DIAGRAM OF FLOW BATTERY. A.) FULLY DISCHARGED FLOW BATTERY, B.) PARTIALLY CHARGED FLOW BATTERY, C.) FULLY CHARGED FLOW BATTERY.......17

FIGURE 2.2: REDOX REACTIONS FOR POTENTIAL FLOW BATTERY CHEMISTRIES[4, 5]18

FIGURE 3.1: ANALYSIS OF SUPPORTING ELECTROLYTE IN A ZINC BROMINE SYSTEM 35

FIGURE 3.2 – DIMENSIONS OF ZINC BROMINE BATTERY SYSTEMS 37

FIGURE 4.1: PRICE PROJECTIONS FOR NAFION BASED ON ANNUAL DEMAND[6].............47

....51

FIGURE 4.2 – PERCENTAGE OF SYSTEM COST FROM INVERTERS FOR 5 HOUR SYSTEMS OF VARIOUS POWER CAPACITIES..52

FIGURE 4.3: BREAKDOWN OF COSTS FOR 1 MW ZINC BROMINE BATTERY SYSTEMS....54

FIGURE 4.4: BREAKDOWN OF PERCENTAGE OF COST FROM EACH COMPONENT IN 1 MW ZINC BROMINE SYSTEMS 54

FIGURE 4.5: PERCENTAGE OF TOTAL COST FROM KEY COST DRIVERS IN A 1 MW/5HR ZINC BROMINE BATTERY SYSTEM...56

....57

FIGURE 4.6: TABLE OF COST FOR 5 HOUR SYSTEMS OF 1KW, 10KW, 100KW, AND 1MW.57

FIGURE 4.7: BREAKDOWN OF THE COST OF A 1 MW/2HR ZINC BROMINE BATTERY SYSTEM 58

FIGURE 4.8: BREAKDOWN OF THE COST OF A 1 MW/10HR ZINC BROMINE BATTERY SYSTEM 59

FIGURE 4.9: RELATIONSHIP BETWEEN COST PER KWH AND THE ENERGY CAPACITY OF ZINC BROMINE SYSTEMS 60

FIGURE 5.1: COMPARISON OF LEAD ACID AND ZINC BROMINE BATTERY COSTS...........65

FIGURE 5.2: COMPARISON OF CYCLE COST BETWEEN LEAD ACID AND ZINC BROMINE BATTERIES...66

FIGURE 5.3: LIST OF THE WHOLESALE ELECTRICITY MARKETS WORLDWIDE..............71

FIGURE 5.4: AVERAGE DIFFERENCE BETWEEN WHOLESALE PEAK AND OFF-PEAK PRICES FROM VARIOUS REGIONS WORLDWIDE..71

FIGURE 5.5: GROWTH OF INSTALLED WIND CAPACITY WORLDWIDE FROM 1995 TO 2007 [25] 73

FIGURE 5.6: CURRENT PERCENTAGE OF TOTAL ELECTRICITY PRODUCTION FROM WIND...74

FIGURE 6.1: COMPARISON OF COST AND STORAGE CAPACITY OF ENERGY STORAGE TECHNOLOGIES (* NOT INCLUDING PCS COSTS) [26]...76

FIGURE 6.2: CYCLE-LIFE AND EFFICIENCY OF ENERGY STORAGE TECHNOLOGIES [27] 77

CHAPTER 1 – INTRODUCTION

Recently energy has been a topic receiving attention from politicians, corporations, and citizens alike. Energy security, energy conservation, and clean energy production are all topics of interest both in the United States and globally. Concern for energy security has given rise to the promotion of alternative liquid fuel and electric vehicle research. Energy conservation promotion has lead to campaigns promoting conservation at the personal level through the national level. Rising concerns for the environment and the climate has caused research and demand for renewable energy to increase drastically in the past few years. In order to succeed in producing clean power, reducing energy consumption, and have energy security, energy storage will play a large role. Energy storage allows intermittent power sources to be reliable and surplus energy to be stored until demanded.

This study examines flow battery technology in order to assess the feasibility of the technology succeeded in entering the market. Flow battery technology was invented in the 1970's; however, it was not until the recent concern and interest in energy solutions that the technology has begun to get traction. Recently, a few companies have formed and some have begun to manufacture flow battery systems.

Increasing installations of wind and solar power have also contributed to the interest in the energy storage space. Renewable power, specifically wind and solar photovoltaics, are highly unreliable and have large fluctuations in power output throughout each day. Fluctuations in power outputs makes wind and solar only capable of being supplemental to the grid. Electricity providers cannot rely on solar or wind due to the variations, neither technology is a reliable power source. Connecting the wind and solar farms to a large-scale energy storage device will enable these power sources to be reliable. Flow batteries or other large storage technologies are capable of storing surplus power and distributing it back on the grid during deficits in power.

Flow batteries are unique from other battery technologies because the power and energy capacity are independent. Flow batteries can store between 1 hour and 10 hours of energy. The power capacity of flow batteries ranges between 1kW and tens of MWs. Due to the independence of the energy and power capacity, flow batteries can be tailored to fit the specific demands of an application. Flow batteries span a wide range of power and energy capacities; however, the most economical sizes for the battery systems are above 100 kW and over 5 hours of energy storage.

1.1 MOTIVATION FOR RESEARCH

The motivation for this study was derived from the recent growth in interest for energy storage technologies. Following the political actions taken this past year, especially the American Recovery and Reinvestment Act, there has been an increase in government funding to energy storage technologies. Vice President Joe Biden announced in April 2009 plans to distribute $615 million for smart grid storage, monitoring and technology viability in addition to the over than $3.3 billion in smart grid technology development grants[1]. The increase in investments in energy storage technologies, there are more energy storage companies being formed.

The government is not alone in funding energy storage technologies, venture capital firms are also investing in the energy storage space. The first quarter of 2009 saw a drop in investments in comparison to past years, with the exception of energy storage. According to an Ernst & Young survey, the first quarter of 2009 saw capital investments in the clean tech industry drop 63% in comparison to the first quarter of 2008. The exception to the drop in investments was the energy storage space. Battery technologies received $69 million in first quarter funding in 2009, a 39% increase from 2008 first quarter. Fuel cell companies raised $45 million in the first quarter of the year, in comparison to no investments in 2008's first quarter [2].

Flow batteries are a technology that was invented in the 1970's; however, there is very little published information on the components of the battery and the breakdown of the cost of the battery. This study aims to give an overview of the flow battery technology, give a detailed description of the Zinc Bromine battery, breakdown the cost of the Zinc Bromine battery, and assess which application flow batteries (specifically Zinc Bromine) are best suited.

Connecting large-scale batteries to renewable energy farms has been noted as a promising way to create renewable distributed generation. Renewable energy sources such as wind and solar are intermittent sources of energy due to weather variations. Energy storage enables these intermittent sources to generate a stable power output. Worldwide there are government programs, incentives, and mandates to increases the percentage of total energy generation by renewable sources. An increase in intermittent renewable energy generation will in turn give rise to higher demands for energy storage. The study aims to catalogue the current supply of renewable energy worldwide, and estimate the growth of renewable energy sources in the future. In addition to assessing the current state and predicting the future growth, there is a need to understand the point at which intermittent renewable energy sources are so prevalent that the energy grid could not accurately match the supply to the demand with out energy storage.

Flow batteries are not limited to merely the large-scale applications such as distributed generation management; flow batteries have the capabilities to become an alternative to lead acid batteries in golf cart, lawn mower, and other smaller scale applications. This study examines the lead acid battery market, assessing the applications which flow batteries may be better suited than lead acid batteries. Accurate comparison of lead acid and flow batteries demands understanding of cost, performance, and specifications. This study aims to evaluate lead acid and flow batteries to determine if flow batteries are capable of replacing lead acid batteries in some applications.

Chapter 2 – Technology Introduction

Batteries are electrochemical power sources. These power sources allow energy to be captured from a chemical reaction to be converted into electricity. Batteries have two main features, to act as a power source and to store electrical energy. Both of these features are important; however, storing electrical energy has received the most attention with the possibility to improve the electricity gird and stabilize intermittent power sources.

There are many different types of batteries, the first battery was invented by Alessandro Volta in 1800[3]. In the past 200 years, there have been many advances in battery technology. Redox Flow batteries are a technology that was established in the 1970s and has developed over the past few decades. This technology differs from other types of batteries because the reactive species are dissolved in the electrolyte, the electrodes do not participate in the reaction, the power and energy capacities are independent and the electrolyte is flowed through the reactive cells.

Flow batteries are able to span a wide range of energy and power capacities, therefore, enabling these batteries to serve the needs of many different applications. The operating temperature of most flow batteries is around ambient room temperature, which reduces the risks associated with high temperature batteries. Additionally, many of the materials and components of these battery systems are readily available, relatively low cost, and recyclable.

This study focuses on assessing the Zinc Bromine flow battery; however, there are many different types of flow batteries. Most flow batteries are characterized by the reactive species in the electrolyte. Every flow battery chemistry has different performance characteristics and costs; however, the basic design of all flow batteries is fairly similar.

2.2 REDOX FLOW BATTERIES

Redox flow battery technology was first developed by NASA research. Through the 1970s and 1980s research in the space developed and soon companies formed to create commercial flow batteries. Flow batteries attracted interest and attention because the batteries operate at near ambient temperatures, are easily scaled up or down in size, can utilize different chemistries, and the majority of the components are low in cost.

The reactive species of redox flow batteries are in solution in the electrolyte. Due to this, the energy capacity of the battery is controlled by the volume of electrolyte, concentration of the reactive species, and redox potential of the reactive species. The electrolyte is cycled through the reactive cell, the anodic electrolyte flows through the negative half of the cell and the cathodic electrolyte through the positive half. Some flow batteries utilize different chemistries for the anodic and cathodic electrolyte and other chemistries use the same electrolyte for both halves of the reactive cell.

Isolating the oxidized and reduced reactive species from reacting with one another is important, the mixing of the oxidized and reduced species would cause self-discharge of the battery. In order to reduce the transport of the reactive species from one side of the reactive cell to the other, there is a microporous separator or ion exchange membrane between the two halves of the reactive cell. This separator reduces the transport of the reacted species between the two halves of the reactive cell. Another crucial feature of the separator is to allow the transport of ions across the membrane in order to maintain electroneutrality and electrolyte balance.

Redox flow batteries can have two different electrolyte solutions, one anodic electrolyte cycling though the negative side of the reactive cell and on cathodic electrolyte cycling through the positive of the reactive cell. However, in some redox flow batteries the electrolyte cycling through the negative and positive sides of the reactive cells are the same composition.

The diagram below depicts the charging of a flow battery. During charging, the unreacted electrolyte is cycled through the reactive cell. As the electrolyte flows through the reactive cell, the reactions take place and the electrolyte now contains the reacted species. The reacted catholyte and anolyte are stored in different tanks, in order to reduce the self discharge of the battery. The diagram below does not show the two tanks for the reacted electrolytes.

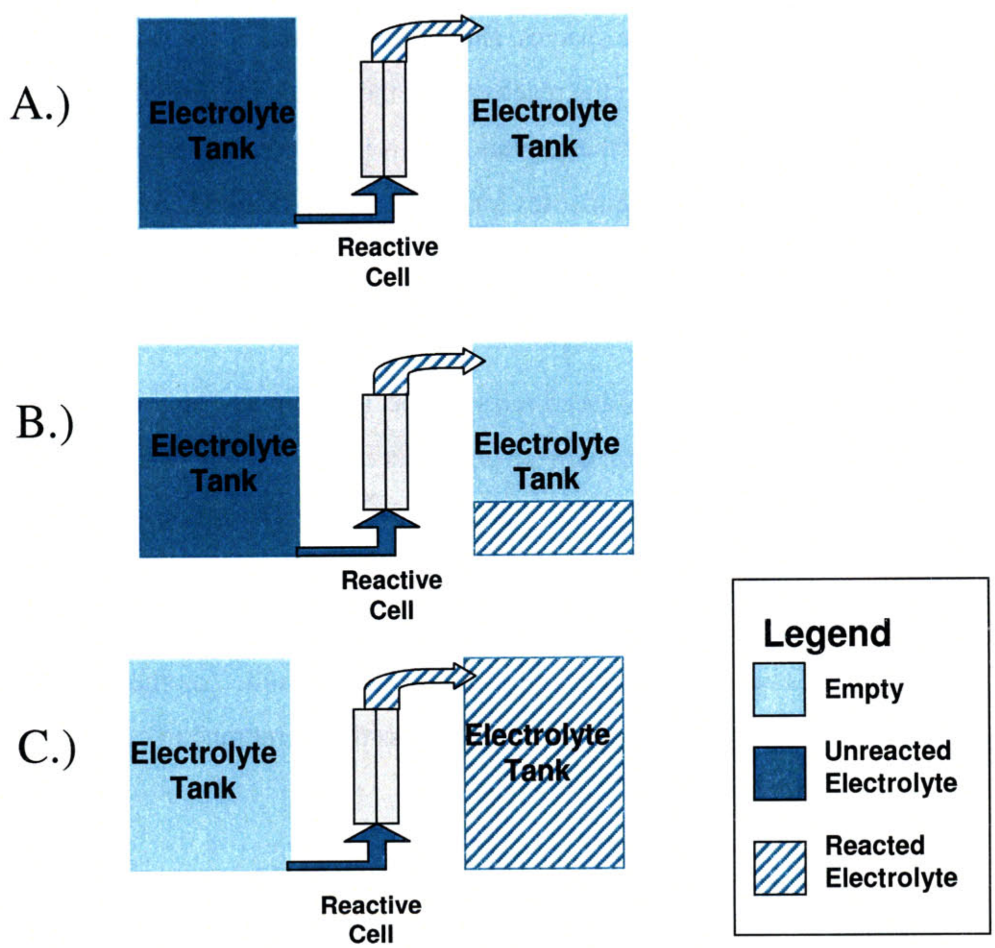

Figure 2.1: Diagram of Flow Battery. A.) Fully discharged flow battery, B.) Partially charged flow battery, C.) Fully charged flow battery

2.2.1 True Redox Flow Batteries

The reactive species of a true redox flow battery are soluble in the electrolyte, in both the reacted and non-reacted state. True redox flow batteries utilize chemistries in which the reactive species will stay in the aqueous solution at both charge states. In these batteries, the electrode serves as the surface for which the reaction takes place; however, there is no deposition or plating upon the electrode.

2.2.2 Hybrid Redox Flow Batteries

Hybrid redox flow batteries are flow batteries in which in one half of the reactive cell, the reactive species plates on the electrode. In the case of the Zinc Bromine battery, zinc is plated on the electrode during charging and is de-plated during discharge. In the other half of the reactive cell, bromine is evolved from bromide at the electrode during charging and returns to bromide ions. Hybrid redox flow batteries are often metal hydride batteries in which the metal plates on the electrode during charging. Although the metal plates on the electrode during charging, the electrode does not take part in the reaction and therefore does not degrade due to multiple cycles.

Unlike true redox flow batteries, hybrid flow batteries do not require the two separate tanks for the reacted electrolyte. Because the metal plates on the electrode during charging, only the reacted hydride is in the electrolyte solution.

2.3 Redox Couples

The driving force for batteries is based in the chemistry of the materials. A redox couple is a term derived from reduction and oxidation reactions, the driving force of batteries.

Most chemical substances have more than one oxidation state at which they are able to exist[3].

The redox potential of the redox couples determine the open circuit potential of the battery. In the chart below there are many of the redox couples which have been tested and researched as possible flow battery chemistries.

Negative Cell			**Positive Cell**		**Potential (V)**
U/U	$U^{4+} + e^- \rightarrow U^{3+}$	-0.607	$UO_2^{2+} + e^- \rightarrow UO_2^+$	0.06	**0.7**
Fe/Ti	$Ti^{3+} + e^- \rightarrow Ti^{2+}$	-0.9	$Fe^{3+} + e^- \rightarrow Fe^{2+}$	0.771	**1.7**
Fe/Cr	$Cr^{3+} + e^- \rightarrow Cr^{2+}$	-0.407	$Fe^{3+} + e^- \rightarrow Fe^{2+}$	0.771	**1.2**
V/V	$V^{3+} + e^- \rightarrow V^{2+}$	-0.225	$V^{5+} + e^- \rightarrow V^{4+}$	0.991	**1.2**
Zn/Br	$Zn^{2+} + 2e^- \rightarrow Zn$	-0.763	$Br_2 + 2e^- \rightarrow 2Br$	1.087	**1.9**
Br/S	$S_4^{2-} + 2e^- \rightarrow 2S_2^{2-}$	-0.265	$Br^{3-} + 2e^- \rightarrow 3Br^-$	1.09	**1.3**
V/O	$V^{3+} + e^- \rightarrow V^{2+}$	-0.255	$O_2 + 4H^+ + e^- \rightarrow 2H_2O$	1.229	**1.5**
Ti/O	$Ti^{3+} + e^- \rightarrow Ti^{2+}$	-0.9	$O_2 + 4H^+ + e^- \rightarrow 2H_2O$	1.229	**2.1**
Cr/O	$Cr^{3+} + e^- \rightarrow Cr^{2+}$	-0.407	$O_2 + 4H^+ + e^- \rightarrow 2H_2O$	1.229	**1.6**
U/U	$U^{4+} + e^- \rightarrow U^{3+}$	-0.607	$UO_2^{2+} + e^- \rightarrow UO_2^+$	0.06	**0.7**

Figure 2.2: Redox reactions for potential flow battery chemistries[4, 5]

The most common chemistries used in flow batteries include the Iron Cromium (Fe/Cr), Vanadium Vanadium (V/V), and Zinc Bromine (Zn/Br). However, there are many other current research projects and companies examining and utilizing other flow battery chemistries.

2.4 Flow Battery Chemistries

Many redox couples have been tested to create flow batteries with different chemistries. The most notable chemistries are the Vanadium-Vanadium, Iron Chromium, Polysulfide Bromide, Zinc Cerium, and Zinc Bromine. Each of the chemistries has unique properties, components and limitations. This study will briefly describe each of the chemistries, but the focus of the study is the Zinc Bromine flow battery.

2.4.1 Zinc Bromine Chemistry

The Zinc Bromine battery chemistry is a promising chemistry due to the high redox potential, low cost of materials, and high efficiencies. This chemistry is a hybrid redox flow battery, as the zinc is plated during charging.

Some of the challenges of the Zinc Bromine battery chemistry are; potential for zinc dendrite growth, bromine gas production, and low current densities. However, the advantages of the system include; low material costs, relatively low hazard risk, and high energy density. Zinc Bromine batteries have a roundtrip AC to AC energy efficiency between 70 and 75%, comparable to other flow battery chemistries and other battery technologies.

2.4.2 Vanadium Vanadium Chemistry

Vanadium Vanadium or all Vanadium chemistry is a redox flow battery in which the reactive species are both Vanadium but at different charge states. The negative electrode utilizes the V(II)/V(III) redox couple and the positive electrode utilizes the V(IV)/V(V) redox couple. An all Vanadium systems employ the same electrolyte on both halves of the reactive cell. The advantage is that if there is crossover of reactive species between the half cells, the electrolyte will remix to the original uncharged state.

Design characteristics of the all Vanadium redox flow battery are; glassy carbon felt electrode, cation selective membrane, and Vanadium and Sulfuric acid aqueous electrolyte. Cation selective membrane allows transport of hydrogen ions between the half cells. One challenge of the all Vanadium battery, the V(V) can damage the membrane. Different membranes have been tested to determine the best membrane for the all Vanadium battery. Current research shows that a polystyrene sulfonic acid cation selective membrane is superior to a polyethylene cation selective membrane; however, research is still being completed to determine the optimal membrane.

All Vanadium batteries operate between 5°C and 40°C. Above 40°C the vanadium is not stable and the efficiency of the battery deteriorates. An advantage of the all Vanadium system is that it is able to operate at room temperature and will be sustain most global temperatures.

Energy density of the all Vanadium battery is limited by the maximum vanadium concentration, lower cell potential, and the single electron exchange in the redox couples. The maximum vanadium concentration in the aqueous electrolyte is 2 mol dm^{-3}[5]. Calculated energy density of an all Vanadium battery is between 23 and 35 Wh/kg [5, 6].

2.4.3 Iron Chromium Chemistry

The Iron Chromium flow battery is a true redox flow battery. The electrolyte on the negative half-cell is a chromium chloride solution. The electrolyte on the positive half-cell is an iron chloride solution. Because the reacted species remain in the solution, there are different storage tanks for the reacted catholyte and anolyte. This chemistry was developed by NASA in the 1970s and has been developed over the past few decades[7].

One challenge facing the Iron Chromium battery is the potential for a parasitic hydrogen reaction to occur on the chromium electrode. However, this has been combated by optimizing the flow rate and the thickness of the electrode.

2.4.4 Polysulfide Bromide Chemistry

The Polysulfide Bromide (PSB) flow battery is a redox flow battery in which there are two separate electrolytes for the positive and negative half cells of the reactive cell. The cathodic electrolyte is a sodium bromide aqueous solution. The anodic electrolyte is a sodium polysulphide aqueous solution. Sodium bromide and sodium polysulphide are both abundant chemicals and are of moderate cost.

A glassy carbon electrode is employed on the positive half cell. The cathodic electrolyte is a 1 mol dm^{-3} NaBr solution saturated with bromine. The positive electrode is a porous Sulphide nickel electrode. The anodic electrolyte is a 1-2 mol dm^{-3} Na_2S solution[5]. One challenge of the two separate electrolytes is reducing the mixing between electrolytes. A cation selective membrane separates the two half cells. Transport of sodium ions across the membrane maintains charge neutrality.

2.4.5 Zinc Chlorine Chemistry

The Zinc Chlorine battery is a metal-halogen cell, similar to the Zinc Bromine battery. Similar to the Zinc Bromine chemistry, during charging zinc is plated during charging. This battery is a hybrid-redox flow battery due to the plating of zinc on the electrode. The redox potential of the cell is 2.12V, causing the Zinc Chlorine battery to have a high energy density in comparison to the other flow batteries[3].

Advantages of the Zinc Chlorine battery include; the availability of chlorine and the high energy density. However, in addition to the advantages of the technology, Zinc Chlorine batteries also face challenges. The challenges for the Zinc Chlorine batteries are; chlorine storage and hydrogen production. Chlorine is highly corrosive and difficult to store in the liquid or gaseous state. In order to store the chlorine, additives are included in the electrolyte to form chlorine hydrate Cl_26H_2O. The solid hydrate can be stored; however it is stable only under 9.6°C[3]. Refrigeration of the hydrate is required to keep the chlorine stable. A refrigeration chamber allows the chlorine to be stored in a stable state; however, the refrigerator is an internal drain of power, causing a decreased overall efficiency of the battery. Hydrogen production in the Zinc Chlorine battery is highly dangerous. The concern is due to the combustive reaction between hydrogen and chlorine gases. In order to reduce the hydrogen gas evolution, the electrolyte composition is controlled and UV radiation is used to control recombination.

Safety is the largest concern for Zinc Chlorine batteries. The possibility of a chlorine gas leak is the most significant safety hazard. Despite the potential dangers associates with chlorine, Zinc Chlorine batteries are still promising due to some advantages of the technology. The advantages of Zinc Chlorine batteries are cost competitiveness, recorded energy efficiencies of 70-75%, and high energy densities[3].

2.4.6 Vanadium Bromine Chemistry

The Vanadium Bromine chemistry is an improvement upon the Vanadium-Vanadium chemistry. There is little information published on the Vanadium Bromine chemistry. However, it is likely to have a higher energy density than the Vanadium-Vanadium chemistry. There is hope that the Vanadium Bromine chemistry will have current densities similar to the Vanadium-Vanadium battery, but have energy density of 50 Wh/kg, considerably higher than the 35 Wh/kg in the Vanadium-Vanadium systems [5].

CHAPTER 3 – ZINC BROMINE BATTERY

This study focuses on the Zinc Bromine chemistry flow battery. Zinc Bromine is a promising chemistry for flow batteries due to the high redox potential and the availability of zinc bromide. Zinc Bromine flow battery is a hybrid flow battery because the zinc is plated on the electrode during charging. The battery systems are easily scalable and can range in size from 1kW up to tens of MWs in power capacity and store energy up to 10 hours. Like all flow batteries, Zinc Bromine battery advantages are the independence of the power and energy capacity, wide range possible in power and energy capacity, long deep-discharging cycle-life, and near room temperature operations.

Along with the advantages of the flow batteries, there are also disadvantages and potential problems which are not always highlighted. Disadvantages and problems include the corrosiveness and toxicity of bromine, complexity of the battery system, possibility of zinc dendrite growth, and low energy to size ratio. Understand advantages and disadvantages allows for better assessment of the technology, as well as highlighting areas for improvement of the technology.

3.1 CELL COMPONENTS

Zinc Bromine batteries are made of many different components. The two main features of the assembled battery are the electrolyte storage tanks and the reactive cell. Large tanks storage the electrolyte in which the reactive species are dissolved. The tanks are connected to the reactive cell through a series of pipes, valves, and pumps. The pumps and valves control the flow of the electrolyte through the reactive cell, ensuring constant charging or discharging of the battery. The reactive cell is made up of two half-cells, each half-cell has an electrode at which the charging and discharging occurs. The half-cells are separated by a cation selective membrane, the membrane allows ions to pass through while preventing self-discharge of the battery. Increasing the power of the system is simple, connecting multiple reactive cells together will increase the power of the Zinc Bromine battery system. Increasing the energy capacity simply entails increasing the amount of electrolyte.

Considerations for the components of the Zinc Bromine battery cells and stacks include performance, reliability, material compatibility, and availability. Multiple materials and products were evaluated for each component, the best material or product was selected based on passing multiple criteria. Cost of each component was taken into account during the selection process; however, a more in depth analysis of the cost is in Chapter 4 – Cost Evaluation.

3.1.1 ELECTROLYTE

Zinc Bromine flow battery electrolyte is an aqueous solution. The reactive species, a supporting electrolyte, and complexing agents are dissolved in water. The catholyte and anolyte are the same solution in the Zinc Bromine battery. The electrolyte is pumped through the battery constantly during charging and discharging.

The reactive species in the Zinc Bromine battery electrolyte is zinc bromide. Zinc bromide is dissolved in the aqueous solution. The zinc bromide dissolves into zinc ions and bromide ions.

$$ZnBr_2 + H_2O \rightarrow Zn^{2+}_{(aq)} + 2Br^{-}_{(aq)} \qquad \text{(Eqn. 3.1)}$$

During charging, the zinc ions accept two electrons and plate as pure zinc on the electrode. The each bromide ion gives off one electron and two bromine atoms evolve at the electrode to become bromine.

$$Zn^{2+}_{(aq)} + 2e^{-} \rightarrow Zn_{(s)} \qquad \text{(Eqn. 3.2)}$$

$$2Br^{-}_{(aq)} - 2e^{-} \rightarrow Br_2 \qquad \text{(Eqn. 3.3)}$$

In order to contain the bromine in the solution, complexing agents are added to the electrolyte. Complexing agents react with the bromine to form a complex immiscible bromine solution. The solution of the complexed bromine is immiscible in the aqueous electrolyte and stored in a separate compartment of the electrolyte tank. Upon discharge, the complexed solution is cycled through the reactive cell and the bromine accepts two electrons to become two bromide ions.

The supporting electrolyte in the Zinc Bromine battery is usually either potassium chloride or ammonium chloride. These salts help improve the conductivity of the electrolyte and the performance of the battery. The salt solution in the battery can range from 1 to 5M according to literature reports. These salts are relatively low cost and do not have significant health or safety risks associated with them.

The complexing agents in the bromine solution are bromide salts. According to reports, many different salts can be used. These salts include: N-methyl, N-ethyl morphilinium bromide, N-methyl, N-ethyl-pyrrolidinium bromide, N-methyl, N-ethyl pyrolidinium bromide, N-methyl, N-ethyl piperidinium bromide. These salts are difficult to find and purchase, it is likely that Zinc Bromine flow battery companies have a relationship with a supplier or make their own bromide salts.

Zinc bromide is the reactive component of the electrolyte. Zinc bromide is commonly used as a salt in the oil industry. There are many suppliers of zinc bromide, both high and low grade.

3.1.2 ELECTRODE

The reactive cell of a Zinc Bromine flow battery is divided into half cells by the membrane. Each half-cell has an electrode, either a cathode or an anode. During charging, the zinc is plated on negative electrode and bromine is formed at the positive electrode. Zinc plates best on a smooth surface, therefore, the electrode in the zinc half-cells must have a smooth surface. Bromine evolves at the positive electrode and the increased surface area increases the area at which bromine can form. In the positive half-cell of the Zinc Bromine battery, the electrode must have a high surface area[8].

Zinc bromide is highly corrosive to metals. The electrode must be resistant to corrosion by the electrolyte. All metals, including platinum are corroded by zinc bromide. Carbon electrodes are the only material that is able to resist corrosion. Therefore, plastic carbon electrodes are used in Zinc Bromine batteries.

In addition to the bipolar carbon electrodes in the Zinc Bromine battery stack, each cell stack has a terminal electrode which acts as the current collector. This electrode must have conductivity laterally and perpendicularly to the electrolyte flow.

3.1.3 Membrane Separator

The membrane separator is a crucial feature of a flow battery. The membrane inhibits the transport of zinc and bromine between the half cells; however, the membrane allows the transport of ions in order to maintain charge equilibrium between the half cells. Zinc Bromine batteries with the complexing agent in the electrolyte solution do not require an ion selective membrane, but merely a micro-porous separator. There are advantages and disadvantages to both the ion-selective membrane and the micro-porous separator. Ion-selective membranes are more efficient at blocking bromine from crossing to the negative half-cell; however, the ion-selective membranes are more expensive and less durable than micro-porous separators. The micro-porous separator inhibits the transport of the complexed bromine between the half cells, but is less efficient than the ion-selective membrane. Both the ion-selective and micro-porous separators reduce the bromine transport and diminish the risk of self-discharge in the battery[8].

Reducing the transport of bromine and zinc between the half cells is critical to the performance of the Zinc Bromine battery. If bromine is able to cross between the half cells, the cell would self discharge. Self discharge decreases the overall efficiency of the battery. Therefore, the membrane is crucial to maintain high efficiency. In addition to acting as a barrier to zinc and bromine, the other critical feature of the half-cell separator is to allow ions to pass through in order to maintain charge equilibrium in the battery.

Different materials can be used as membrane or separator in Zinc Bromine batteries. Important features of the membrane include durability, conductivity, and scalability. Durability is necessary as flow batteries have a lifetime of thousands of cycles. Replacing the membrane frequently would cause for additional maintenance costs as well as the cost of shutting off the battery system. Conductivity is the ease of which the ions can pass through the membrane. Higher conductivity of the membrane indicates easier transport of ions across, in turn leading to a more stable equilibrium. Reactive cells of Zinc Bromine flow batteries range in size from the cm^2 scale to the m^2 scale. Membranes must be large enough to fit in the largest reactive cells as well as easily be cut to the size of the smallest reactive cells.

DuPont produces a cation selective membrane, Nafion. Nafion membrane is available in various thicknesses. Membrane thickness correlates directly with durability and inversely with conductivity. A balance between the durability and conductivity must be achieved. A study assessed the different membrane thicknesses and found that Nafion membrane of 115 nm thickness was the best suited for flow battery applications.

Nafion is an ion-selective membrane; other possible separators are micro-porous polymer membranes. These membranes are often called non-selective membranes to differenciate from the ion-selective membranes. Micro-porous polymer membranes are more durable and less expensive than ion-selective membranes.

3.1.4 Pumps and Flow Meters

Pumps are crucial in cycling the electrolyte through the reactive cell. The pumps must maintain a constant mean linear velocity of the electrolyte across the electrode. Each tank has a pump to control the flow rate to the battery stacks. Constant linear velocity of the electrolyte across the electrode ensures high performance of the battery, variations in the flow rate decrease the overall efficiency of the battery. Pump sizes are dependent on the size of the electrode. The electrolyte must have constant flow across the entire electrode area, therefore, a larger electrode requires a stronger pump to pump the electrolyte across the membrane.

Pumps in a flow battery are an internal drain on the power output of the battery system. The pumps require power in order to operate. Flowing the electrolyte through the battery stacks decreases the overall efficiency of the battery, but is required for battery operation. This is a self drain on the battery and affects the overall performance of the system.

In addition to the pump flowing the electrolyte through the reactive cells, a flow meter is attached to the pipes connected to each reactive cell. Flow meters control the flow of the electrolyte and assist in maintaining a constant flow rate.

3.1.5 PIPES

Pipes and connections between the electrolyte tanks and the reactive cell enable the electrolyte to flow through the battery. Cost, availability, and corrosion resistance were the top criteria in the material selection process.

Resistance to corrosion is the most significant characteristic required of the pipe material. Due to the corrosive nature of dilute zinc bromide solution, the material options were limited to those highly resistant to corrosion. Stainless steel and polymers were the most feasible material options.

Selecting between stainless steel and polymer as the material for the pipes, considerations of cost and availability were taken. As in any product, cost is a driving force for material selection in flow battery design. Possible materials for the pipes were analyzed based on the total cost of the pipes. An additional characteristic which was analyzed is the availability and diversity of pipes made of the material. Flow batteries are able to be scale from small to very large systems. Different sized systems require different length and diameter of pipes. Therefore, in order to accurately select the best material for the Zinc Bromine flow battery pipes, the range of pipe sizes for each material was examined.

Stainless steel is four times the cost of polyvinyl chloride pipes[9, 10]. Additionally, polyvinyl chloride is 30% less in cost than ultra high molecular weight polyethylene[11]. Polyvinyl chloride pipes resist corrosion, are low in cost, and are manufactured at different sizes and shapes. Polyvinyl chloride pipes are the best material for the pipes of the Zinc Bromine flow battery.

Polyvinyl chloride pipes have the best material properties of any material candidate for Zinc Bromine flow battery pipes. However, there are more considerations and important features of the pipe beyond the material selection. Leaks, cracks, and ruptures are possible causes for failure of the battery system.

To reduce the potential of leaks, each pipe is attached to the tanks and reactive cell by polymer gaskets and tubing. The gasket ensures a liquid tight seal, and the tubing reduces the strain on the pipes if the systems moves or shifts slightly. The tubing is flexible polyethylene and attaches the polyvinyl chloride piping to the tanks and reactive cells.

Cracks and ruptures in the piping and tubing could cause the battery system to fail, regular maintenance and inspection reduces the risk of failure. Understanding the material properties and in which environments the materials operate best is critical to reduce the risk of material failure. Ensuring that materials are able to withstand the environmental conditions is crucial. Although flow batteries are typically sheltered from the harsh environment, PVC is UV and corrosion resistant.

Pipes are a complex component of the Zinc Bromine flow battery. Cost, design, availability, and durability are all key factors in the material selection process. Polymers are the most reasonable choice based on cost and corrosion resistance. PVC is the most common choice due to the availability, variety, and cost.

3.1.6 FRAME

In order to support the cell structure, each cell stack is encased in a frame. Frames give support to the reactive cells and reduce leakage of the electrolyte. Significant design characteristics of the frame are; lightweight, corrosion resistant, low cost, and processability. Weight is an important feature in the smaller scale systems, for systems which are being carried or moved around a key factor is weight. The electrolyte in the battery is corrosive; the frame is in contact with the electrolyte and must be resistant to corrosion. Materials which will corrode or degrade in the aqueous zinc bromide environment are not suitable for the battery stack frame. Cost is an important feature for any product. Driving cost below competitors will allow a new product to break into the market. One of the key features of flow batteries is the scalability. Materials for the frame must be easily processed to shape the size and dimensions of a specific battery stack.

Although many metals are able to withstand greater loads and have higher strength, the materials best suited for battery stack frames are high density polymers. High density polymers provide strength at a moderate cost while remaining light in weight. While zinc bromide solution is corrosive to metals, the solution has little effect on polymers. Processability of polymers is high, different shapes and forms can easily be created. The polymers utilized in most Zinc Bromine battery stack frames are high density polyethylene and polyvinylchloride. Both of these polymers are widely available and are easily molded. In order to assess the polymer best for the frame of the Zinc Bromine, the cost, and environmental impact of both polymers were evaluated.

PVC costs for a 12 inch square 0.5 inch thick sheet is $18.45, where the HDPE sheet of the same dimensions is $6.62[12]. The environmental impact of both materials were examined, PVC has toxic by-products and is difficult to recycle, whereas HDPE has little production emissions and is easily recycled. HDPE is the best material choice for the frame of Zinc Bromine batteries based on cost, processability, performance, and environmental effects.

3.1.7 End-Plates

Cells stacks are sandwiched together. In order to hold the cells together and support the stacks, the stacks are assembled with aluminum end-plates supporting the stack. These plates have holes in each corner, large rods are used to connect the end-plates. Threaded ends on the rods and nuts are used to maintain the seal between the cells in the stack.

The end-plates are sheets of aluminum. Aluminum is a relatively low cost and weight metal. The sheets used to support the battery stacks are 1 cm thick. The important features of the end-plates are strength, durability, and cost. Despite the corrosive nature of the Zinc Bromine electrolyte, metals were considered in the material selection process for the end-plates because the plates are not likely to be in contact with the electrolyte.

3.2 Performance Characteristics

In addition to the components of the battery cell, another significant part of the Zinc Bromine battery is the performance characteristics. The performance characteristics include the current density, energy density, efficiency, and durability of the battery. In assessing the technology, understanding the components, performance, and cost are the key features to evaluate the technology.

Current density of the battery is the assessment of the current per area of electrode. Power capacity is related to the current density of the battery. For a selected power capacity, the higher the current density of the battery, the smaller the electrode. Low current density indicates that larger electrodes are needed in order to match the power output specified. Zinc Bromine batteries have current densities higher than non-flowing aqueous batteries; however, in comparison to other flow batteries, the current density of the Zinc Bromine battery is lower.

Energy density of the battery is related to the energy capacity of the battery. Because the reactive species in flow batteries are in the electrolyte, the volume of the electrolyte determines the total energy capacity. The energy density of flow batteries is the amount of energy in each liter of electrolyte. An additional energy density can be calculated for the whole battery system. This energy density is the energy per kilogram, this measurement includes all components of the battery system. Due to the high redox potential of Zinc Bromine battery the energy density of the battery is higher than that of other flow batteries with lower redox potentials.

Energy efficiency of the battery is the energy out of the battery during discharge divided by the energy put in during charging. High energy efficiency is important because any energy lost is a loss in potential profits. Batteries with higher efficiencies are able to be priced higher than lower efficiencies. This is because if the battery has a higher efficiency, in order to get the same energy output, less energy must be put into the system during charging. Flow batteries have internal drains on efficiency because the pumps which circulate the electrolyte through the battery require constant power in order to operate. Zinc Bromine flow batteries have efficiencies comparable to most batteries. The efficiency of Zinc Bromine batteries is between 75 and 80%.

3.2.1 Current Density

Current density of flow batteries is a distinguishing feature in comparison to aqueous non-flowing batteries. In static batteries, the current density is limited by the diffusion of the species in the electrolyte. However, in flow batteries there is both diffusion and convection occurring. The additional flow enables more reactions to occur at the electrode, therefore increasing the reactions per unit area. Current density of flow batteries is therefore higher than with other batteries.

Zinc Bromine batteries are charged and discharged at current densities between 15 and 40 mA/cm^2 [8]. This is considerably lower than other flow battery technologies which are able to reach current densities of 100 mA/cm^2.

3.2.2 Energy Density

Energy density of the Zinc Bromine flow battery is controlled by the concentration of reactive species in solution, the potential of the cell, and the number of electrons transferred per mole during discharge. Cell potential and number of electrons transferred per mole during discharge are properties of the redox couples and are constant. The concentration of zinc bromide in the electrolyte solution determines the energy density of a Zinc Bromine battery. Zinc Bromide concentration is between 1 mol dm^{-3} and 7 mol dm^{-3}[5].

The calculated energy density of a Zinc Bromine battery with 2 mol dm^{-3} is 59 Wh/kg. Energy density for Zinc Bromine batteries is capable of approaching 80 Wh/kg. Zinc Bromine energy density is higher than many other flow batteries due to the high solubility of zinc bromide and the large redox potential. Lead acid battery energy density is comparable to the energy density of the Zinc Bromine batteries.

3.2.3 Efficiency

Energy efficiency of the Zinc Bromine battery system is between 70 and 80%. Many factors contribute the efficiency of the battery system. Zinc Bromine batteries have reduced performance when the discharge rate is too high. The efficiency of a battery discharged at 100 A is 72%, in comparison to a battery discharged at 50 A which has an efficiency of 77%[8]. Other factors that contribute the efficiency are self-discharge, electrode surface, auxiliary energy, and standing time.

Membranes reduce the possibility for self-discharge of the battery. Zinc plates best on a smooth electrode surface. It is important for Zinc Bromine batteries to be discharged completely, as the zinc is deplated from the electrode during discharge. When the battery is completely discharged, the electrode surface is smooth; however, if the battery is not discharged completely, the zinc must plate on top of zinc which is not as smooth[8]. Zinc Bromine batteries have pumps, valves, and controls which consume energy during battery operation. These devices consume approximately 1% of the total energy of the system. Zinc Bromine batteries experience losses in energy when standing at a charged state. Each hour the battery is standing, the system loses 1% of the energy capacity. This is due to the self-discharge of battery.

Supporting electrolyte improves the efficiency of the battery. The salts added to the electrolyte increase the conductivity of the electrolyte, which reduces the internal ohmic energy losses. Addition of supporting electrolyte can increase the total efficiency of they system up to 2% [8].

Many factors contribute to the energy efficiency of the Zinc Bromine system; however, most systems have efficiencies between 70 and 80%.

3.2.4 LAB TESTING

To assess the accuracy of the published results, the author tested the electrolyte of the Zinc Bromine battery. The supporting electrolyte was tested to determine the impact in the performace of the battery. Ammonium chloride was used as the supporting electrolyte. The electrolyte solution was 3M NH_4Cl and 2M $ZnBr_2$ in an aqueous solution. A three electrode system was used; the reference electrode was Ag/AgCl, the counter electrode was platiunum, and the working electrode was glassy carbon. The system was cycled from -1.2V to 1.2V as a scan rate of 50mV per second.

The results indicate that the concentration of the supporting electrolyte has little effect on the current density of the system.

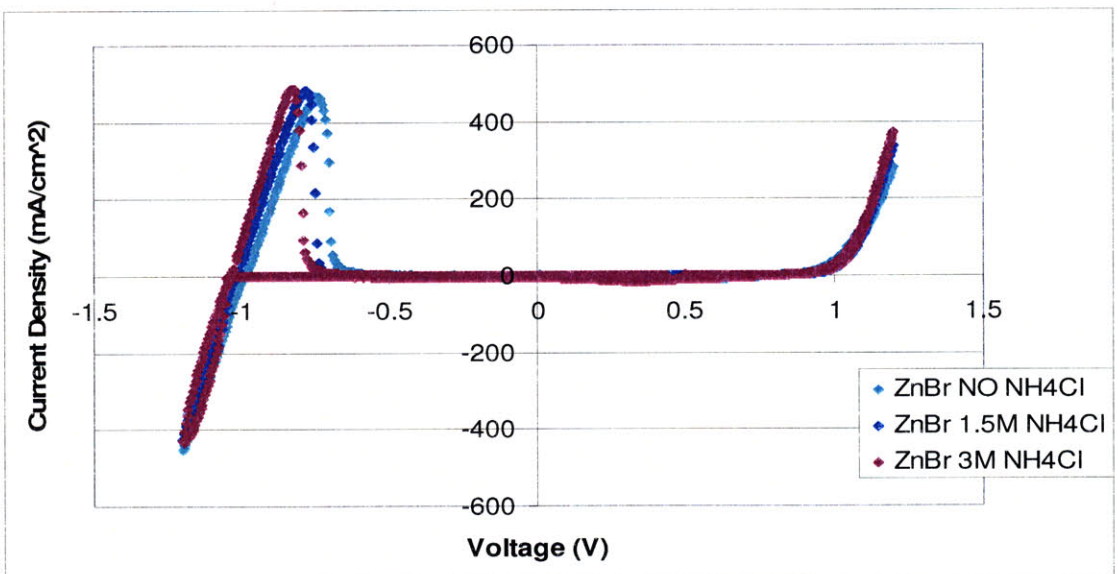

Figure 3.1: Analysis of Supporting Electrolyte in a Zinc Bromine System

Further analysis and testing must be done before accurately determining the impact of the supporting electrolyte. However, based on these results, the significance of the supporting electrolyte is minimal.

3.3 BATTERY SYSTEMS

Zinc Bromine cells are made up of the components described in section 3.1 Cell Components. In order to make large batteries, many cells must be assembled together in stacks. Each cell stack has many cells sandwiched together. Because of the bipolar electrode, each electrode works as the negative electrode in one reactive cell and the positive electrode in the next reactive cell.

3.3.1 Cell Stacks

Flow batteries have the advantage of being modular. A reactive cell is composed of a positive glassy carbon electrode, a membrane and a negative glassy carbon electrode, all encased in a PVC frame. Additional cells can easily be added together, creating a sandwich of reactive cells, in order to easily add cells together, bipolar glassy carbon electrodes are used in the cell stacks. The bipolar glassy carbon electrode is the negative electrode in one cell and the positive electrode in another. An example of a three cell stack would be glassy carbon electrode, membrane, bipolar glassy carbon electrode, membrane, bipolar glassy carbon electrode, membrane, glassy carbon electrode. Cell stacks can range from a couple of reactive cells up to tens of cells in the stack.

3.3.2 System Size

A key feature of flow batteries is the modularity of the technology. Flow batteries can be assembled in systems that vary in energy and power capacity from that of a lawn mower battery up to that of a small power plant. Flow battery stacks are able to be connected in parallel or in series in order create a large battery system. The largest flow battery systems are up to ~20MW in power capacity and 200MWhr in energy capacity.

Increasing the energy capacity of a battery system requires additional electrolyte. More or larger tanks can increase the energy capacity of a system up to over ten hours of capacity. Power capacity of a battery system is increased by adding additional cells to the system. Multiple cell stacks can simplify a flow battery system, multiple cell stacks can share the same electrolyte storage tank. The pipe system is more complex, but the overall cost is lower because fewer tanks are needed.

Battery stacks dimensions scale up with the power and energy capacity of the system. The energy capacity scales with the amount of electrolyte and the power capacity scales with the size of the electrodes. The figure below indicates the dimensions of various battery systems. These estimates are based on the quantity of electrolyte, size of the reactive cells, and the number of cells and stacks in the system.

System	Length	Width	Height
1 kW 3 hr	50cm	50cm	50cm
5 kW 3hr	100cm	100cm	60cm
10 kW 3 hr	220cm	220cm	100cm
100 kW 3 hr	220cm	460cm	150cm

Figure 3.2 – Dimensions of Zinc Bromine Battery Systems

Advantages of the modularity of flow batteries include maintenance and adaptability. A modular flow battery system reduces the time at which the system is unable to operate due to maintenance. If there is a problem or routine inspection, only the stack or section being inspected is shut off; reducing the total downtime of the system. Additionally, the modular design allows for individual dimensions. Flow batteries can be assembled to meet the dimensions of a specific space or location.

3.4 Challenges of Technology

Zinc Bromine batteries are a technology that has potential to be used in many different applications; however, there are some challenges which must be solved before the technology will be adopted on a large scale.

Zinc Bromine batteries require a constant mean linear flow of the electrolyte across the electrode. The constant flow across the electrode will provide constant rate of deposition of zinc and evolution of bromine. The variation in the flow rate can reduce the efficiency of the battery. However, maintaining a constant flow rate can be difficult even with the best pumps available. To assist in regulating the flow, valves and flow meters are used.

Back mixing of the reacted bromine electrolyte with the zinc can cause self discharge of the battery. In order to combat this, the complexed bromine is stored in a separate tank within in the reacted electrolyte tank. The complexed bromine has a higher density than the electrolyte and will separate due to gravity. Separation of the bromine and from the zinc will reduce the self-discharge. Additionally, the separator between the half-cells reduces the transport of bromine across the membrane.

Multiple auxiliary parts can cause for additional maintenance. Zinc Bromine batteries have many different components and parts. Although the battery has a high lifetime, some of the parts may breakdown or require maintenance. Because very few Zinc Bromine systems have been tested over a long period of time, the frequency and cost of maintenance is still a question and concern.

3.5 Health and Environmental Impact

Current demands on products require the evaluation of environmental impact of the materials and potential for hazard or harm. Many decisions are made in the process of creating a product, however, arguably no decisions have as great of an impact on the overall environmental performance of a product as those involving material selection [13]. The materials selected influence the processing technology and distribution of the supply chain, affecting the overall environmental profile of the product throughout its life cycle. Environmental impact of a material is not only the effects on the environment, but also the risk and dangers of the materials to humans. To assess the safety of a product, extensive research into the dangers of each product or materials in use is required. Many of the materials in the Zinc Bromine battery system are not flexible; however, the environmental impact of the materials selected was evaluated and suggestions of potential alternatives are given below. Factors included in this study's evaluation of material environmental profiles are; toxicity to humans, toxicity to plant-life and animals, availability of resource, processing by-products, ease of recycling, and energy to produce. Additionally, the study examined which materials are produced in the United States and are only available outside of the country.

Components of the system which were examined in the study are; pipes, frames, tanks, membrane, electrode, and zinc bromide. The material selected for each component was evaluated in terms of the environmental impact. Alternative materials were suggested for materials with a poor environmental profile.

Polyvinylchloride is the material selected for the pipes connecting the tanks to the reactive cells. Polyvinylchloride (PVC) is production is the largest consumption of chlorine gas[14]. In addition to the potential dangers of the chlorine gas, it is important to note that chlorine production is the most energy intensive industrial process. PVC production also releases by-products into the environment, dioxins, phthalates, and heavy metals. Dioxins are a by-product of chlorine production, PVC burning or incineration and are carcinogenic. Phthalates are a type of plasticizer commonly used in PVC production to make the product less brittle; phthalates have been linked to reproductive damage. Heavy metals are used to reduce PVC from catalyzing its own decomposition, if the heavy metals leach out of the PVC they are highly toxic and cause brain and development damage to humans, particularly children[14]. Potential toxins are not the only environmental impact of PVC. PVC is a very difficult material to recycle. Only 1% of the PVC in the United States is recycled, most PVC is eventually discarded in a landfill.

Alternative polymers could be used in substitution of the PVC for the pipes in the Zinc Bromine battery system. Other polymers that pipes are made from are polypropylene (PP) and high density polyethylene (HDPE). For a 1.5 inch diameter 5 foot long pipe, PVC costs $6.69, PP costs $25.52 and HDPE costs $19.50[10, 15]. Due to the high discrepancy of the cost between PVC and both PP and HDPE, it is likely that PVC will continue to be used in Zinc Bromine batteries. However, those with deep concern for the environmental impact of the product may consider other material options of the pipes.

One critical feature of Zinc Bromine batteries is that zinc bromide is extremely dangerous. Zinc bromide is severely hazardous if ingested, inhaled, or in contact with skin. Additionally, it is toxic to lung tissue and mucous membranes[16]. Zinc bromide is very dangerous, however in the operating battery; the concentration of zinc bromide is relatively low. Caution must be taken to ensure the people handling the zinc bromide and creating the electrolyte take precautions and follow appropriate safety instructions. Furthermore, ensuring that the seals and gaskets are leak-proof will prevent damage or harm from any of the electrolyte leaking out of the battery when in operation. In the battery, during charging, both bromine and zinc are produced. Bromine is toxic to internal organs and mucous membranes to humans if inhaled. Bromine is also deadly to animals if ingested or inhaled[17]. Although bromine is toxic, there is very little bromine in the battery system. Because the bromine is complexed into a ploybromine, there is very little cause for concern over bromine production.

Overall, the Zinc Bromine battery has few health and safety concern; however, all of the concerns and considerations must be taken into account before selecting a Zinc Bromine battery for an application.

3.6 Technology Summary

Zinc Bromine flow battery technology is promising because of the scalability of the power and energy capacities. Additionally, the energy density and affiance of the Zinc Bromine battery is comparable with other batteries and the performance is not effected by changes in temperatures.

Zinc Bromine batteries, like other flow battery technologies, have many different parts and components. All of the components of the system can lead to the potential for additional maintenance.

Overall, Zinc Bromine technology is an impressive battery. The performance of the battery is comparable with other batteries, the components are readily available, and the safety and hazard risks are fairly low. Further study into the cost of the battery system is analyzed in Chapter 4 – Cost Evaluation.

Although the technology has improved in the past, future improvements will enable Zinc Bromine batteries to be the optimal choice. The improvements necessary in the future are; a reduction in number of components, improved and stable efficiency, increased current density, and proven reliability, if these improvements can be made to the technology, it is likely that Zinc Bromine batteries will be the favorite choice for large energy storage applications.

CHAPTER 4 – COST EVALUATION

The cost of flow batteries is an important feature in determining the potential success for the technology. Any new technology must be cost competitive with competing technologies. This study investigates the relationship between cost and the power and energy capacity of the battery system.

In addition to the total cost of the system, the cost of each component of the system is important to understand. Zinc Bromine batteries have many different components and features, therefore it is important to understand the cost of each component and the effect of the component on the total cost of the battery system.

The key cost drivers of the total cost of the battery system are evaluated. This study also examines how the costs of the battery systems and specific components may change in the future. Economies of scale and market competition may cause features of Zinc Bromine flow battery costs to come down in the future.

4.1 ZINC BROMINE COST MODEL

In order to accurately determine the cost of flow batteries, an extensive bottoms-up cost model was created. In the model, each feature of the battery was analyzed and included in the total cost of the battery system. The model was created for a zinc-bromine flow battery. Multiple iterations of the model were examined to determine the relationship between cost and both energy and power.

To assess the accuracy of the model, a comparison to published data was completed. The model returned values within the range of published values.

4.1.1 ASSUMPTIONS

The model contains many assumptions. The key assumptions involve some of the material, overhead, and labor costs.

The material costs included in the model were those that were available to the author. Costs may vary based on the quantity ordered and quality required of the material. Many of the material costs included in the model are scaled up from the costs for smaller quantities. Additionally, some materials, such as the complexing salts for the bromine were not available to the author; the complexing agent was omitted from the study. The material costs for the other electrolyte components were based on estimates from large chemical suppliers. These costs are likely accurate due to the expected volume of the material needed. The values for non-selective membranes were not available; therefore Nafion was used as the membrane material in this study. Discussions of the assumptions and the effects on the total costs are evaluated in this chapter.

Overhead for the model was calculated as 10% of the component and additional costs. Labor costs were estimated based on the approximate time for assembly of the systems. Hourly wages were estimated at $35/hr. The time estimation for the system assembly was made by the author, this may not be accurate, but is likely within 30% of the true value.

Transportation costs were estimated based on a 1,500 mile trip. This was an average distance based on the size of the United States. Transportation costs were based on estimates from transport companies, and based on dimensions and weight of the systems.

It was assumed that all systems were assembled and distributed within the United States. There was no research done into the cost differential of manufacturing these systems outside of the United States or importing or exporting the systems.

4.2 COMPONENT COST

In order to accurately estimate the cost of a Zinc Bromine battery system, this study researched the cost of each individual component of the battery system. The cost model is a bottom-up calculation of Zinc Bromine battery systems. Costs of system components were estimated based on research of various suppliers catalogues and cost estimates.

4.2.1 ELECTROLYTE

Zinc bromide, ammonium chloride, and bromide are in an aqueous solution in the Zinc Bromine battery electrolyte. The aqueous electrolyte concentration is assumed to be; 2 mol dm^{-3} $ZnBr_2$, 1 mol dm^{-3} Br, and 3 mol dm^{-3} NH_4Cl. The electrolyte in Zinc Bromine systems also includes bromide salts; however, due to the inaccessibility of the costs for these materials, they were omitted from the model.

The chemical costs were collected from wholesale suppliers of chemicals. Due to the quantity of the chemicals needed, high-end chemical suppliers could not supply the quantity needed for a large scale battery. Each liter of electrolyte requires 450g of $ZnBr_2$, 80g Br, and 160g NH_4Cl. Therefore, the estimate costs are from low-end suppliers from outside of the United States.

Estimated costs are: zinc bromide is $0.33/kg, bromine is $0.63/kg[18], ammonium chloride is $3.00/kg [19].

4.2.2 TANK

The tanks selected for the Zinc Bromine battery were polyethylene tanks. Depending on the size and capacity of the system, the tank sizes range from 100 to 2,000 liter capacity. Polyethylene tanks were selected based on the price and material performance. The price of 2,000 liter tanks is $550 [20]. Tank prices for smaller tanks range from $135 for a 100 liter tank to $210 for 500 liter tank[21].

Stainless steel and other polymer tanks were evaluated, and the polyethylene tanks were the lowest cost tanks. Additionally, the polyethylene tanks come in many different sizes and scale up to 2,000 liters. Stainless steel tank sizes were limited to 100 to 300 liters[21]. Not only were stainless steel tanks limited in size, higher in cost, but are also easily corroded by zinc bromide [16].

Polyethylene is the lowest cost material suitable for the electrolyte storage tanks. New research indicates that durable polymer bags could be used as the electrolyte storage devices. Polymer bags may be lower cost than polymer tanks; however, additional research must be done to determine durability and reliability.

4.2.3 ELECTRODE

Zinc Bromine batteries operate best when employing a glassy carbon plate electrode. As most battery systems contain more than one stack per cell, a bipolar plate electrode is the most economical electrode. The price for the bipolar glassy carbon electrode could not be found, therefore, the electrode used in the model was the bipolar graphite plate electrode sold for fuel cell construction[22]. To accurately estimate the cost per square meter, the fuel cell electrode cost was scaled to a 1m by 1m electrode.

Estimated bipolar glassy carbon plate electrode is $\$83/m^2$[22]. This cost is merely an assumption as the actual price could not be found. However, if Zinc Bromine batteries continue to increase in production, there is likely to be economies of scale for the bipolar glassy carbon plate electrodes. With higher demand there will likely be more suppliers and the cost will be driven down.

4.2.4 MEMBRANE

Although micro-porous separators are often used in Zinc Bromine flow batteries, this study utilizes Nafion membranes because the cost of the micro-porous polymer membrane could not be found. The membrane separating the positive and negative half cells of the reactive cell is a cation selective membrane. Nafion membrane from DuPont was used in the cost model for the Zinc Bromine battery. Nafion comes in various thicknesses and sizes; the Nafion used in this study is Nafion 115.

Prices for Nafion depend on the thickness and the size of the order. This study used Nafion prices of $250 per square meter. Wholesale purchases of Nafion may decrease the cost per meter for the membrane. Additionally, with the current increase in production of flow batteries and fuel cells, there is likely to be a decrease in price of Nafion due to the increased demand. The chart below represents DuPont's predictions for the price of Nafion as the demand for the product increases.

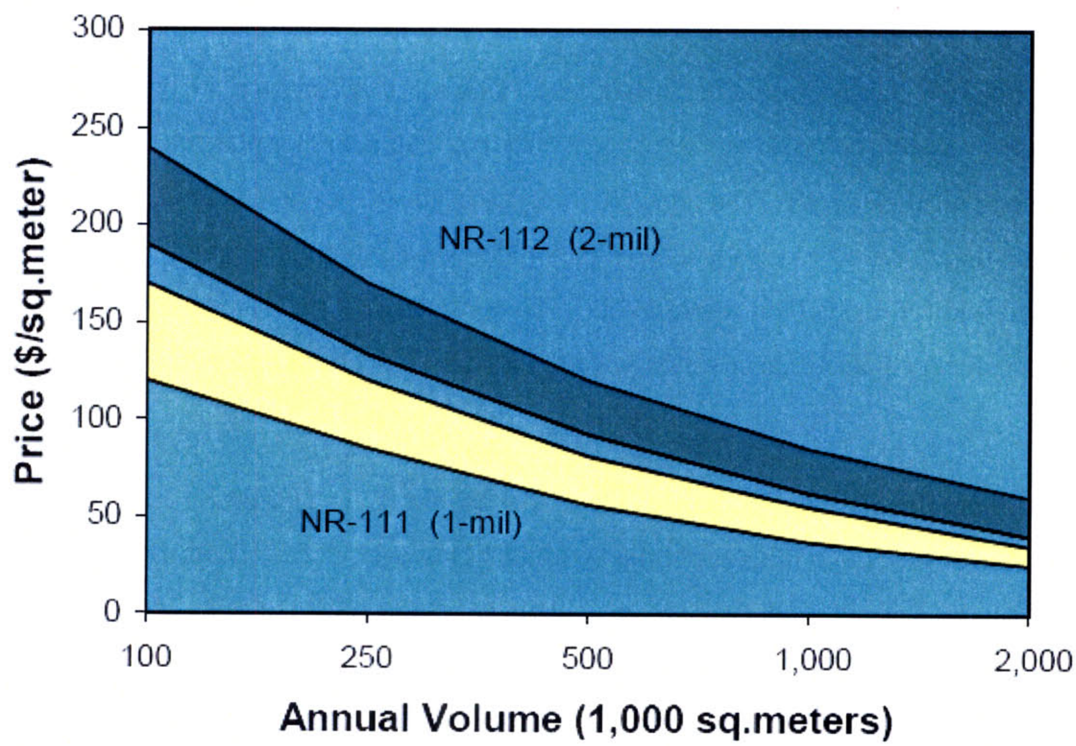

Figure 4.1: Price Projections for Nafion based on Annual Demand[6]

Nafion prices of under $100 per square meter will have a large impact on the total price of the battery systems. Additionally, if competitors enter the ion-exchange membrane market, this could cause large drops in the price of membranes.

Additionally, for Zinc Bromine batteries utilizing the bromine complexing agents, a lower cost micro-porous membrane can be used instead of the higher cost cation selective membrane. The micro-porous membrane is typically made from a low cost polymer. Although the price of this material is not known, more analysis into the effects of the membrane cost will be completed in this study.

4.2.5 PUMPS AND FLOW METERS

The pumps for circulating the electrolyte are DC brushless pumps. It was assumed that each tank requires a pump and the price of the pump was found to be $400[23]. In addition to the pumps to circulate the electrolyte, flow meters are required to maintain constant flow into the reactive cells. It was estimated that each stack of cells requires two flow meters to control the flow in and out of the reactive cell. The cost of the flow meters was found to be $210.

These costs are for the pumps and flow meters likely used in megawatt scale systems. Therefore, the cost of these must be scaled down for the smaller kilowatt scale systems. Future prices for the pumps and flow meters are not likely to change drastically. These devices are not only used in flow batteries, other applications have driven the cost to a fair market price. There are many manufacturers and suppliers of pumps and flow meter, indicating fair economic prices for these devices.

4.2.6 PIPES

Pipes for the Zinc Bromine flow battery cost model were polyvinylchloride. PVC pipes are widely available and come in varying sizes and shapes. The shapes and sizes are necessary as the different sized systems require different diameter and lengths of pipes. PVC piping also has different elbow and joint pieces that enable the flow battery system to connect the tanks easily to the reactive cells. The prices for the piping varies based on the length of piping needed, number of elbow junctions, and the diameter of the pipes.

Large and small systems use the PVC piping as well as PVC tubing to connect the reactive cells to the pipe system. PVC is the least expensive polymer piping material. The cost of PVC, high-density polyethylene, and polypropylene pipes were analyzed in order to determine the best material to use for the piping in the battery systems. The price of a 1.5 diameter pipe made from PVC is over 50% less than pipes made from HDPE and PP. Additionally, PVC piping is available in a wide range of lengths and diameters.

Pricing for the pipes of the battery system are related to the diameter and length of the pipe. In the cost model, the cost for the piping was assumed to be $9 per meter. This cost is an average based on the range of diameters of the piping used in different battery systems. The elbow joints are each priced at $3.80[10]. Tubing is necessary to connect the pipes to the reactive cells. High-density polyethylene (HDPE) was used in the model. The price of HDPE is $10.30 per meter.

The quantity of piping, attachments, and tubing was estimated based on the number of cell stacks in the battery system. It was assumed that each cell stack required 3 meters of pipes, 4 elbow joints, 3 meters of tubing, and 2 gasket connections. These assumptions are based on 20 cells in each stack and 1 m^2 reactive cells.

4.2.7 Frame

In order to support the modules, each module is encapsulated in a polyvinylchloride frame. The frame provides support and reduces leakage of the electrolyte.

The cost of the frames was calculated off of the bulk price of polyvinylchloride. Initially, the author researched the price of sheets of polyvinylchloride which could be cut in order to fit the geometric requirements of the frame; however, the cost of these sheets was over $100 per module. This cost of polymer sheets seemed excessive. Therefore

4.3 Labor Cost

Cost of labor for each battery system was calculated based on the estimated time for assembly and number of workers required for each task. Cost of labor for each worker was estimated at $35 per hour. Due to the large scale systems, it was assumed that there is no assembly line or automated sections of the assembly process. Each step is completed by human workers, and each component is assembled for specifically for one battery system.

The labor cost estimate is more accurate for the larger systems, those greater than 100kW. Systems of this size are typically custom-ordered and designed for an individual customer. These systems require laborers to custom assemble the battery system to meet the design characteristics of the application. However, the smaller on the order of 1 to 10kW could easily be mass manufactured, using assembly lines and machines to assemble the systems. Creating the assembly line would increase the initial capital cost of the manufacturing plant; however, over time the cost of assembling each individual battery system would decrease.

4.4 Overhead Cost

The overhead cost is estimated as 10% of the component cost and 10% of the power conditioning system cost. This is an estimate but accurately assumes that there are additional overhead prices associated with the Zinc Bromine batteries.

4.5 Transportation Cost

Zinc Bromine flow battery systems can range in size from that of a moving box to that of a moving truck. In order to transport these systems from the manufacturing plant to the customer site, the best method is freight train or freight truck. Train transportation is less expensive than truck, however, upon arriving, a truck must load the battery system from the train and take it to the customer site. Freight truck transportation is able to take the battery system directly to the customer site.

Transportation cost varies for various sized systems. Large systems must be shipped with a designated freight car on a train or courier a freight truck. Smaller systems can be shipped without requiring designated freight cars or a truck.

Freight estimates are made based on dimensions and weight. The freight estimate for a 1MW 5 hour system is $3,000. This estimate is assuming the shipping is 1,500 miles. Shipping prices for the smaller system start at $200. These prices are conservative estimates on the cost of shipping these systems. Larger orders may have economies of scale, and with the smaller systems, there could be many orders consolidated based on the final destination.

4.6 Additional Costs

The total cost of the Zinc Bromine battery system includes features and costs beyond that of just the components of the battery cell and stacks. Batteries output is direct current (DC), in order to utilize the battery to operate devices or connect to the grid; it must be converted to alternating current (AC). An inverter is required to invert the DC to AC power and vice versa for discharging and charging respectively. Voltage and power output of the battery system must be regulated, the control system regulates the power output of the battery system as well as indicates and tracks the state of the battery. Power electronics are needed to connect the battery stacks to the inverter and control system.

4.6.1 INVERTER

The inverter is the most significant cost driver for the Zinc Bromine flow battery. This model indicates that over 30% of the total cost for a 1 MW system is the price of the inverter. In order to drive down the cost per kW and make Zinc Bromine batteries market competitive, the price of the inverter must come down.

Although inverter prices for batteries are quite high at this time, there is hope for the inverter price to decline over time. The wind industry has seen a great decrease in inverter prices. The current price for invertors for the battery industry is $200/kVA[6] and wind industry is $75/kVA[24]. If the battery industry continues to grow, it is to be expected that there will be economies of scale and the inverter prices will decrease.

To determine the impact of the inverter price on the total price of the Zinc Bromine battery system, an analysis was completed with varying inverter prices. Assessing the impact of inverter price, the analysis included inverter prices of $75/kVA to $200/kVA. This encompasses the low end price of wind inverters and the current price of battery inverters.

Inverter Prices	1MW 5 hr System		100kW 5 hr System		10 kW 5hr System		1kW 5 hr System	
	% of Total Cost from Inverter	$/kW for System	% of Total Cost from Inverter	$/kW for System	% of Total Cost from Inverter	$/kW for System	% of Total Cost from Inverter	$/kW for System
$200/kVA	28%	$1,022	23%	$1,223	13%	$2,235	7%	$4,115
$175/kVA	24%	$984	20%	$1,188	11%	$2,200	6%	$4,080
$150/kVA	21%	$949	17%	$1,153	9%	$2,165	5%	$4,045
$125/kVA	17%	$914	14%	$1,118	8%	$2,130	4%	$4,010
$100/kVA	14%	$879	11%	$1,083	6%	$2,095	3%	$3,975
$75/kVA	10%	$844	9%	$1,048	5%	$2,060	3%	$3,940

Figure 4.2 – Percentage of System Cost from Inverters for 5 Hour Systems of Various Power Capacities

The chart above indicates that the price of the inverter has a large impact on the total price of the Zinc Bromine system for batteries above 10 kW in power capacity. Inverters are priced per kW and unlike other cost components such as material and labor, the prices does not scale down for the larger systems.

The future price changes for the inverters will have a significant effect on flow batteries. If inverter prices drop significantly in the next few years, flow batteries will be very competitive with lower cost energy storage technologies.

4.6.2 Power Electronics

The power electronics include the wiring and connection between the battery stacks and the inverter and control system. The cost for the power electronics of the system scales with the power capacity of the system. The power electronics include the transformer, cabling, contactors, and breakers. Power electronics are assumed to cost $50/kW[6].

4.6.3 Control System

The control system of the Zinc Bromine battery system is important in regulating the current and voltage output of the battery system as well as monitoring and reporting the charging and discharging history of the battery. Control system price in the model was $20/kW. The cost of the control system scales with the power of the system.

4.7 Model of 1MW Battery System

Zinc Bromine flow batteries are unique in that the batteries are easily scaled from 1kW to 1MW in power capacity. However, to completely understand the breakdown of the cost, the study assesses the 1 MW battery systems. The breakdown of the costs and the key cost drivers are examined for 1 MW battery systems.

4.7.1 Breakdown of Cost

The zinc-bromine cost model highlighted the key cost drivers of the battery system. The costs of various sized battery systems were broken down to determine the costs from different components of the system. The model includes the eight segments: cell structure, pumps and pipes, electrolyte, power system, control system, labor, shipping, and overhead. Cell structure includes; frames, screws, Nafion membrane, and bipolar electrode. Pumps and pipes include all of the pipes, tubing, connections, and pumps. Electrolyte includes all of the reactant chemicals, complexing agents, water, and storage tanks. Power system includes the transformer, cables, connections, and invertors.

The figure below indicates the portion of the total cost for which each segment is responsible. Power system, cell structure, and labor are the largest contributors to the total cost of the system.

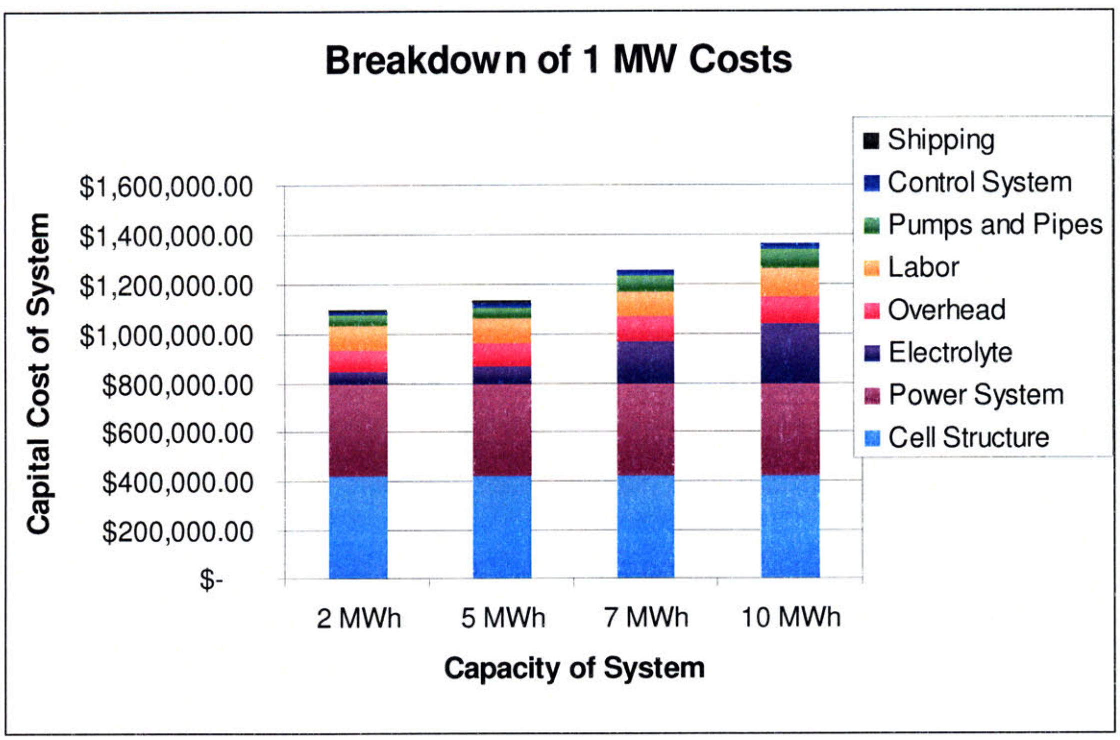

Figure 4.3: Breakdown of costs for 1 MW Zinc Bromine Battery Systems

The largest cost components for the 1 MW battery systems are the cell structure and the power system. Further analysis into the cost of the structure leads to understanding the components which drive the total cost of the system.

Regardless of the energy capacity of the system, the cell structure is a key cost driver. To more accurately assess how the various components affect each battery system, the percentage of cost from each component was calculated. The figure below indicates the percentage of the total cost from each component for various energy capacity systems.

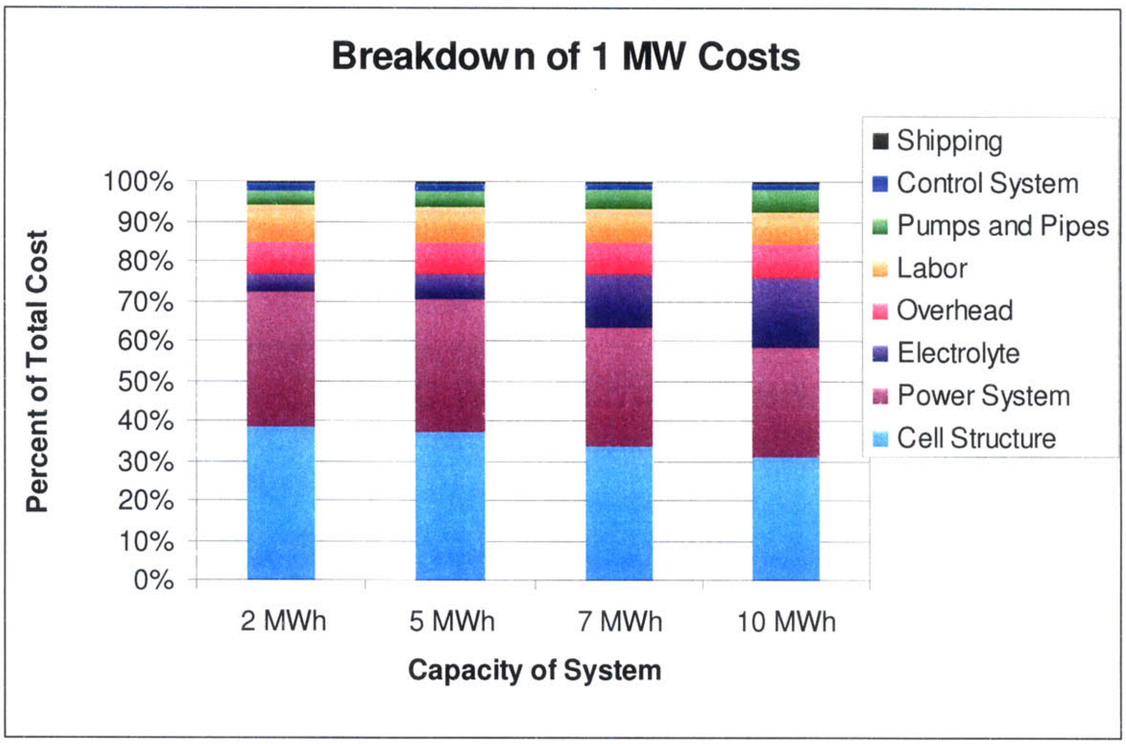

Figure 4.4: Breakdown of percentage of cost from each component in 1 MW Zinc Bromine systems

The key features to note are how the components scale with the energy capacity of the system. The percentage of total cost from the cell structure decreases as the energy capacity increases. Cell structure, control system, pumps and pipes are correlated to the power capacity of the battery system. The tanks and electrolyte are correlated to the energy capacity of the system. Therefore, the percentage of cost from the cell structure, control system, pumps and pipes scales inversely with the energy capacity of the system. Conversely, the percentage of cost from the electrolyte and tanks scale with the energy capacity of the system.

As mentioned previously in the study, the labor cost is an estimate based on individual laborers assembling the system. The time estimation for the system assembly was 3,000 working hours. This estimate was based on the approximate time for each task in the assembly summed by the total parts being assembled. Laborers may work faster or machines may be able to assemble the battery systems faster in order to drive down the manufacturing costs.

Cell structure encompasses the electrodes, membranes, frames, screws, and end plates of the battery system. There are many different components in the cell structure; this study estimated the cost of each component based on available information. Purchasing the components wholesale may drive down the total cost of the cell structure.

4.7.2 KEY COST DRIVERS

The key cost drivers for the Zinc Bromine battery system are the inverter, Nafion membrane, glassy carbon electrode, and the pumps and pipes. In order to breakdown the cost further, an evaluation of how the percentage of cost from different components varies with the energy capacity of the system.

The inverter and Nafion were the largest components of the total cost. To determine the total percentage from these two components, the total cost of a 1 MW/5hr system was broken down. The figure below indicates that the Nafion contributes 27% and the inverter 26% of the total cost of the battery. These two components attribute for over half of the total cost of the battery system.

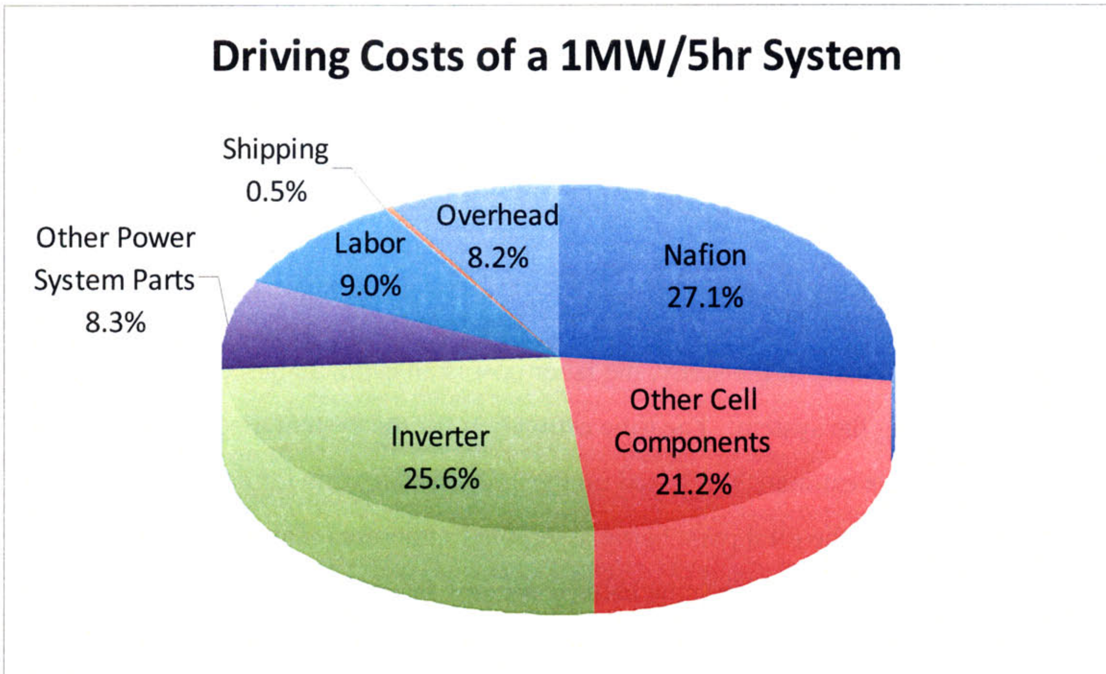

Figure 4.5: Percentage of Total Cost from Key Cost Drivers in a 1 MW/5hr Zinc Bromine Battery System

Inverters and Nafion have a large effect on the total cost of the Zinc Bromine battery. However, both of these components are likely to come down in cost in the future. As mentioned earlier, the membrane for the

4.8 Power Capacity Variation

Flow batteries have the potential to work in many different applications. In order to determine the feasibility for these different applications, there must be an understanding of how the cost varies with the power of the system. Zinc Bromine flow batteries can scale from 1 kW to many MW in power capacity, it is important to examine the costs of each system as the cost of the system does not scale linearly with the power capacity.

The figure below indicates the total cost as well as cost per kilowatt and kilowatt-hour for four different power sizes. This highlights that many of the costs are driven down by increasing the power of the system. Key cost drivers change for the different power sized systems. In a 1kW system, the storage tanks, pumps, and shipping contribute the most to the total cost in contrast to the inverter and bipolar electrode of the 1MW system.

System Size	1 MW 5hr		100 kW 5hr		10 kW 5hr		1 kW 5hr	
Cost Components	Cost	% of Total	Cost	% of Total	Cost	% of Total	Cost	% of Total
Cell Structure	$ 332,825	32%	$ 42,282	35%	$ 7,047	32%	$ 584	14%
Electrolyte	$ 72,280	7%	$ 12,805	10%	$ 2,300	10%	$ 987	24%
Pumps and Pipes	$ 44,133	4%	$ 4,898	4%	$ 2,699	12%	$ 981	24%
Power System	$ 375,240	36%	$ 37,100	30%	$ 3,710	17%	$ 371	9%
Control System	$ 20,000	2%	$ 3,000	2%	$ 1,000	4%	$ 200	5%
Labor	$ 99,608	10%	$ 10,017	8%	$ 2,108	9%	$ 538	13%
Shipping	$ 5,000	0%	$ 3,000	2%	$ 2,000	9%	$ 200	5%
Overhead	$ 82,448	8%	$ 9,196	8%	$ 1,484	7%	$ 253	6%
Total Capital Cost	$ 1,031,534		$ 122,299		$ 22,348		$ 4,115	
$/kW	$ 1,032		$ 1,223		$ 2,235		$ 4,115	
$/kWh	$ 206		$ 245		$ 447		$ 823	

Figure 4.6: Table of cost for 5 hour systems of 1kW, 10kW, 100kW, and 1MW

Assumptions may play a role in the costs. It was assumed that each system would ship individually, however, in reality, multiple 1kW systems could ship together. Furthermore, with the smaller systems, there could be an assembly line instead of individual laborers on each system. All of these assumptions may affect the total cost of the system.

Although many of the key costs for the system change based on the power of the system, it is important to look at the overall cost per kilowatt-hour. Below is the figure which indicates the significant drop in cost per kilowatt-hour from a 1kW system up to the larger systems. It can be noted that at 100kW and larger systems, the cost per kilowatt-hour for a 3 hour system asymptotes to around $300/kWh.

4.9 ENERGY CAPACITY VARIATION

Power and energy are the two key features of a battery rating. Flow batteries have the capability of varying the power and energy independently. In this study the dependence of the cost on the energy capacity of a multiple power capacity systems were analyzed. The model computed the cost per kilowatt-hour for battery systems of 1, 2, 3, 5, 7, and 10 hours of storage.

Although the capital cost of a system is important, more significant costs are the cost per kilowatt and cost per kilowatt-hour. Varying the energy capacity of a Zinc Bromine system has a large impact on the cost per kilowatt-hour. Because the cell structure scales with power capacity, the only components varying in cost are the electrolyte and tanks. The figures below indicate the breakdown of the costs of 1 MW systems of 2hr and 10hr capacities to indicate the differences in cost when varying the energy capacity.

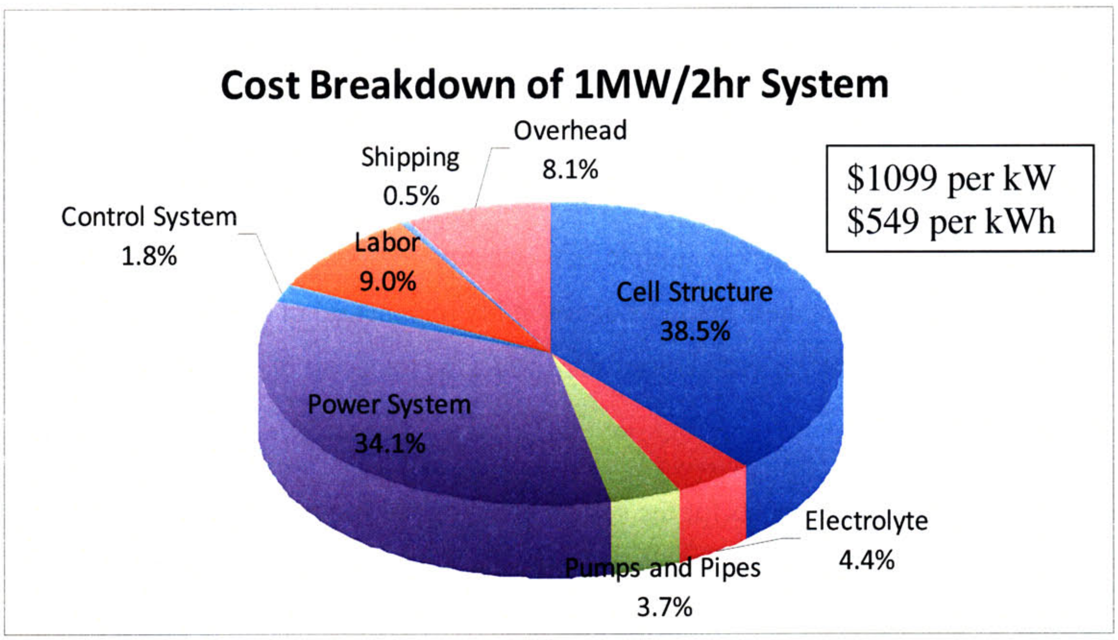

Figure 4.7: Breakdown of the cost of a 1 MW/2hr Zinc Bromine battery system

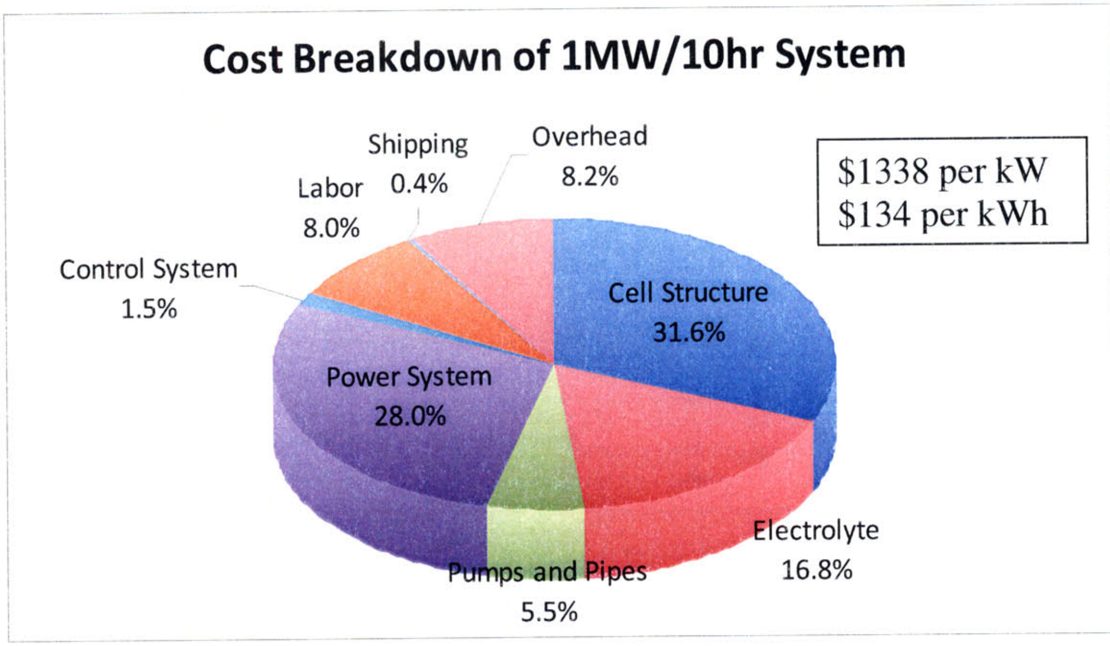

Figure 4.8: Breakdown of the cost of a 1 MW/10hr Zinc Bromine battery system

Although the percentages of cost from the components do not vary greatly, the cost per kilowatt-hour dramatically decreases as the energy capacity increases. Because the electrolyte is a relatively small cost of the whole system, the increase in capacity drives the cost per kilowatt-hour down. A 1 MW/2hr system costs $550 per kilowatt-hour, while a 1 MW/10hr system costs only $135 per kilowatt-hour.

Different applications need different energy capacities. In applications with quick cycles and only short demand times, a smaller energy capacity will suffice. However, applications that require hours of power output will require larger energy capacities of the system. Electrolyte capacity is the driver for the energy capacity of a system.

The figure below indicates the relationship between cost per kilowatt-hour and energy capacity of Zinc Bromine battery systems. As the electrolyte is not a large cost driver, the cost per kilowatt-hour decreases as the energy capacity increases.

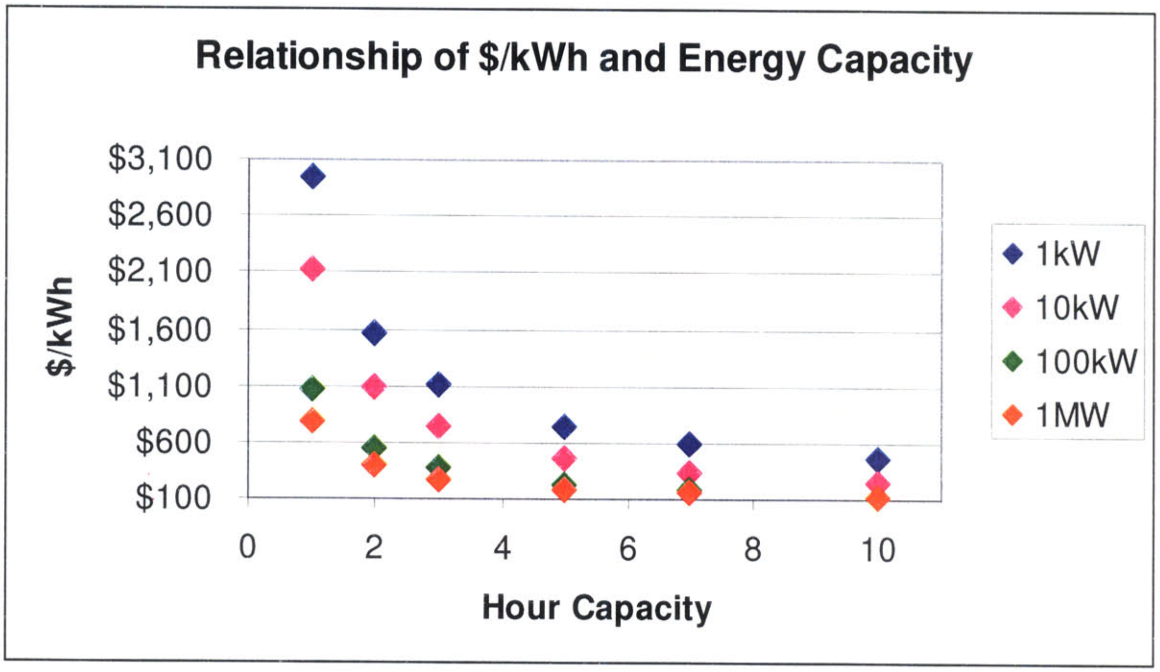

Figure 4.9: Relationship Between Cost per kWh and the Energy Capacity of Zinc Bromine Systems

Most energy storage applications do not require 10 hours of storage. However, the relationship between cost per kilowatt hour and energy capacity indicates for 100kW and 1MW battery systems asymptotes near $200 per kilowatt hour above 5 hours of storage. Smaller systems however remain at a higher cost even at 10 hours of energy storage. This is driven by the total cost of the power of the system. Smaller systems have higher cost per kilowatt, and therefore the cost per kilowatt hour too is higher.

4.10 Sensitivity Analysis

To assess the accuracy of the bottoms up analysis of Zinc Bromine batteries, the author compared the calculated costs with the costs and prices reported by Zinc Bromine companies and in literary papers. Reports indicate that the price per kilowatt for Zinc Bromine systems is between $800 and $1500, which for the systems above a few kilowatts power capacity is accurate. Additionally, reports suggest the cost per kilowatt-hour is between $200 and $300; these numbers are also supported by the model in this study.

4.11 Cost Summary

Zinc Bromine flow batteries have many different components and features that make up the total cost of the battery system. The components that make up the largest percentage of the total system are the cell structure and the inverter. If there is an increase in demand for these materials and components as flow batteries start to increase in production, there will likely be a decrease in the price in many of the components of the system.

Also, the power capacity of the system has a large impact on the cost of the system and cost per kilowatt. Zinc Bromine flow batteries are most competitive at power capacities above 100kW. However, some of the assumptions in the model could have lead to false calculations for the cost of the smaller battery systems. Overall, the costs of the battery systems over 100kW are competitive with other energy storage technologies, yet the smaller systems must come down in price in order to become competitive. Similar to the cost of components, as flow batteries start large scale production, the cost of the smaller systems is likely to come down. This study assumed that each battery system was created individually, when produced through assembly lines and with materials purchased in bulk, the cost of small power capacity Zinc Bromine batteries will drop dramatically.

Energy capacity of Zinc Bromine systems dramatically affects the cost per kilowatt-hour. Zinc Bromine batteries are most cost competitive when the energy storage capacity is above 5 hours. Above 5 hours, the cost per kilowatt-hour is varies only slightly.

Based on the current study of the cost of Zinc Bromine flow batteries, these batteries are most cost competitive above 100 kW in power capacity and 5 hours in energy capacity. However, with future increase in flow battery production, smaller systems and lower energy capacities are likely to become competitive as well.

CHAPTER 5 – APPLICATIONS AND MARKETS

Due to the modularity and energy capacity variation of flow batteries, Zinc Bromine batteries can be used in various applications. These batteries range from 1kW to multiple MW and can discharge over 1 to 10 hours. Lifetime of the battery is another distinguishing feature of the Zinc Bromine system. Unlike many other electrochemical storage technologies, Zinc Bromine batteries can cycle thousands of times with out degrading the battery performance.

Zinc Bromine battery is promising for many different applications; this study assessed the applicability of Zinc Bromine batteries in both small niche and large utility applications. The power and energy demand of each application; frequency of demand, duration of demand, and capacity of demand, were assessed to determine for which applications Zinc Bromine batteries are best suited. Zinc Bromine batteries are able to span the needs of various applications, the batteries respond quickly similar to flywheels and other batteries, but are also able to discharge over multiple hours similar to pumped hydro and compressed air energy storage (CAES). This study analyzed all the potential applications for Zinc Bromine flow batteries and determined for which the battery is best suited.

Technologies are selected for energy storage applications based on capital cost, maintenance cost, reliability, cycle-life, power capacity, and energy capacity. Each application prioritizes different energy storage characteristics, this study aims to assess the priorities of each application and discuss the applicability of Zinc Bromine flow batteries with the proposed application. For the applications discussed in the following sections, the existing energy storage technology is compared to flow batteries. The advantages and disadvantages of flow batteries in comparison to the existing technology are evaluated and discussed.

5.1 SMALL-SCALE APPLICATIONS

Despite the large interest in grid-tied energy storage applications, there are also many smaller markets and applications for energy storage devices. Currently, lead acid batteries are often used in these smaller applications. Zinc Bromine batteries are comparable to lead acid batteries in terms of energy density; however, Zinc Bromine batteries have a longer cycle-life and larger operating temperature range. Zinc Bromine batteries are compared to lead acid batteries for many of the applications in which lead acid batteries are currently being used.

5.1.1 OFF-GRID AND MICRO-GRID SUPPORT

Many homes in the United States and worldwide are not connected to the electricity grid. These homes have either no electricity, or require generators to power the houses. Worldwide over 2 billion people live with out electricity. Flow batteries give the opportunity to power these homes off of renewable energy and supply constant output of power.

In the United States there are over 180,000 homes that are off of the electricity grid. The number of homes off of the gird is increasing each year. Many of these homes rely on solar or wind to generate power, yet most of these homes have back up generators to cover the times during which the renewable sources are not providing power. Flow batteries are a quite, reliable, and safe alternative to generators. Additionally, flow batteries do not require any fuel to operate. Although flow batteries fit the needs of off-grid homes in terms of power and energy capacity, one challenge of the application is the cycle frequency. In the United States, many of the homes not connected to the electricity grid are non-primary homes. These may be summer cottages or vacation homes. Zinc Bromine batteries operate optimally if they are frequently cycles, which would likely not be the case for these homes.

Worldwide, flow batteries can assist in creating micro-grids and providing power to remote locations. When attached to a solar or wind farm, flow batteries can ensure that there is constant power output to power the home or homes attached to the system. In regions where there is no electricity grid established, flow batteries can assist in creating micro-grids to power villages and towns. Zinc Bromine batteries have advantages over other batteries for this applications. Zinc Bromine batteries, like most flow batteries, have a long cycle life between 1,500-3,000 cycles and operating temperatures near ambient temperatures. Lead acid batteries also have near ambient operating temperatures; however, Zinc Bromine batteries have twice the energy density, increased cycle-life, and do not degrade when in temperatures above 25°C. Due to the toxic nature of the electrolyte, and training for the maintenance is required. However, once trained, due to the ambient operating temperatures of the battery systems, the maintenance is fairly low risk.

5.1.2 Lawnmower and Golf Carts

Lawnmowers and golf carts currently rely on lead acid batteries for power. Commercial lawnmowers and gold carts operate between 1kW and 5kW. Flow batteries have the potential to work for in these applications, as flow batteries have energy capacities higher than lead acid batteries. Considerations such as cost, lifetime, size, and weight are important for lawnmower and golf cart applications.

In commercial applications, these devices are in use for up to 12 hours per day. Assuming that a professional gardener works 12 hours per day, and they use the lawn mower half of the time, the lawn mower would need to operate for 6 hours each day. However, the lawn mower does not operate at full power capacity during the whole shift. Taking on the assumption that the lawnmower averages half the power capacity for the 6 hour shift, the battery needs to be able to store 3 hours of charge.

Golf carts are used similarly to lawnmowers. Golf courses are open from dawn to dusk, which averages to approximately 12 hours each day. Each round of golf takes approximately 3 hours, but the golf cart is being used for only 30 minutes of that time. Therefore, if a golf cart is being used for 4 rounds of golf each day, the battery needs to store 2 hours of charge.

Lawnmowers and golf carts in commercial use operate at least five days a week. These applications require the battery to cycle approximately 250 times each year. Lead acid batteries degrade when deeply discharged. Therefore, after around 200 to 300 cycles, the battery has lost a considerable portion of the power capacity. Unlike lead acid batteries, flow batteries work optimally in deep discharge applications and degrade only slightly after hundreds of cycles. In commercial applications in which lawn mowers and golf carts are being discharged everyday, flow batteries are able to last considerably longer than lead acid batteries. The chart below compares the prices of lead acid and flow batteries for golf cart and lawnmower applications.

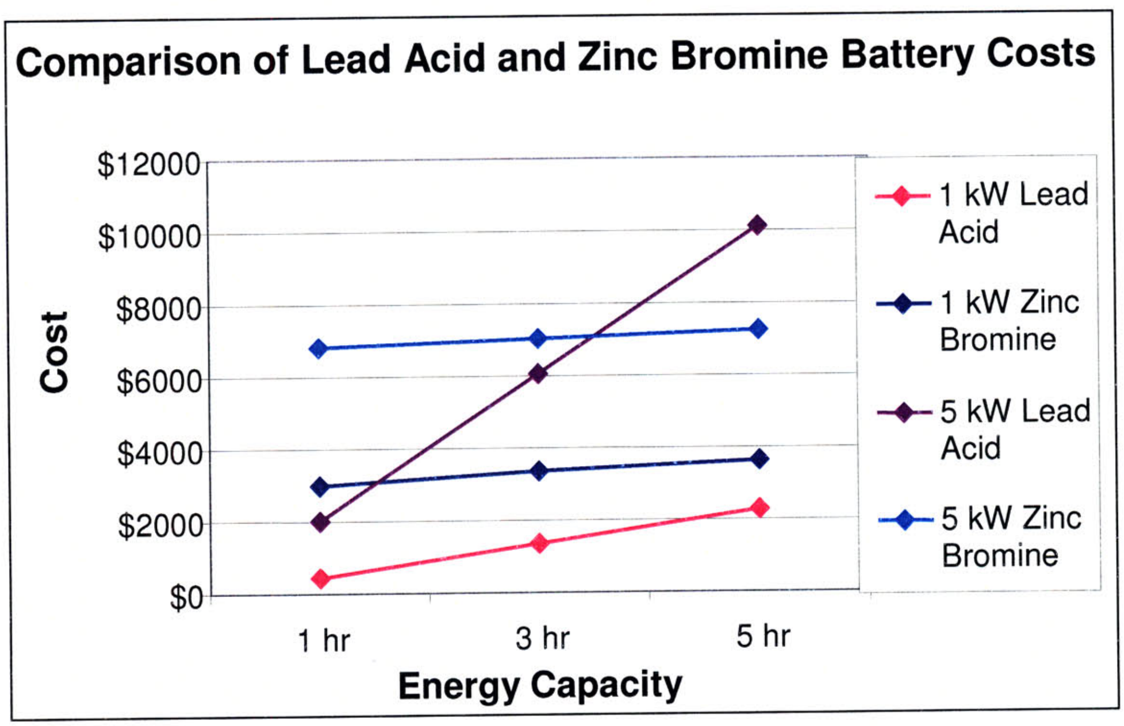

Figure 5.1: Comparison of Lead Acid and Zinc Bromine Battery Costs

Zinc Bromine flow batteries cost less than lead acid batteries for 5 kW power capacity and energy capacities above three and a half hours. Lower power capacity prices for Zinc Bromine flow batteries are currently too high to compete with the cost of lead acid batteries. However, when assessing the price per discharge cycle, Zinc Bromine batteries are much more cost competitive with lead acid batteries. The chart below assumes 400 cycles for the lead acid battery and 1500 for the Zinc Bromine battery.

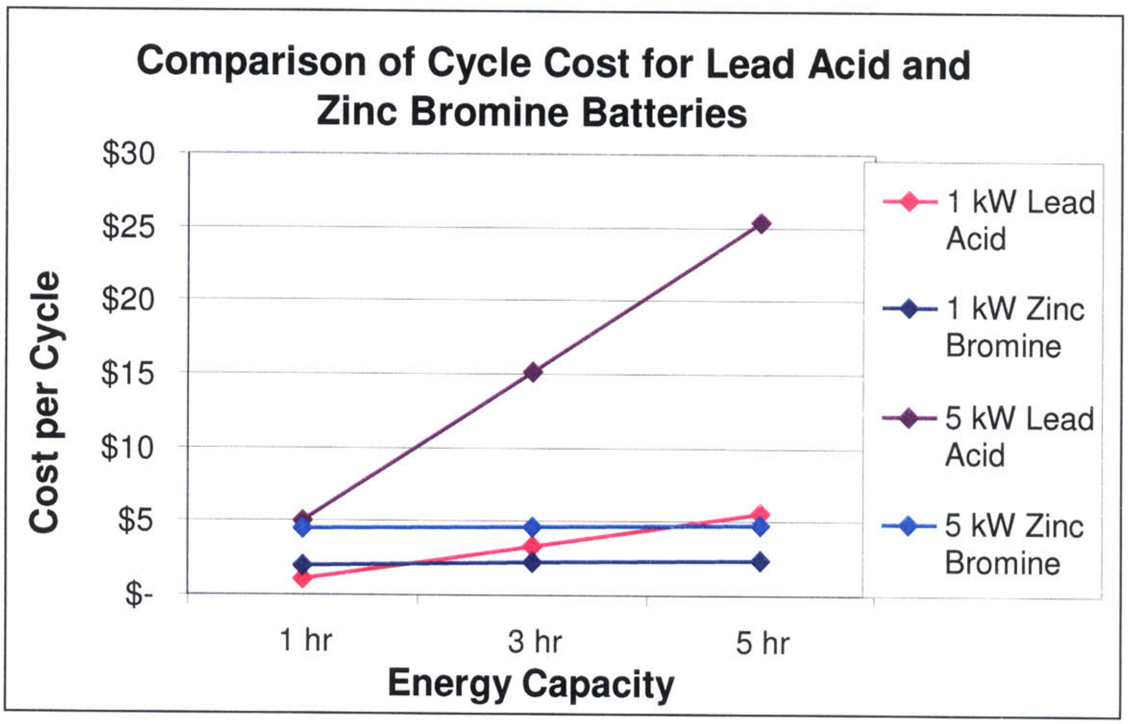

Figure 5.2: Comparison of Cycle Cost between Lead Acid and Zinc Bromine Batteries

Zinc Bromine batteries are highly cost competitive with lead acid batteries when comparing the price per cycle. A 1kW Zinc Bromine flow battery is cost competitive with a 1kW lead acid battery above 3 hours of energy capacity. Zinc Bromine batteries are cost competitive with lead acid at 5kW power capacity above 1 hour energy capacity. Additional considerations must be taken into account with the cost per cycle for these battery systems. Time value of money and the utility of the cycle life are other considerations.

The capital costs of the Zinc Bromine batteries are higher than that of the lead acid batteries. Despite the longer lifetime of the battery, the customer is with out the additional cash spent on the flow battery. If the customer purchases the lead acid battery, they are able to invest the money (difference between the Zinc Bromine battery and the lead acid battery).

Lawnmower and golf carts which are not used frequently are not well suited for flow batteries. Personal lawnmowers which are typically cycled once a week are better suited to stay with the lead acid battery.

5.1.3 Electric Wheelchairs, Trams and Scooters

Similar to golf carts and lawnmowers, electric wheelchairs, trams, and scooters are other possible applications for flow batteries. These applications require batteries as they are used indoors and cannot have emissions. Comparisons between Zinc Bromine flow batteries and other battery chemistries were analyzed in order to determine batteries best suited for these applications.

Zinc Bromine batteries have been used in prototypes for electric vehicles, such as the Austrian Postal Service vehicle powered by a Zinc Bromine battery from Studiengesellschaft für Energiespeicher und Antriebssysteme [8]. Although there has been less interest in Zinc Bromine batteries for electric vehicles due to the relatively low energy density, applications in which the energy density has less effect on the performance may be better suited for Zinc Bromine batteries.

Wheelchairs, trams, and scooters are all possible applications for Zinc Bromine batteries. Because the operating temperatures are rarely above 50°C, there is little hazard of burns from the batteries. Zinc Bromine batteries have higher energy density than many other flow batteries, but have a cycle-life longer than lead-acid batteries.

5.2 Large-Scale Applications

In comparison to the smaller applications for flow batteries, gird connected applications are often larger in size and volume. Grid connected applications include ancillary services, load leveling and renewable energy stabilization. Larger applications give rise to the potential for more income. However, there are also more requirements in these applications. Additionally, utilities are often slow to adopt new technologies; it is not likely that these entities would willingly take on new ventures with out proof of the technology and a guarantee of profits.

Large scale applications also require additional support from the utility providers. Zinc Bromine batteries are able to fit the needs of these large scale applications; however, the Independent System Operators or Regional Transmission Operators are often reluctant to allow new technologies in the utility space.

5.2.1 Wholesale Electricity Markets

Zinc Bromine batteries have the potential to regulate the price of electricity by charging during off-peak hours and discharging during peak hours. Understanding the opportunity for this requires an understanding of the electricity market. The wholesale electricity market is the price of electricity from the generators to the large electricity retailers. This price is much lower than the price of electricity for the residential user.

Worldwide, there are many different wholesale electricity markets. These markets are typically separated by country or region. The United States has Independent System Operators (ISOs) and Regional Transmission Operators (RTOs). Typically, RTOs control the electric power transmission across larger areas than ISOs.

Below is a list of many of the wholesale markets worldwide and the regions which they cover. These markets include ISOs, RTOs, and energy exchanges. Each country and region has different regulations for the markets.

Name of Market	**Region**	**Website**
California ISO (CAISO)	California, United States and Baja California, Mexico	www.caiso.com
ISO New England (ISO-NE)	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont, United States	www.iso-ne.com
New York ISO (NYISO)	New York, United States	www.nyiso.com
Electric Reliability Council of Texas (ERCOT)	Texas, United States	www.ercot.com
Midwest Independent Transmission System Operator (MISO)	Minnesota, North Dakota, South Dakota, Iowa, Nebraska, Missouri, Illinois, Ohio, Wisconsin, Indiana, and Kentucky, United States and Manitoba, Canada	www.midwestiso.org
PJM Interconnection	Delaware, Illinois, Indiana, Kentucky, Maryland, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and District of Columbia, United	www.pjm.com

	States	
Southwestern Power Pool	Kansas, Oklahoma, and parts of New Mexico, Texas, Louisiana, Missouri, Mississippi, and Arkansas, United States	www.spp.org
Alberta Electric System Operator (AESO)	Alberta, Canada	www.aeso.ca
Independent Electricity System Operator (IESO)	Ontario, Canada	www.ieso.ca
Nord Pool	Sweden, Norway, Denmark, and Finland	www.nordpool.com
Powernext	France	www.powernext.fr
Elexon	Great Britain	www.elexon.co.uk
Single Electricity Market	Ireland	www.allislandmarket.com
European Energy Exchange	Germany, Switzerland, Austria	www.eex.com
Operador del Mercado Iberico de Energie (OMEL)	Spain	www.omel.es
Romanian Power Market Operator (OPCOM)	Romania	www.opcom.ro
Australian Energy Market Operator	Australia	www.aemo.com.au
New Zealand Electricity Market	New Zealand	
Energy Market Company (EMC)	Singapore	Singapore.emc.com
Wholesale Electricity Spot Market (WESM)	Philippines	www.wesm.ph
Japanese Electric Power Exchange (JEPX)	Japan	www.jepx.org

Korea Power Exchange	South Korea	www.kpx.or.kr
Indian Energy Exchange (IEX)	India	www.iexindia.com
Camara de Comercializacao de Energia Electrica (CCEE)	Brazil	www.ccee.org.br
Administrador Del Marcado Mayorista (AMM)	Guatemala	www.amm.org.gt

Figure 5.3: List of the Wholesale Electricity Markets Worldwide

To further understand to opportunity for Zinc Bromine batteries to be used to off-set the price differential between peak and off-peak hours, an analysis of hourly prices from various wholesale markets were assessed. The average difference between peak and off-peak prices were calculated for each day from various months. The difference in peak and off-peak prices is depicted in the figure below.

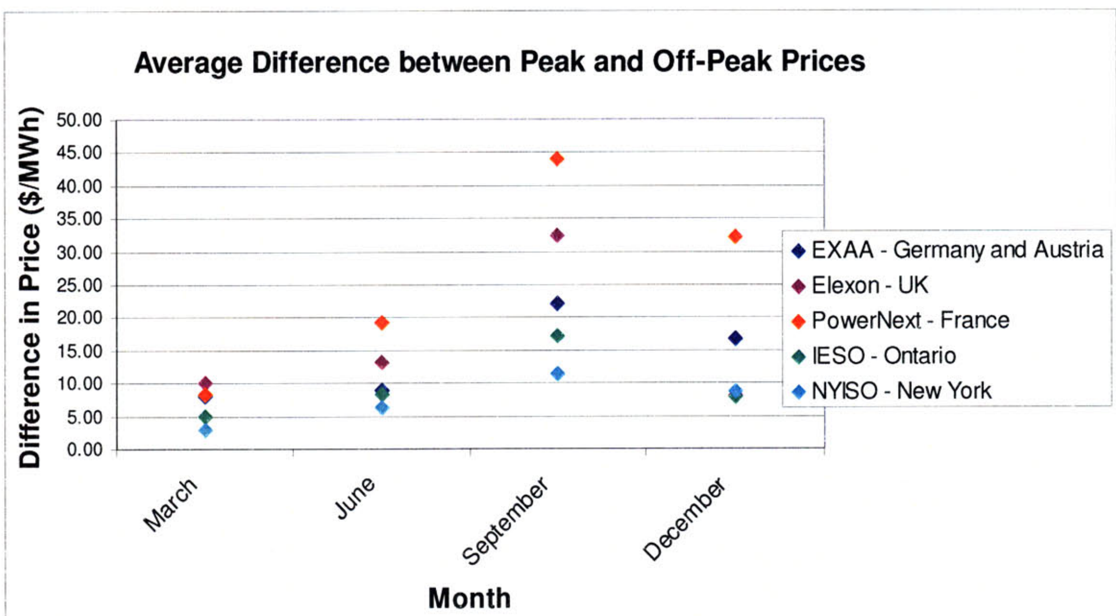

Figure 5.4: Average Difference between Wholesale Peak and Off-Peak Prices from Various Regions Worldwide

The price variation depends on the time of year as well as the region. The maximum price differential is $45 per MWh, which is $0.045 per kWh. Assuming that a Zinc Bromine battery (1MW/5hr) costs $225 per kWh, the battery would need to cycle 5,000 times at an average price difference of $45 per MWh in order to break even. Zinc Bromine batteries have an expected cycle-life of around 3,000. Additionally, the average difference between peak and off-peak prices is $15 per MWh. To break even cycling 3,000 times, a 1 MW/5hr battery would need to cost $45 per kWh. It is not likely that Zinc Bromine batteries will be used in the near future for wholesale load leveling. For the current Zinc Bromine battery to break even cycling 3,000 times, the price differential would need to be $75 per MWh.

In order to Zinc Bromine batteries to be successful in energy arbitrage, the cost must come down to $45 per kWh with the current cycle-life expectations or the lifetime must increase to 15,000 cycles.

5.2.2 Renewable Energy Stabilization

Although it is not likely that Zinc Bromine batteries will be used to reduce the variation between peak and off-peak prices for utilities, the potential for Zinc Bromine batteries to stabilize renewable energy outputs is high. Renewable energy sources such as wind and solar are weather dependent and intermittent. With the current interest in increasing the amount of energy from renewable sources, there is likely to be a need for energy storage as well. Zinc Bromine batteries are well suited for renewable energy stabilization because the energy and power capacity can be designed to meet the needs of the wind or solar farm. Additionally, Zinc Bromine batteries can store up to 10 hours of energy.

Both wind and solar energy production is increasing, in the United States and worldwide. The graph below indicates the recent growth of installed wind worldwide. Although the trend will not continue at the same rate, there is still expected to be an increase in installed wind over the next decade.

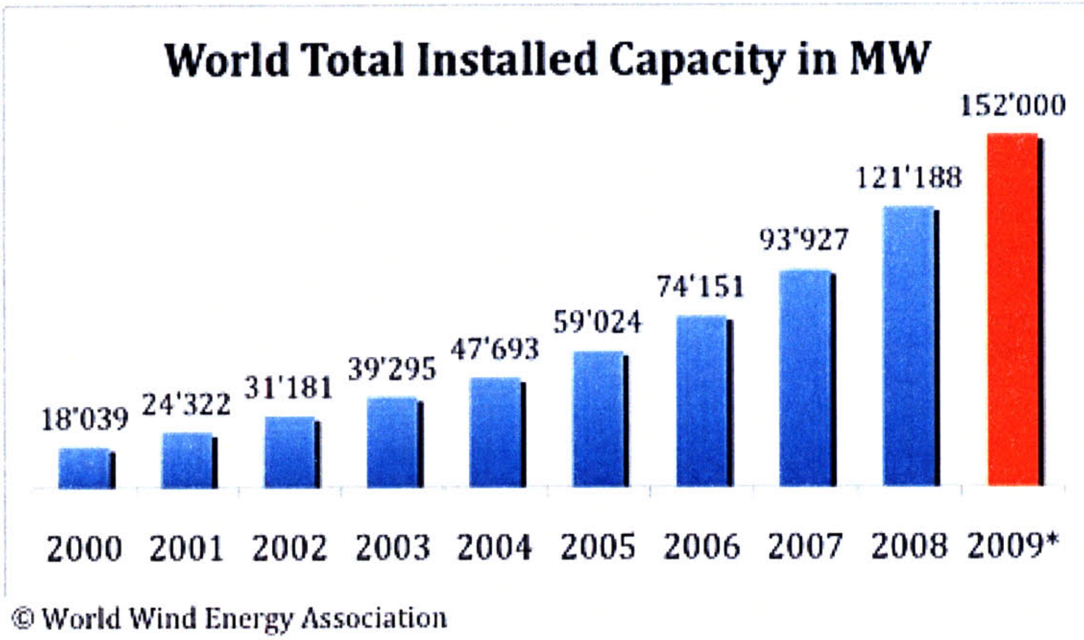

Figure 5.5: Growth of Installed Wind Capacity Worldwide from 1995 to 2007 [25]

The wind industry expects a 25% increase from 2008 to 2009. These increases are likely to continue as many countries are supporting wind and other renewable energy sources. The United States has proposed a plan for 20% Wind Energy by 2030.

The graph below indicates the current percentage of electricity from wind for various countries. Currently, no country has above 18% of the total electricity supplied by wind power.

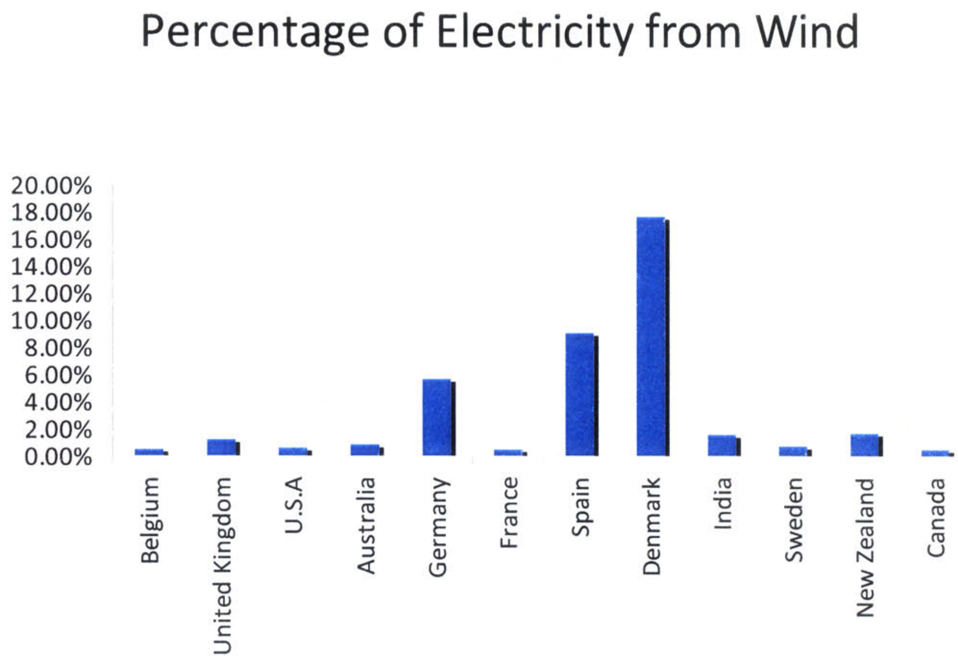

Figure 5.6: Current Percentage of Total Electricity Production from Wind

The future growth of the wind industry may lead to opportunities for Zinc Bromine batteries. Assuming that wind requires 7 hours of storage, and that the Zinc Bromine battery cycled completely once each day for 3,000 days, a 1 MW Zinc Bromine battery would cost $0.06 per kWh. The United States expects that by increasing the total wind energy to 20% of the total energy, that the additional costs of the intermittency will be only 0.5 cents per kWh, this is ten times less than the cost of Zinc Bromine batteries.

Although currently Zinc Bromine batteries may not be economical for stabilizing wind energy, if there is continued interest in "clean" energy, it is likely that energy storage for renewable energy stabilization will be considered. Energy storage enables wind power to be a reliable clean energy source. This eliminates the need for back-up power production from additional power plants and reduces the carbon dioxide emissions.

CHAPTER 6 – COMPETING TECHNOLOGIES

There are many different competing technologies for Zinc Bromine batteries as they span a wide range of power and energy capacities. Energy storage technologies can be categorized by the power capacities or duration of storage. The technologies analyzed in this report are; compressed air, pumped hydro, lead acid batteries, nickel cadmium batteries, sodium sulfur batteries, flywheels, superconducting magnets, and supercapacitors.

In addition to the capacity of each technology, comparisons between the technologies are made based on the performance of the technology and the cost. Performance entails many features of a technology, the cycle-life, efficiency, operating temperature, and size. Costs of systems are compared based on installed cost per kilowatt-hour, as well as the total capital cost of the system.

6.1 COMPARISON OF TECHNOLOGIES

There are many different storage technologies, in order to compare the technologies it is best to understand the power capacity, energy capacity, cost, and cycle-life of the technologies. The figure below breaks down the costs of various energy storage technologies and determines an estimate for the cost per kilowatt. The Zinc Bromine cost calculated in this study is nearly 30% lower than the numbers given for flow batteries in the figure below.

The chart below also indicated the storage capacity of the systems. Different energy storage technologies fit the needs of different applications based on cost, power capacity, cycle-life, and storage capacity. Flow batteries are able to meet the needs of many different applications due to the scalability of the power and energy capacities. However, it is not likely that flow batteries will compete with technologies that aim to meet the needs of applications requiring a few seconds to minutes of storage.

Technology	$/kwh	Storage hours	Total Capital Cost $/kw*
Compressed air energy storage			
Large (100-300 megawatts), below ground	102	10	600-750
Small (10-20 megawatts), above ground	200-250	4	1,000-1,800
Pumped hydro (1,000 megawatts)	100-200	10	2,500-4,000
Battery (10 megawatts)			
Lead acid	330-480	4	1,740-2,580
Sodium sulfur (NAS)	350-400	4	1,850-2,150
Flow battery	280-450	4	1,545-3,100
Flywheel (10 megawatts)	1,340-1,570	0.25	3,695-4,313
Superconducting magnetic storage	650,000-860,000	1 second	350-489
Supercapacitors	20,000-30,000	10 seconds	300-450

Figure 6.1: Comparison of Cost and Storage Capacity of Energy Storage Technologies (* not including PCS costs) [26]

It is important to note that Zinc Bromine batteries would likely not compete with flywheels, superconducting magnetic storage, or supercapacitors. Zinc Bromine batteries are not optimal to operate in applications which require power for only a short duration of time.

Other batteries, pumped hydro, and compressed air energy storage are the competing technologies for Zinc Bromine batteries. A feature of pumped hydro and compressed air energy storage is that unlike batteries, is that these systems have geographical constraints. Pumped hydro and compressed air energy storage systems are permanent, unlike batteries which can easily be moved from one location to another.

The figure below assesses the cycle life and efficiency of the competing technologies. Zinc Bromine batteries have a cycle life comparable to other high-performance batteries; however, batteries cannot compete with pumped hydro and compressed air in terms of cycle life.

Technology	**Cycle Life**	**Efficiency**
Lead Acid	200-1,000	75-85%
Nickel Cadmium	1,000-3,000	60-70%
Sodium Sulfur	2,000-6,000	70-80%
Pumped Hydro	10,000+	70-80%
Compressed Air Energy Storage		75-80%
Zinc Bromine	**1,500-3,000**	**70-80%**

Figure 6.2: Cycle-Life and Efficiency of Energy Storage Technologies [27]

Zinc Bromine batteries are cost competitive with other batteries. Additionally, the efficiencies of the batteries are comparable to other energy storage technologies. The challenge facing flow batteries; is creating a battery that is economical for energy storage applications. Higher reliability and a lower cycle-life are ways in which Zinc Bromine batteries could be improved in order to compete for large-scale energy storage applications.

CHAPTER 7 – INTELLECTUAL PROPERTY

New and emerging technologies must assess the prior art and intellectual property space already in the research area. Flow batteries were first invented in the 1970s; there are many patents in the space. Some patents have expired; however, there have been much advancement made on the initial patents in the flow battery space. New patents have lead to the development of the technology, many challenges initially facing flow batteries have been solved and the technology has advanced due to the research and development over the past few decades.

The plethora of patents and research in the flow battery space has improved the technology; however, it has made it challenging for new players to come into the sector. In order to compete, companies or persons must develop and improve upon the research of the past. Entering into the flow battery space requires new advancements and a great deal of research.

In addition to the many patents in the Zinc Bromine space, there are also companies manufacturing Zinc Bromine batteries. Additionally, there are many other existing and start-up companies in the flow battery space. These companies utilize many of the different battery chemistries mentioned earlier in this report.

7.1 PATENTS

Flow batteries, including the Zinc Bromine chemistry are a technology that was invented in the 1970s. Because this technology is not new, there are many patents in the space. Research institutes, individuals, and corporations all own patents in the Zinc Bromine battery space. Many of these patents have expired, yet many of the newer patents are improvements upon the older expired patents.

This study categorized patents in the Zinc Bromine space. In each category, the most significant and important patents were detailed and analyzed. Many of the patents fall into two different categories, those concerning the electrolyte and those concerning the device structure.

It is important to note who owns the patents in the space. Many of the Zinc Bromine patents were filled by ZBB Energy Corporation, Electric Power Research Institution, Exxon Research and Engineering Company, and Kabushiki Kaisha Meidensha.

7.1.1 Zinc Bromine Electrolyte Patents

Patents in the Zinc Bromine electrolyte space often include potential additives and different mixes of chemicals in order to improve the operations of the battery. There are many patents in the electrolyte space for each flow battery chemistry. Researching and understanding the previous patents in the space is important for a person or company trying to enter into the market.

Below is a list of some of the more significant patents in the Zinc Bromine electrolyte space. These patents describe improvements made to the Zinc Bromine battery based on the composition of the electrolyte solution.

Electrolyte for zinc bromide battery United States Patent 5188915
Electrolyte additive for improved battery performance United States Patent 4818642
Zinc-bromine batteries with improved electrolyte United States Patent 4491625

The patents in the electrolyte space have patented the additives and solution of the electrolyte. These patents have determined the amount of complexing agents required to complex all of the bromine in production. Additionally, they indicate the salts used as supporting electrolyte and the amount required to maximize the efficiency of the battery. Although many of these patents were filled in the 1980's, in order to create new patents, there must be improvement upon the expired patents.

7.1.2 Zinc Bromine Device Patents

The electrolyte of the Zinc Bromine battery is not the only part of the battery which is commonly patented. The device structure and design is important to these batteries. The complexity and multiple cells allow these batteries to be configured in many different designs. Minimizing materials is important to drive the cost of these batteries down. Additionally, creating the simplest design for the battery system is important to reduce cost and maintenance.

The patents listed below are related to the device structure of Zinc Bromine batteries. Patents in this space have significant impacts on the design, layout and components of the Zinc Bromine systems.

Zinc-Bromine Secondary Cell United States Patent 3382102

Zinc-bromine battery with long term stability United States Patent 4482614

Zinc-bromine battery United States Patent 4663251

Zinc Bromine battery United States Patent 4677039

Method and apparatus for maintaining the pH in zinc-bromine battery systems United States Patent 4540639

Zinc-bromine battery with circulating electrolytes United States Patent 5607788

Battery circulation system with improved four-way valve United States Patent 6242125

These patents have all been filled and have helped the Zinc Bromine battery improve over the decades. However, all of the patents now must be improved upon in order to create new patents in the Zinc Bromine space.

7.1.3 IMPORTANT FLOW BATTERY PATENTS

In addition to the patents in the Zinc Bromine space, there are also significant patents which pertain to all flow batteries. These patents are often older patents which describe the operation of flow batteries.

Multiple Cell Redox Battery United States Patent 3540934

Apparatus for circulating electrolyte around multi-section batteries United States Patent 4025697

7.2 COMPETITORS IN SPACE

Flow battery technology was developed over 30 years ago. There have been many companies formed in the past few decades as well as new companies forming in the past few years. Flow battery companies typically focus on specific battery chemistry; there are currently companies in Zinc Bromine, Vanadium-Vanadium, and Iron Chromium.

Currently there are two corporations in the Zinc Bromine battery space. Although many different research institutes research Zinc Bromine batteries, only two companies are currently producing Zinc Bromine batteries.

Although there are only two companies in the Zinc Bromine space, there are many other companies in the redox flow battery space. These companies utilize different battery chemistries. Despite the different chemistry, all flow batteries have similar performance and system characteristics. Therefore, all of the flow battery companies are competing with one another.

7.2.1 ZINC BROMINE BATTERY COMPANIES

The current companies in the Zinc Bromine battery space at ZBB Energy Corporation and Premium Power. ZBB Energy Corporation has been established for many years and was one of the pioneers in Zinc Bromine energy research. Premium Power was established in 2002.

ZBB Energy Corporation

ZBB Energy Corporation began research on Zinc Bromine batteries in the 1980s. ZBB has 45 patents in the flow battery space and has developed and improved the technology over the past few decades. ZBB has installed systems in various locations worldwide. The systems are for; Future House USA Beijing Olympic Games (Beijing, China) , Pacific Gas and Electric Company (San Francisco, USA) , United, Energy Limited (Melbourne, Australia) , Detroit Edison (Detroit, USA) , Sumitomo Corporation (Tokyo, Japan) , Sandia National Laboratories (Albuquerque, USA) [29].

ZBB has two different products, a 25kW/2hr system and a 250kW/2hr system. ZESS 50 is the 50kWh system, and the ZESS 500 is a 500kWh system. The ZESS 500 is ten of the 25kW systems configured in two series.

Premium Power

Premium Power is a Zinc Bromine company located in Massachusetts. They were founded in 2002. Premium Power's products are; Zinc-Flow 45 a 3kW system, Powerblock 150 a 100kW/1.5hr system, Transflow 2000 a 500kW/5.5hr system. Premium Power has claimed that their technology costs 2 cents per kilowatt-hour over the lifetime of the battery. Additionally, they support that their costs are $100 per kWh and $300 per kW. These costs are considerably lower than those calculated in this model. These costs may omit the transportation and power conditioning systems.

7.2.2 Other Redox Flow Battery Companies

There are many different flow battery companies currently in early stage production or starting to form. Given the many different battery chemistries which are able to utilize the flow battery technology, different companies utilize different battery chemistries.

The list below includes the companies that are currently in the flow battery space. These companies range in age from early stage start-ups to decade old companies.

PRUDENT ENERGY

Prudent Energy acquired VRB Power in January of 2009. VRB Power went bankrupt in 2008, at which Prudent Energy acquired the company and technology. VRB Power utilized the Vanadium-Vanadium chemistry; Prudent Energy is likely to continue to use this chemistry. Prudent is backed by Draper Fischer Jurvetson and DT Capital. Prudent Energy is located in Beijing, China.

DEEYA ENERGY

Deeya Energy is a flow battery company that has attracted a lot of interest in 2009. Deeya Energy utilizes the Iron Chromium chemistry. The current focus of Deeya Energy is on stabilizing the power for Indian telecom. Deeya Energy aims to utilize flow batteries in any application currently using diesel generators. Current prices for the 2kW systems from Deeya Energy are $4,000 per kW; however, these costs are estimated to come down.

In July 2009, Deeya Energy shipped the first battery systems to India to be installed for telecom base stations. These systems are 2kW/3hr systems. These systems claim a 5,000 cycle-life. Deeya Energy expects to scale up their batteries from the 2kW/3hr system to a 60kW/3.5hr system.

V-FUEL

Located in Australia, V-Fuel utilizes the Vanadium-Vanadium chemistry and is currently creating a second generation Vanadium Bromine battery. V-Fuel has the exclusive rights to the Vanadium Bromine chemistry from University of New South Wales. The company was established in 2005.

CELLSTROM

Cellstrom is an Austrian company. Established in 2002, they have turn-key Vanadium-Vanadium battery systems. In addition to a large system, Cellstrom also has solar filling stations. These stations utilize solar panels to generate electricity; the electricity is stored in the flow battery and then discharged to charge an electric vehicle.

ENERVAULT

Enervault is a flow battery company currently in stealth mode. Enervault has not released information on the battery chemistry which they are using. This company is relatively young and started attracting attention in 2009.

ENSTORAGE

Enstorage is another relatively new start-up company in the flow battery space. Enstorage has not released information on the chemistry they are using. Greylock Partners, Canaan Partners, and by Siemens Technology-to-business (TTB) fund all are backing Enstorage [28].

CHAPTER 8 – TECHNOLOGY ROADMAP

Flow battery technology is promising in today's market. There are many potential applications, and the ability to span different power and energy capacities ensures that flow batteries can fit the needs of many different applications. Current political pushes to increase the production of clean energy from renewable energy sources will likely give rise to many opportunities for flow batteries. Similar political interests in conserving energy and reducing wasted energy will allow flow batteries to enter the market.

Flow battery technology is fairly established. Still concerns over the complexity of the systems and the lifetime performance of the batteries may limit the widespread adoption of the batteries. Despite the fact that flow batteries are a good solution for many of the ancillary services for ISOs and RTOs, these corporations will not invest in technologies with out a proven history. Although the large-scale applications are likely to be the best suited for flow batteries and most likely raise the most income for the battery space, it is important to prove the technology before expanding into the market.

Experience and improvements are advantages that flow batteries have over some of the emerging energy storage technologies. However, the problem with the years of experience has also lead to many companies entering the market and many patents in the space. New companies will have a difficult entering the flow battery space unless they have an important patent or have developed different electrolyte chemistry.

8.1 PROOF OF TECHNOLOGY

Critics of flow batteries want proof that the technology is able to meet the claims currently stated. In order to prove that flow batteries are a reliable and cost-effective solution, demonstrations of the technology must established. There are currently many different flow battery systems operating world-wide; however, the data from these systems must me collected and published in order to prove the validity of the technology's claims.

Reliability is a key feature for energy storage technologies. Demonstrations of both small and large scale systems which operate for thousands of cycles must be established in order for flow batteries to gain credibility as an energy storage technology. Additionally, these demonstrations must indicate the amount of maintenance and support needed for the battery systems. Flow batteries have more parts and components than other batteries; therefore, there is concern that these additional components require more maintenance.

Utilities are historically slow at adopting new technologies. Therefore, it is critical to have flow batteries enter other markets before attempting to develop utility scaled applications. Developing smaller systems for mobile applications, private homes, and manufacturing plants is the best way for flow batteries to prove the technology before attempting to enter the utility scale market.

8.2 FUTURE PROJECTIONS

Zinc Bromine batteries have a promising future. Although there technology must be proved before wide-spread adoption of the technology, Zinc Bromine batteries will likely increase in demand in the future. Flow batteries are a low cost battery when at storage capacities above 5 hours and of power capacities above 100 kW. In order to flow batteries to become widely adopted for large-scale applications, the total price of the system must be $100/kW. The cost model in this analysis estimated costs near $1000/kW; however, this cost is not including any profit for the manufacturer.

Although Zinc Bromine batteries are a promising technology, one of the challenges facing any party interested in entering the market is the intellectual property space. Because flow batteries have been researched over the past few decades, there are many different patents and owners of the patents. A new company must either develop a significant improvement upon the current technology or enter a licensing agreement with the company or person owning the patent.

Zinc Bromine batteries may be a challenging market to enter, utilizing new chemistries to create different flow batteries may be a promising future for new companies. Many of the redox couples have been researched; however, there may be other chemistries or compositions of electrolytes which will give rise to a promising flow battery chemistry.

CHAPTER 9 – CONCLUSION

Zinc Bromine batteries have been improved significantly over the past 30 years. With high efficiencies, high energy density, and low operating temperatures, these batteries are getting increased attention. The advantage of these battery systems is in their modularity and scalability; however, the largest obstacles for this technology are cost and reliability. Large-scale applications such as energy arbitrage and wind energy stabilization, these systems must cost 2 cents per kilowatt hour over the lifetime of the battery. The current cost over the expected lifetime of 3,000 cycles is 6 cents per kilowatt hour. In order to make Zinc Bromine batteries feasible for these applications, the cost must come down significantly or the cycle-life must be increased.

It is likely that with increased interest in energy storage that flow batteries will continue to succeed. Once the current demonstrations of the technology prove the performance, cost, and reliability over the lifetime of the battery, it is likely there will be more interest in large orders.

Zinc Bromine batteries are very cost competitive with other batteries; the availability of the materials, low operating temperatures, high cycle-life, ability to deep-cycle discharge makes these batteries a promising technology. The challenge facing flow batteries and other energy storage technologies is making them competitive with back-up power. However, if political and public interest in energy security and the environment continue, there may be incentives for clean energy storage. In that case, flow batteries would likely succeed due to their advantages over other electrochemical energy storage technologies.

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APPENDIX

COST MODEL FOR A 100KW/3HR ZINC BROMINE BATTERY SYSTEM

The cost model below was used in the study. The inputs were varied based on the power and energy capacity of the battery system. The 100kW/3hr model is depicted below, the same model was used for all of the battery system cost estimated in this study.

Battery Components	What needed	Unit Price	Unit	Amount	Total	% Total Cost	Link
ZnBr2		$ 0.33	kg	2965.448	$ 978.60	2%	ZnBr2 Cost
Br2		$ 0.63	kg	1052.237	$ 662.91	1%	Bromine Cost
NH4Cl		$ 3.00	kg	1056.576	$ 3,169.73	6%	Ammonium Chloride
Water	DI water	$ 0.17	L	3950.629	$ 671.61	1%	Water price
Storage Tank	2079L tanks	$ 550.00	tank	4	$ 2,200.00	4%	Buy Tanks
Pump	DC brushless pumps	$ 400.00	pump	4	$ 1,600.00	3%	Buy Pump
Pipe		$ 9.00	m	18	$ 162.00	0%	Buy Pipes
Pipe elbows		$ 3.92		24	$ 94.08	0%	Buy Elbows
Tubing		$ 10.55	m	18	$ 189.83	0%	Buy Tubing
Tube/pipe connections		$ 13.75		24	$ 330.00	1%	Buy Fittings
Flow controller		$ 210.20		12	$ 2,522.40	5%	
Nafion	3m^2 sheets	$ 250.00	m^2	120	$ 30,000.00	55%	Buy Nafion
Bipolar Graphite Plate		$ 70.29	m^2	120	$ 8,435.28	15%	Buy Graphite
Screw rods		$ 11.45	rod	24	$ 274.80	1%	Buy rods
PVC Frames		$ 12.00	frame	120	$ 1,440.00	3%	Buy Frames
End Plates	Aluminum	$ 177.70	plate	12	$ 2,132.40	4%	Buy Plates
				Total	**$ 54,863.63**	**100%**	
				$/kW	**$ 548.64**		
				$/kWh	**$ 182.88**		

Power System	Unite Price	Total Price
Invertor	$200/kVA	$ 28,000.00
Transformer	$40/kVA	$ 5,600.00
Cables, connections, etc.	$25/kVA	$ 3,500.00
		$ 37,100.00

Control System for Plant	1	$3,000.00
Manufacturing Hours	$286.19	
Labor per Hour	$35.00	
Total Manufacturing	$10,016.82	
Shipping Cost	$ 5,000.00	
Overhead	$ 9,196.36	

Components	Cost	% of Total Cost
Cell Structure	$ 42,282.48	50.59%
Electrolyte	$ 7,682.84	9.19%
Pumps and Pipes	$ 4,898.31	5.86%
Power System	$ 3,500.00	4.19%
Control System	$3,000.00	3.59%
Labor	$10,016.82	11.99%
Shipping	3000	3.59%
Overhead	$ 9,196.36	11.00%
	$ 83,576.81	
	$ 835.77	
	$ 278.59	