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Study Level Design and Economic Analysis of a 7 MW Bromine-Polysulfide Redox Flow Battery

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To Whom It May Concern:

This paper was generated via request by Dr. Robert Counce to create a study level design and economic analysis to determine the feasibility of a 7 MW bromine-polysulfide redox flow battery (BPSRFB). The study was conducted by creating a flowsheet of the BPSRFB process, providing capital and operating cost estimates, and comparing the economic potential of five different cases of varying voltage and current density. All calculations were done in Microsoft Excel.

As stated in the paper, there was an annual net loss for cases 1 through 4; however, there was an annual net profit of $1,464 at 388 cycles per year in case 5. This loss of profit comes largely from the cost of the cell components. The choice of voltage and current density impacted the cell components the most, thus it was the main parameter deciding the economic potential. We concluded the BPSRFB system was not a viable option compared to current power sources due to its low economic feasibility. Until improvements are made with the problems facing mass transfer and ohmic resistance in the battery, it will be unlikely to commercialize a BPSRFB system.

Sincerely,

Lawson Allen Kelli Byrne Amanda Jones Allie Southerland

CBE 488

Study Level Design and Economic Analysis of a 7 MW Bromine-Polysulfide Redox Flow Battery (BPSRFB)

Instructor: Dr. Robert Counce

Group # 7
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Final Submission
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1.0 Introduction

The purpose of this report is to document a study-level design and economic analysis of an electrical grid-scale bromine-polysulfide redox-flow battery (BPSRFB).Redox flow batteries (RFBs) are the subjects of wide scale development activities due to their ability to store large amounts of electrical energy relatively cheaply and efficiently. Renewable-energy sources, such as solar and wind, arebeing deployed in larger numbers than ever before, but these sources are intermittent and often unpredictable and require energy storage for effective incorporation into the electrical supply grid. The BPSRFB is thought to have economic advantages over other energy storage battery concepts. The BPSRFB utilizes sodium bromide as the positive electrolyte and sodium polysulfide as the negative electrolyte. In this system, all of the electro-active species are anions, so a cation-exchange membrane is needed to prevent mixing of the anolyte and catholyte streams. Charge is carried via sodium ions through the membrane.

The design objectives of this project are (1) to develop a flowsheet of a grid-size BPSRFB process and (2) to provide estimates of capital and operating costs at different operating current densities to determine their effect on overall cost and thus the best operating conditions. The power level of this project is expected to be in the range of 1 to 10 MW with charge/discharge times of up to 12 hours. The charge discharge cycle is less than 365 cycles with an expected on-stream efficiency of 95%. The economic estimates are in 2014 US dollars. Details of important calculations are found the Appendix.

This project is supported by the Electric Power Research Institute in Palo Alto California (USA) and the Tennessee Solar Conversion and Storage using Outreach, Research and Education (TN-SCORE) project (NSF EPS 1004083). This report documents a study-level design and economic analysis of an electrical grid-scale bromine-polysulfide redox-flow battery (BPSRFB) and was prepared in Spring Semester, 2014 as fulfillment of course requirements of CBE 488 (Sustainable Design Internship) at the University of Tennessee.Advisors for this project are D. S. Aaron and R. M. Counce. Liaison with EPRI is provided by Chris Trublood.

2.0 Synthesis Information for the Process

Redox flow batteries (RFBs) have a wide range of benefits when compared to current electric power sources. They have the ability to store power during off-peak hours when electricity is cheap and in excess, such as during the day when solar and wind power are at their supply peak but demands for energy are low. Then they can supply this energy during on-peak hours when electrical power is in higher demand and more expensive. Other advantages include high overall efficiency, low temperature operation, and separation of energy capacity and power capacity which both can be easily varied. The energy capacity is dependent on volume and concentration of electrolyte solutions, while the power capacity is dependent on the size of the electrodes and the number of cells in each stack.[2]

A schematic for a typical BPSRFB system is presented in Figure 1. The positive side contains sodium bromide solution, and the negative side contains sodium polysulfide solution. The solutions are pumped into the cell where they make contact with a cation exchange membrane (Nafion). During charging and discharging, sodium ions are transported across the membrane, but anionic species remain separated.

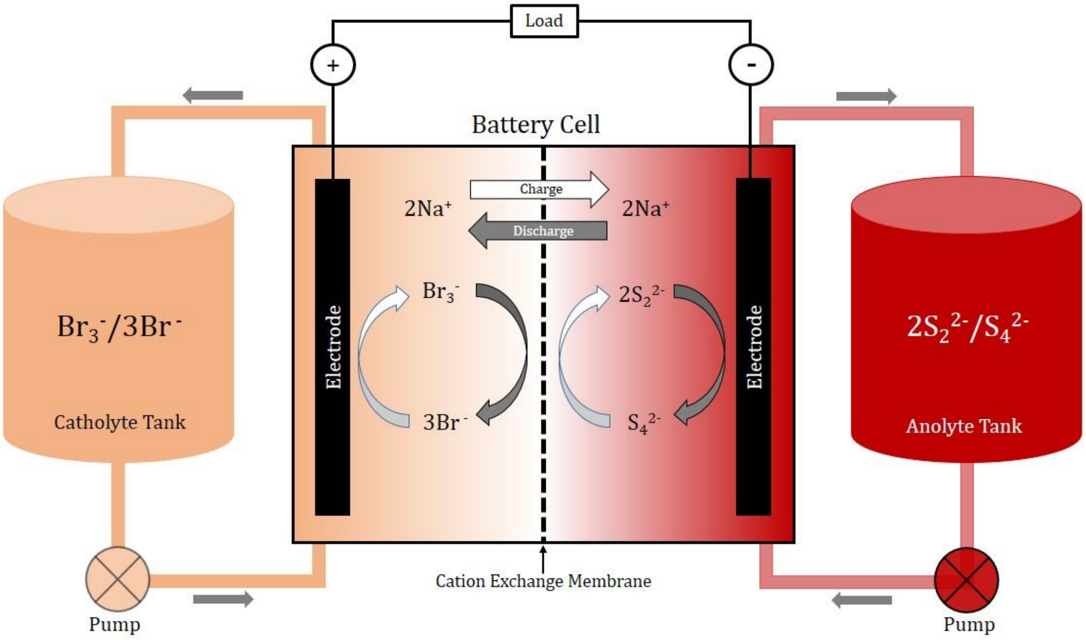

Figure 1: BPSRFB System

There is an increasing amount of research being done on the BPSRFB system due to the reasonable cost and abundance of readily-available electrolyte. However, there are some complications preventing mass-implementation into the power grid, including:[5]

a) cross-contamination of electrolyte solutions
b) deposition of sulfur species on the membrane
c) $H_2S(g)$ and $Br_2(g)$ formation

Because of these setbacks, there is still a significant amount of research required to make BPSRFB's commercialized.

Mathematical models have been performed in the past, predicting the overall cost overtime of running a BPSRFB at a 120 MWh/15 MW utility scale storage plant. [1] This model had a net loss of 0.45 p kWh^{-1} at an optimum current density of 500 Am^{-2}, and an efficiency of 64%. This study had also mentioned that the cost would decrease as more energy is provided by renewable sources, such as solar and wind. This would also increase the need for a mass energy storage system.

Investigations into improving this type of RFB are being done to increase overall efficiency and stability over time, which could also improve the net cost of a plant-size BPSRFB. The key component of many batteries is the electrode used. Different electrode materials have different effects on mass transport losses in performance. Experimental studies have shown that metal sulfide and transition metal catalysts can improve the kinetics of reaction when compares to using carbon-only electrodes. In laboratory tests, nickel foam as the negative electrode had shown significant increase in overall performance.[9] A more in depth laboratory-scale study compared carbon felt and activated carbon based electrodes for the BPSRFB, finding a cobalt-coated carbon felt negative electrode had up to 81% efficiency over 50 cycles at 40 mA cm^{-2}. This electrode had less sulfur deposition when compared to a cobalt-coated activated carbon electrode similar to the one used in the Regenesys cell.[8] Nevertheless, these studies show that cell voltage efficiency is also limited by the difference in internal ohmic resistance that increases with number of charging and discharging cycles. Once mass transport and ohmic losses are solved, BPSRFB's will have a longer lifetime, less maintenance and worthwhile economically.

Level 1: Input Information for BPSRFB

Level 1 includes the information needed to develop a base-case flow sheet: reaction information, product and by-product information, raw material information, constraints, and data specific for the plant and site. The BPSRFB can be considered a batch system. Level 1 provides basic information but does not necessarily reflect an optimal design. Cost data is given in 2014 US dollars. The input information is the following:

- Reaction Related Information
  - Stoichiometry – Discharge Reactions
    - Cathode: $3Br^- \rightarrow Br_3^- + 2e^-$
    - Anode: $S_4^{2-} + 2e^- \rightarrow 2S_2^{2-}$
  - E° Overall: 1.5V
  - Temperature: 25°C
  - Pressure: 1 atmosphere
  - Concentration of Bromine: 5M
  - Concentration of Polysulfide: 1M
  - Power Capacity: 7 MW
  - Energy Discharge Capacity: 42 MW-hr
  - State of Charge: Minimum = 10%, Maximum = 90%
- Design Details
  - Cycles per year: <365.25
  - Charge/Discharge Time: 6 hours
  - Size of Cell: 1 m^2
  - Current Density: [80, 170, 250, 320, 400] A/m^2
  - Charge Efficiency: 100%
  - Discharge Efficiency: 95%
  - Tank Material: carbon steel
  - Pressure Drop of the Pump: 0.5 bar
- Cost Information (tentative)
  - Fuel Cost: $7/GJ
  - Price of Output Power: $0.16/kW-hr
  - Price of Input Power: $0.01/kW-hr
  - Cell Construction Materials
    - Cation Exchange Membrane (Nafion): $25/$m^2$
    - Current Collectors: $50/$m^2$
    - Carbon Felt: $20/$m^2$ (2 per cell)
    - Cost of Assembly: 10% of Cell Component Cost
  - Power Conditioning: $100/kW
  - Transformer Costs: $37/kW
  - Breakers, Contacts, Cabling, etc.: $18/kW
  - Costs are to be estimated in 2014 US Dollars (ChE Index = 570.6)

Five different operating current densities (and their corresponding voltages) were chosen from a typical polarization curve for a BPSRFB system, as shown in Figure 2. Further analysis will help identify the most profitable operating conditions.

Case	Voltage (V)	Current Density (A/m^2)
1	1.4	80
2	1.25	170
3	1.1	250
4	0.95	320
5	0.8	400

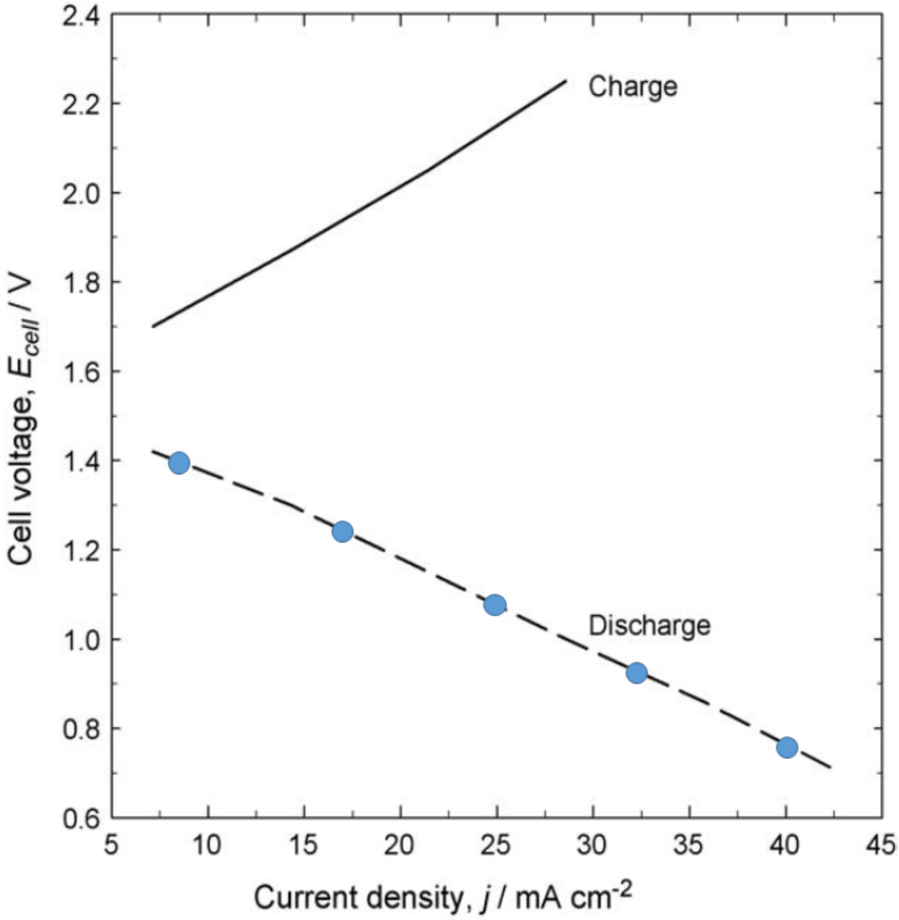

Figure 2: Voltage versus Current Density for a BPSRFB

3.0 Method of Approach

Level 2: Input-Output Analysis

The maximum (Level 2) economic potential of a BPSRFB is the difference in the value of the energy discharged from the battery and the energy used to charge the battery multiplied by the number of cycles per year. In this case, a cycle is considered a full charge-discharge procedure, and the number of cycles per year is a design variable. The amount of energy required for charging and the amount of energy produced by discharging depends on the battery capacity and efficiency. The following equations can be used to calculate the Level 2 economic potential.

1. $EP_2 = (E_{discharging} \times \frac{\$}{kWh_{discharging}} - E_{charging} \times \frac{\$}{kWh_{charging}}) \times \frac{cycles}{year}$
2. $E_{discharging} = E_{capacity} \times \xi_{discharging}$
3. $E_{charging} = E_{capacity}/\xi_{charging}$

$$EP_2 = (42{,}000kWh \times \$0.16/kWh - 42{,}000kWh/0.95 \times \$0.01/kWh) \times cycles/year$$
$$EP_2 = \$6{,}953/cycle \times cycles/year$$

Level 3: Power Capacity Considerations

The next major cost of a BPSRFB is the power capacity consideration. The costs that scale with the power of a BPSRFBare the pumps, the cells themselves, and the power conditioning system (PCS) which converts electricity from AC to DC. The PCS directly depends on the desired energy capacity of the system. Pumps are scaled based on bromine and polysulfide flow rates. The total number of cells also depends on the desired energy capacity, but this number can be affected by changing operating current density and voltage. Higher voltage and lower current density require a larger number of cells, whereas lower voltage and higher current density require a lesser number of cells.

$$EP_3 = EP_2 - annualized\ cost\ of\ cell\ stacks - annualized\ cost\ of pumps \\ - annualized\ cost\ of\ PCS$$

Level 4: Energy Capacity Considerations

The next major cost of a BPSRFB is the energy capacity consideration.The masses of sodium bromide and sodium tetrasulfide required for BPSRFB operation determine the energy capacity of the system. These masses can be calculated from the desired energy capacity and can then be used to calculate the cost of purchasing and storing the appropriate quantities of sodium bromide and sodium tetrasulfide.

$$\begin{aligned} EP_4 = EP_3 &- annualized\ cost\ of\ sodium\ bromide \\ &- annualized\ cost\ of\ sodium\ tetrasulfide \\ &- annulized\ cost\ of\ storage\ tanks \end{aligned}$$

Level 5: Balance of Plant Costs

The last major cost of a BPSRFB are those associated with the balance of plant costs, which include the costs of contruction, the costs of the control system, and the building and site preparation costs. Building and site preparation costs were estimated to be \$900/m^2 in 2007. At an inflation rate of 3% this corresponds to a value of \$1,107/m^2 in 2014. A suitable estimate for the size of the facility is 500m^2/MW. Again adjusting for inflation, the control system is estimated at \$24,596 and the remaining costs are \$61.19/kW. Level 5 is designed to capture any remaining capital costs elements that are not functions of power or energy capacity.

$$EP_5 = EP_4 - balance\ of\ plant\ costs$$

4.0 Results

The economic potentials of Cases 1-5 are summarized in Figures 3-7, respectively. Each figure outlines the economic potential for levels 2-5 for up to 600 charge/discharge cycles per year. Tables with more detailed capital cost data for levels 3-5 as well as overall capital cost summaries can be found in the appendix.

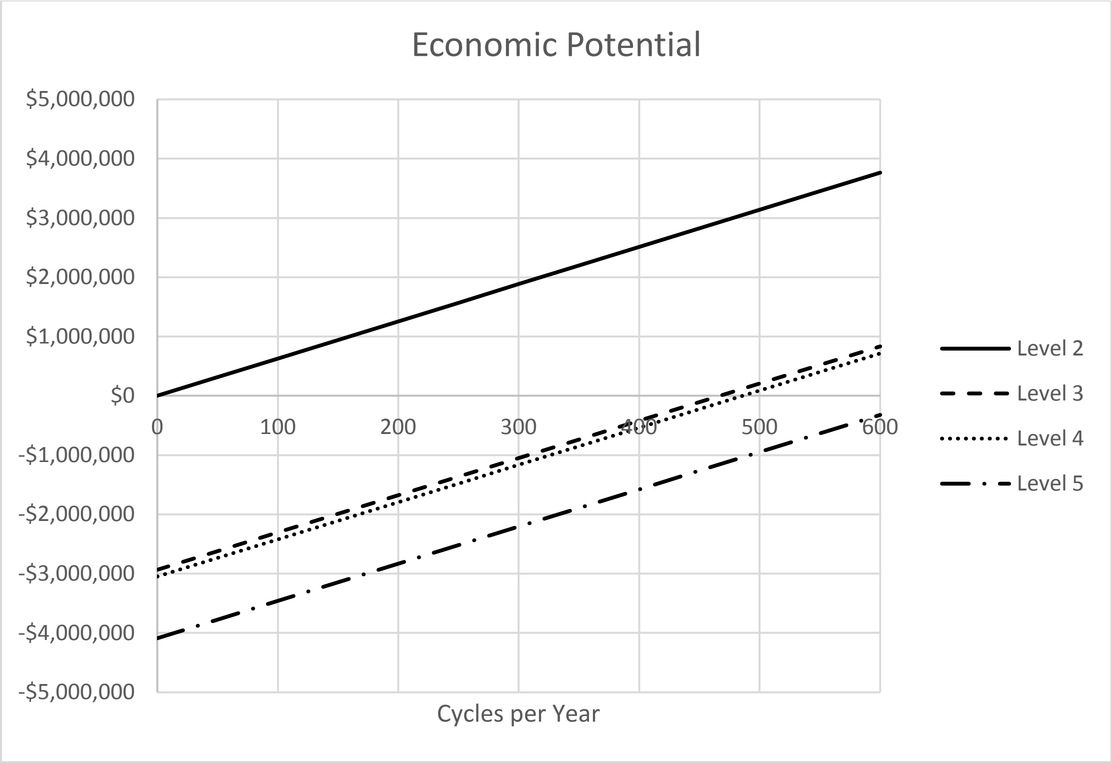

Figure 3: Case 1, 1.4V, 80A/m^2

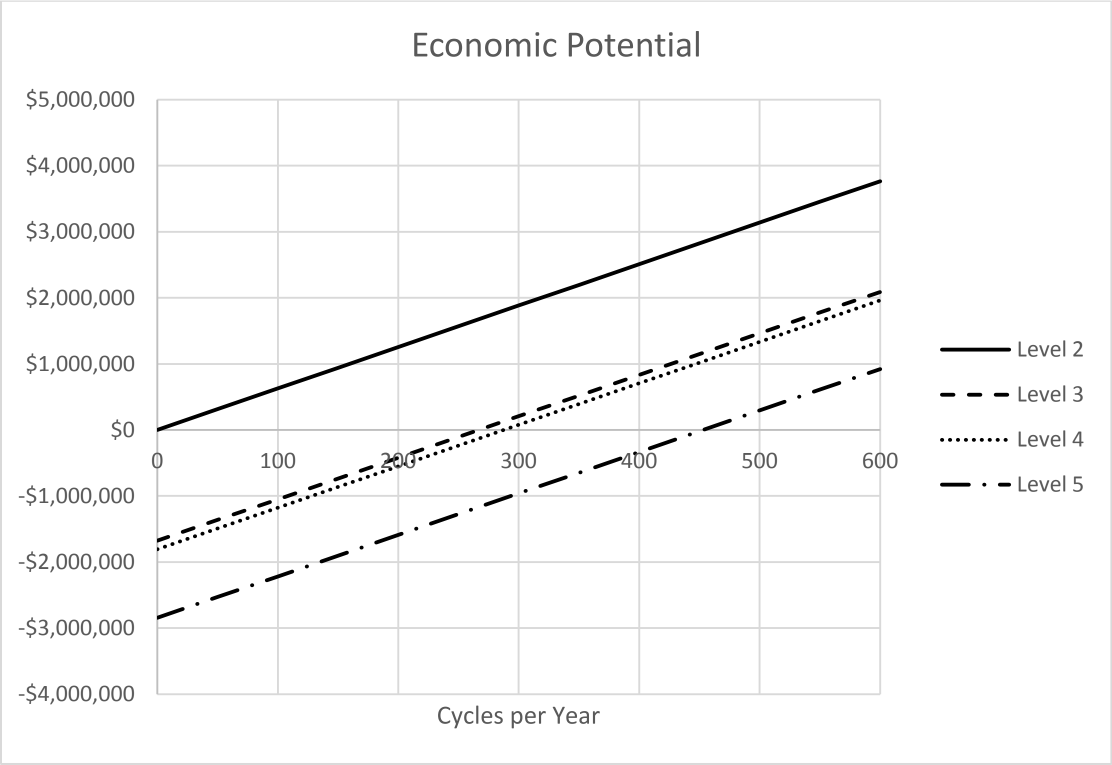

Figure 4: Case 2, 1.25V, 170A/m^2

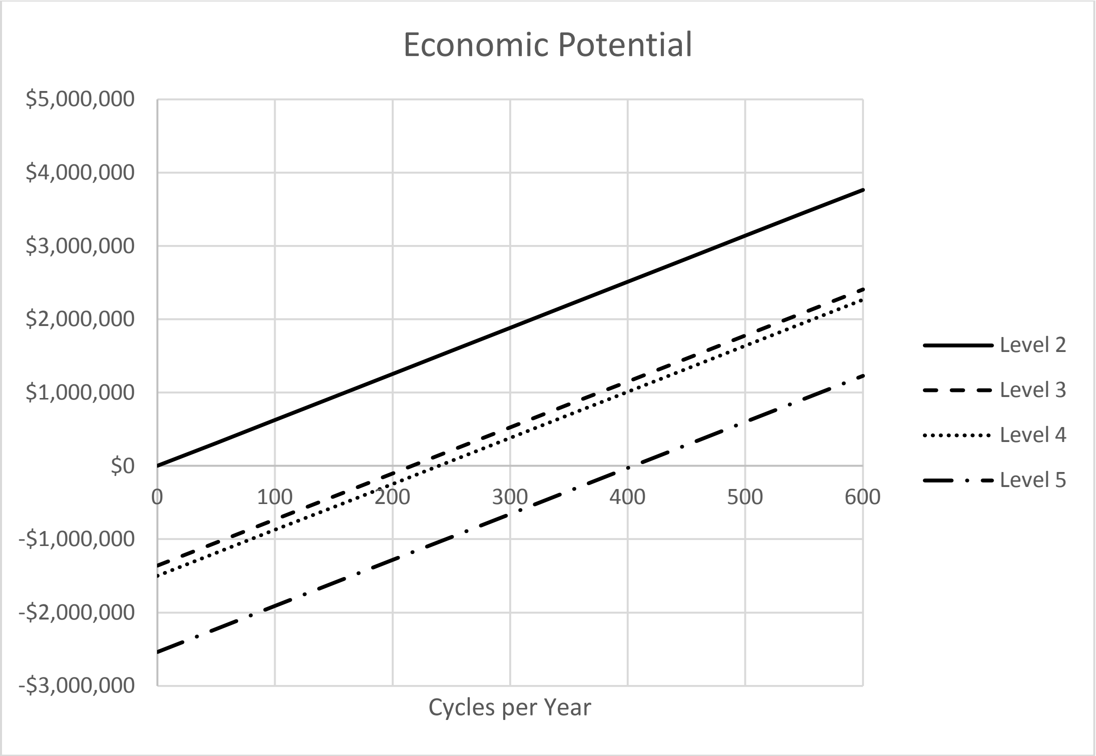

Figure 5: Case 3, 1.1V, 250A/m^2

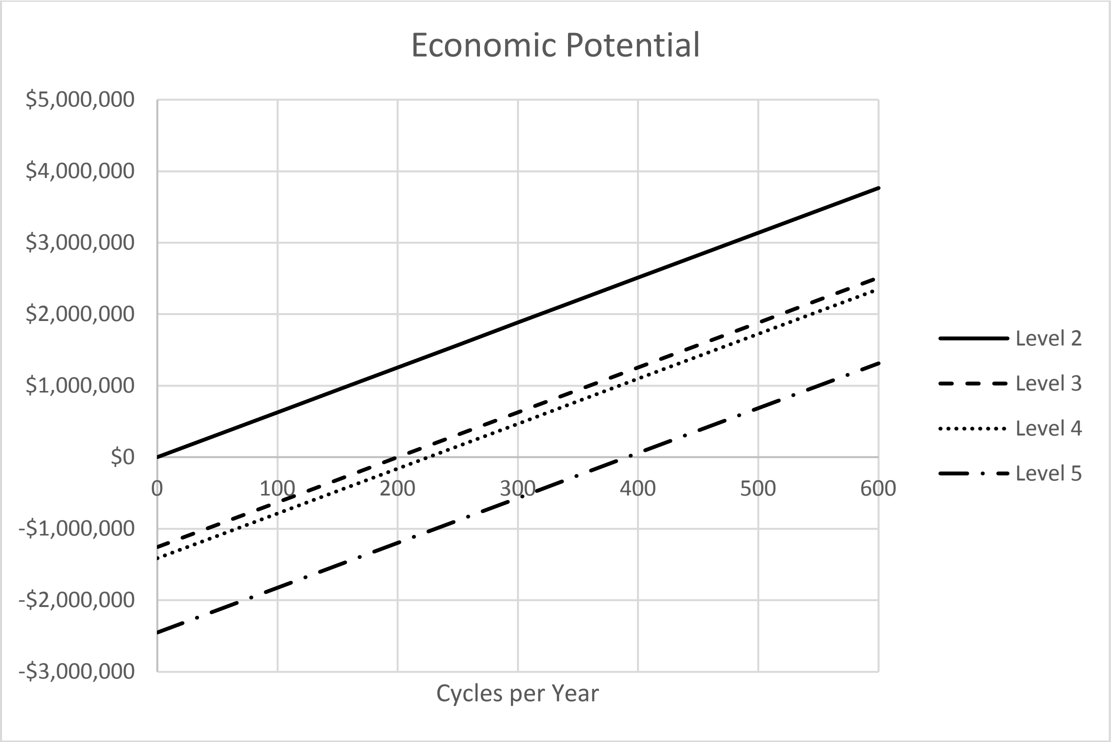

Figure 6: Case 4, 0.95V, 320A/m^2

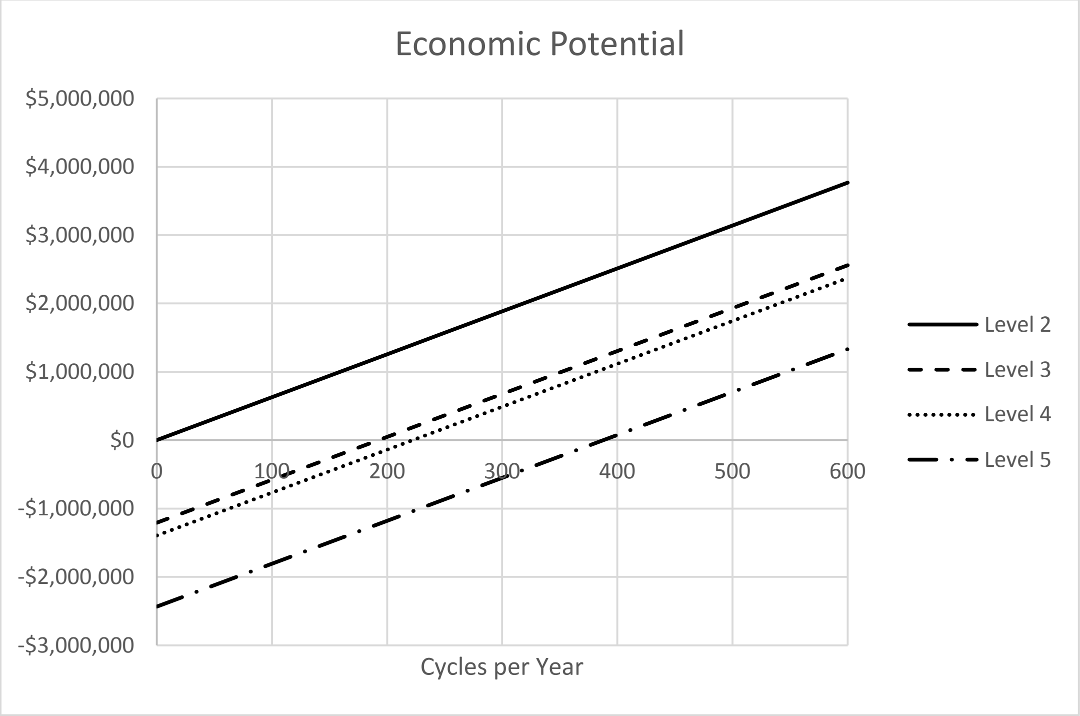

Figure 7: Case 5, 0.8V, 400A/m^2

To help determine the optimal operating current density, Figure 8 details the behavior of economic potential at 350 cycles per year as it varies for each case.

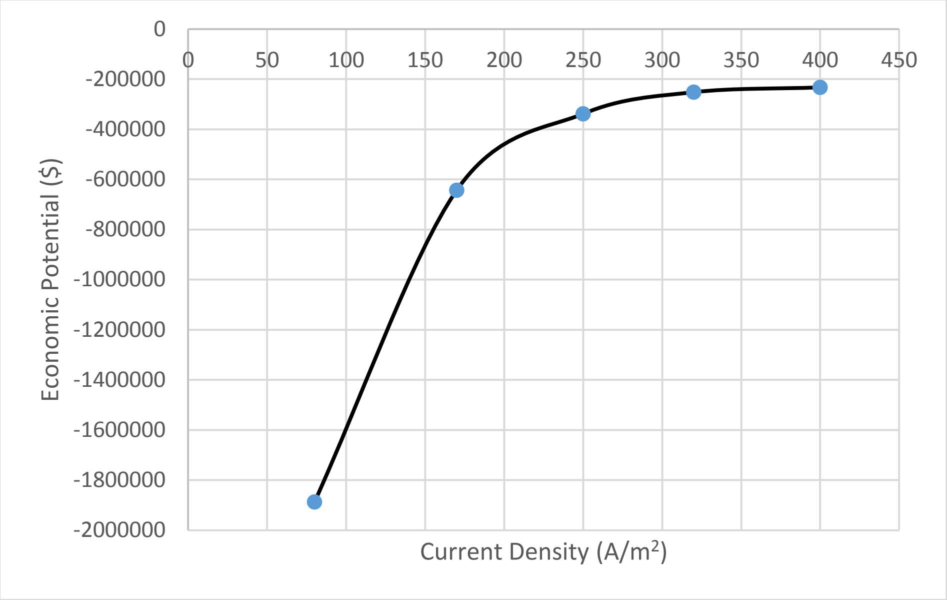

Figure 8: Economic Potential versus Current Density

5.0 Discussion of Results

Evaluating each of the five test cases, a consistent increase in economic profitability associated with decreasing voltage and increasing operating current density was observed. The most economically unfit case was Case 1, which employed a voltage of 1.4 V and an operating current density of 80 A/m^2. In this case, the economic potential evaluated at Level 5 did not reach a positive value. Even at 600 cycles per year, this case yielded a loss of $321,455. At the opposite extreme, in Case 5, the lowest voltage tested (0.8 V) and the highest current density (400 A/m^2) were used, yielding a Level 5 economic potential of $1.33 million at 600 cycles per year. Furthermore, at these operating conditions, positive economic potential is reached at 388 cycles per year, which is a lower turning point than any of the other test cases. At 388 cycles per year, Case 5 yields an economic potential of $1,464.

The other 3 cases evaluated support the aforementioned trend of low voltage and high current density leading to greater economic development. Voltage and current density had the most significant impact on cell components, which contributed most to overall cost. Reducing the cost of cell components should be of utmost importance when trying to optimize economic potential. Other parameters, such as pump and tank material and type, were also investigated, but no significant effect on economic potential was observed. Thus, as evidenced by the five different test cases shown, lower voltage and higher operating current density support greater economic potential in the BPSRFB battery.

6.0 Conclusions

As can be seen from the results, the BPSRFB system must be operated at a lower voltage and higher operating current density in order to avoid an annual net loss of profit. The fact that Case 5 yielded an economic potential of $1,464 at 388 cycles means improvements need to be implemented in order to make the battery economically feasible. There were no significant impacts on the economic potential from other parameters. So, once improvements are made upon the problems with mass transfer and ohmic resistance, the BPSRFB system will benefit from a longer life and greater efficiency, making it a viable option compared to other existing power sources. Until then, it will be highly unlikely to commercialize a BPSRFB system for practical use due to its low economic potential compared to other power sources.

7.0 Recommendations

Currently, there is not an economically feasible way to implement a bromine-polysulfide redox flow battery system into the power grid. In order for the demand of plant-size renewable energy storage systems to increase, the power supplied by renewable energy will also need to increase. Once solar, wind, biomass and other renewable energy sources become more prevalent, large-scale redox flow batteries will then have a significant role in the power grid to store energy during off-peak hours. Power generated by non-renewable fossil fuels will become more expensive in the future, making renewable energy systems more cost effective. Our recommendation would be to conduct more research on bromine-polysulfide redox flow batteries until that time when society is in need of renewable energy storage and they are more economically practical. Suggestions on research topics would include increasing the bromine-polysulfide redox flow battery’s efficiency by studying catalyst usage, electrode and current-collector material, and to find an electrolyte management system to prevent cross-contamination. Resolving these challenges would ensure a long cycle life, decrease maintenance costs, and make the bromine-polysulfide redox flow battery overall cost effective.

8.0 References

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Appendix A: Case 1 Data

Level 3 Capital Costs	
Membrane Area	62,500m^2
Cost of Membrane	\$25/m^2
Total Cost of Membrane	\$1,562,500
Cost of Current Collectors	\$50/m^2
Total Cost of Current Collectors	\$3,135,000
Cost of Carbon Felt Electrodes	\$20/m^2
Total Cost of Carbon Felt Electrodes	\$2,508,000
Total Cost of Stacks	\$11,096,470
Annualized Cost of Stacks	\$2,663,153
Cost of Pumps	\$38,444
Annualized Cost of Pumps	\$9,227
Cost of Power Conditioning System	\$100/kW
Transformer Cost	\$37/kW
Cost of Breakers, Contents, and Cabling	\$18/kW
Total PCS and Associated Items	\$1,085,000
Annualized Cost of PCS and Associated Items	\$260,400
Level 3 Total Annualized Capital Cost	\$2,932,779

Level 4 Capital Costs	
Volume of Electrolyte (Sodium Bromide)	139,920L
Cost of Sodium Bromide	\$2/kg
Total Cost of Sodium Bromide Solution	\$158,366
Annualized Cost of Sodium Bromide Solution	\$38,008
Sodium Bromide Storage Tank Size	153,912L
Total Cost of Sodium Bromide Storage Tank	\$59,913
Annualized Cost of Sodium Bromide Storage Tank	\$14,379
Volume of Electrolyte (Sodium Tetrasulfide)	699,601L
Cost of Sodium Tetrasulfide	\$1/kg
Total Cost of Sodium Tetrasulfide Solution	\$134,088
Annualized Cost of Sodium Tetrasulfide Solution	\$32,181
Sodium Tetrasulfide Storage Tank Size	769,561L
Total Cost of Sodium Tetrasulfide Storage Tank	\$134,804
Annualized Cost of Sodium Tetrasulfide Storage Tank	\$32,353
Level 4 Total Annualized Capital Cost	\$116,921

Level 5 Capital Costs	
Size of Facility	500m^2/MW
Cost of Building and Site Preparation	$1,107
Total Cost of Building and Site Preparation	$3,874,102
Annualized Cost of Building and Site Preparation	$929,785
Total Cost of Control System	$24,596
Annualized Cost of Control System	$5,903
Remaining Costs	$61.19
Total Remaining Costs	$428,349
Annualized Remaining Costs	$102,804
Level 5 Total Annualized Capital Cost	$1,038,491

Capital Cost Summary					
Equipment ID	Capacity/Specifications	Purchase Cost	Installation Factor	Actual Cost	Annualized Cost
Cell Stacks (313 cells/stack)	200 stacks	$7,926,050	1.4	$11,096,470	$2,663,153
Sodium Bromide Pump	centrifugal, cast iron, 0.52kW shaft power, 0.5barg	$3,994	3.5	$13,980	$3,355
Sodium Tetrasulfide Pump	centrifugal, cast iron, 1.98kW shaft power, 0.5barg	$6,990	3.5	$24,464	$5,871
PCS	7,000kW	$1,085,000	1	$1,085,000	$260,400
Sodium Bromide Solution	139,920L	$143,969	1.1	$158,366	$38,008
Sodium Bromide Storage Tank	153,912L, floating roof, carbon steel	$28,530	2.1	$59,913	$14,379
Sodium Tetrasulfide Solution	699,601L	$121,898	1.1	$134,088	$32,181
Sodium Tetrasulfide Storage Tank	769,561L, floating roof, carbon steel	$64,193	2.1	$134,804	$32,353
Balance of Plant Costs		$4,327,048	1	$4,327,048	$1,038,491
Total Cost		$13,707,672		$17,034,134	$4,088,192

Appendix B: Case 2 Data

Level 3 Capital Costs	
Membrane Area	32,941m^2
Cost of Membrane	\$25/m^2
Total Cost of Membrane	\$823,529
Cost of Current Collectors	\$50/m^2
Total Cost of Current Collectors	\$1,657,059
Cost of Carbon Felt Electrodes	\$20/m^2
Total Cost of Carbon Felt Electrodes	\$1,325,647
Total Cost of Stacks	\$5,861,602
Annualized Cost of Stacks	\$1,406,785
Cost of Pumps	\$39,942
Annualized Cost of Pumps	\$9,586
Cost of Power Conditioning System	\$100/kW
Transformer Cost	\$37/kW
Cost of Breakers, Contents, and Cabling	\$18/kW
Total PCS and Associated Items	\$1,085,000
Annualized Cost of PCS and Associated Items	\$260,400
Level 3 Total Annualized Capital Cost	\$1,676,771

Level 4 Capital Costs	
Volume of Electrolyte (Sodium Bromide)	156,711L
Cost of Sodium Bromide	\$2/kg
Total Cost of Sodium Bromide Solution	\$177,370
Annualized Cost of Sodium Bromide Solution	\$42,569
Sodium Bromide Storage Tank Size	172,382L
Total Cost of Sodium Bromide Storage Tank	\$59,913
Annualized Cost of Sodium Bromide Storage Tank	\$14,379
Volume of Electrolyte (Sodium Tetrasulfide)	783,553L
Cost of Sodium Tetrasulfide	\$1/kg
Total Cost of Sodium Tetrasulfide Solution	\$150,179
Annualized Cost of Sodium Tetrasulfide Solution	\$36,043
Sodium Tetrasulfide Storage Tank Size	861,908L
Total Cost of Sodium Tetrasulfide Storage Tank	\$149,783
Annualized Cost of Sodium Tetrasulfide Storage Tank	\$35,948
Level 4 Total Annualized Capital Cost	\$128,939

Level 5 Capital Costs

Size of Facility	$500m^2$/MW
Cost of Building and Site Preparation	$1,107
Total Cost of Building and Site Preparation	$3,874,102
Annualized Cost of Building and Site Preparation	$929,785
Total Cost of Control System	$24,596
Annualized Cost of Control System	$5,903
Remaining Costs	$61.19
Total Remaining Costs	$428,349
Annualized Remaining Costs	$102,804
Level 5 Total Annualized Capital Cost	$1,038,491

Capital Cost Summary

Equipment ID	Capacity/Specifications	Purchase Cost	Installation Factor	Actual Cost	Annualized Cost
Cell Stacks (165 cells/stack)	200 stacks	$4,186,859	1.4	$5,861,603	$1,406,785
Sodium Bromide Pump	centrifugal, cast iron, 0.57kW shaft power, 0.5barg	$4,280	3.5	$14,978	$3,595
Sodium Tetrasulfide Pump	centrifugal, cast iron, 2.19kW shaft power, 0.5barg	$7,133	3.5	$24,964	$5,991
PCS	7,000kW	$1,085,000	1	$1,085,000	$260,400
Sodium Bromide Solution	156,711L	$161,246	1.1	$177,370	$42,569
Sodium Bromide Storage Tank	172,382L, floating roof, carbon steel	$28,530	2.1	$59,913	$14,379
Sodium Tetrasulfide Solution	783,553L	$136,526	1.1	$150,179	$36,043
Sodium Tetrasulfide Storage Tank	861,908L, floating roof, carbon steel	$71,325	2.1	$149,783	$35,948
Balance of Plant Costs		$4,327,048	1	$4,327,048	$1,038,491
Total Cost		$10,007,946		$11,850,838	$2,844,201

Appendix C: Case 3 Data

Level 3 Capital Costs	
Membrane Area	25,455m^2
Cost of Membrane	\$25/m^2
Total Cost of Membrane	\$636,364
Cost of Current Collectors	\$50/m^2
Total Cost of Current Collectors	\$1,282,727
Cost of Carbon Felt Electrodes	\$20/m^2
Total Cost of Carbon Felt Electrodes	\$1,026,182
Total Cost of Stacks	\$4,535,720
Annualized Cost of Stacks	\$1,088,573
Cost of Pumps	\$41,939
Annualized Cost of Pumps	\$10,065
Cost of Power Conditioning System	\$100/kW
Transformer Cost	\$37/kW
Cost of Breakers, Contents, and Cabling	\$18/kW
Total PCS and Associated Items	\$1,085,000
Annualized Cost of PCS and Associated Items	\$260,400
Level 3 Total Annualized Capital Cost	\$1,359,038

Level 4 Capital Costs	
Volume of Electrolyte (Sodium Bromide)	178,080L
Cost of Sodium Bromide	\$2/kg
Total Cost of Sodium Bromide Solution	\$201,557
Annualized Cost of Sodium Bromide Solution	\$48,374
Sodium Bromide Storage Tank Size	195,888L
Total Cost of Sodium Bromide Storage Tank	\$62,909
Annualized Cost of Sodium Bromide Storage Tank	\$15,098
Volume of Electrolyte (Sodium Tetrasulfide)	890,401L
Cost of Sodium Tetrasulfide	\$1/kg
Total Cost of Sodium Tetrasulfide Solution	\$170,658
Annualized Cost of Sodium Tetrasulfide Solution	\$40,958
Sodium Tetrasulfide Storage Tank Size	979,441L
Total Cost of Sodium Tetrasulfide Storage Tank	\$155,774
Annualized Cost of Sodium Tetrasulfide Storage Tank	\$37,386
Level 4 Total Annualized Capital Cost	\$141,815

Level 5 Capital Costs	
Size of Facility	500m^2/MW
Cost of Building and Site Preparation	$1,107
Total Cost of Building and Site Preparation	$3,874,102
Annualized Cost of Building and Site Preparation	$929,785
Total Cost of Control System	$24,596
Annualized Cost of Control System	$5,903
Remaining Costs	$61.19
Total Remaining Costs	$428,349
Annualized Remaining Costs	$102,804
Level 5 Total Annualized Capital Cost	$1,038,491

Capital Cost Summary					
Equipment ID	Capacity/Specifications	Purchase Cost	Installation Factor	Actual Cost	Annualized Cost
Cell Stacks (127 cells/stack)	200 stacks	$3,239,799	1.4	$4,535,719	$1,088,573
Sodium Bromide Pump	centrifugal, cast iron, 0.62kW shaft power, 0.5barg	$4,565	3.5	$15,977	$3,834
Sodium Tetrasulfide Pump	centrifugal, cast iron, 2.45kW shaft power, 0.5barg	$7,418	3.5	$25,962	$6,231
PCS	7,000kW	$1,085,000	1	$1,085,000	$260,400
Sodium Bromide Solution	178,080L	$183,234	1.1	$201,557	$48,374
Sodium Bromide Storage Tank	195,888L, floating roof, carbon steel	$29,957	2.1	$62,909	$15,098
Sodium Tetrasulfide Solution	890,401L	$155,143	1.1	$170,658	$40,958
Sodium Tetrasulfide Storage Tank	979,441L, floating roof, carbon steel	$74,178	2.1	$155,774	$37,386
Balance of Plant Costs		$4,327,048	1	$4,327,048	$1,038,491
Total Cost		$9,106,342		$10,580,603	$2,539,345

Appendix D: Case 4 Data

Level 3 Capital Costs	
Membrane Area	23,026m^2
Cost of Membrane	\$25/m^2
Total Cost of Membrane	\$575,658
Cost of Current Collectors	\$50/m^2
Total Cost of Current Collectors	\$1,161,316
Cost of Carbon Felt Electrodes	\$20/m^2
Total Cost of Carbon Felt Electrodes	\$929,053
Total Cost of Stacks	\$4,105,681
Annualized Cost of Stacks	\$985,363
Cost of Pumps	\$43,936
Annualized Cost of Pumps	\$10,545
Cost of Power Conditioning System	\$100/kW
Transformer Cost	\$37/kW
Cost of Breakers, Contents, and Cabling	\$18/kW
Total PCS and Associated Items	\$1,085,000
Annualized Cost of PCS and Associated Items	\$260,400
Level 3 Total Annualized Capital Cost	\$1,256,308

Level 4 Capital Costs	
Volume of Electrolyte (Sodium Bromide)	206,198L
Cost of Sodium Bromide	\$2/kg
Total Cost of Sodium Bromide Solution	\$233,382
Annualized Cost of Sodium Bromide Solution	\$56,012
Sodium Bromide Storage Tank Size	226,818L
Total Cost of Sodium Bromide Storage Tank	\$68,900
Annualized Cost of Sodium Bromide Storage Tank	\$16,536
Volume of Electrolyte (Sodium Tetrasulfide)	1,030,991L
Cost of Sodium Tetrasulfide	\$1/kg
Total Cost of Sodium Tetrasulfide Solution	\$197,604
Annualized Cost of Sodium Tetrasulfide Solution	\$47,425
Sodium Tetrasulfide Storage Tank Size	1,134,090L
Total Cost of Sodium Tetrasulfide Storage Tank	\$158,769
Annualized Cost of Sodium Tetrasulfide Storage Tank	\$38,105
Level 4 Total Annualized Capital Cost	\$158,077

Level 5 Capital Costs	
Size of Facility	500m^2/MW
Cost of Building and Site Preparation	$1,107
Total Cost of Building and Site Preparation	$3,874,102
Annualized Cost of Building and Site Preparation	$929,785
Total Cost of Control System	$24,596
Annualized Cost of Control System	$5,903
Remaining Costs	$61.19
Total Remaining Costs	$428,349
Annualized Remaining Costs	$102,804
Level 5 Total Annualized Capital Cost	$1,038,491

Capital Cost Summary					
Equipment ID	Capacity/Specifications	Purchase Cost	Installation Factor	Actual Cost	Annualized Cost
Cell Stacks (115 cells/stack)	200 stacks	$2,932,629	1.4	$4,105,681	$985,363
Sodium Bromide Pump	centrifugal, cast iron, 0.7kW shaft power, 0.5barg	$4,850	3.5	$16,975	$4,074
Sodium Tetrasulfide Pump	centrifugal, cast iron, 2.79kW shaft power, 0.5barg	$7,703	3.5	$26,961	$6,471
PCS	7,000kW	$1,085,000	1	$1,085,000	$260,400
Sodium Bromide Solution	206,198L	$212,165	1.1	$233,382	$56,012
Sodium Bromide Storage Tank	226,818L, floating roof, carbon steel	$32,810	2.1	$68,900	$16,536
Sodium Tetrasulfide Solution	1,030,991L	$179,640	1.1	$197,604	$47,425
Sodium Tetrasulfide Storage Tank	1,134,090L, floating roof, carbon steel	$75,605	2.1	$158,769	$38,105
Balance of Plant Costs		$4,327,048	1	$4,327,048	$1,038,491
Total Cost		$8,857,449		$10,220,320	$2,452,877

Appendix E: Case 5 Data

Level 3 Capital Costs	
Membrane Area	21,875m^2
Cost of Membrane	\$25/m^2
Total Cost of Membrane	\$546,875
Cost of Current Collectors	\$50/m^2
Total Cost of Current Collectors	\$1,103,750
Cost of Carbon Felt Electrodes	\$20/m^2
Total Cost of Carbon Felt Electrodes	\$883,000
Total Cost of Stacks	\$3,901,783
Annualized Cost of Stacks	\$936,428
Cost of Pumps	\$47,930
Annualized Cost of Pumps	\$11,503
Cost of Power Conditioning System	\$100/kW
Transformer Cost	\$37/kW
Cost of Breakers, Contents, and Cabling	\$18/kW
Total PCS and Associated Items	\$1,085,000
Annualized Cost of PCS and Associated Items	\$260,400
Level 3 Total Annualized Capital Cost	\$1,208,331

Level 4 Capital Costs	
Volume of Electrolyte (Sodium Bromide)	244,860L
Cost of Sodium Bromide	\$2/kg
Total Cost of Sodium Bromide Solution	\$277,141
Annualized Cost of Sodium Bromide Solution	\$66,514
Sodium Bromide Storage Tank Size	269,346L
Total Cost of Sodium Bromide Storage Tank	\$89,870
Annualized Cost of Sodium Bromide Storage Tank	\$21,569
Volume of Electrolyte (Sodium Tetrasulfide)	1,224,301L
Cost of Sodium Tetrasulfide	\$1/kg
Total Cost of Sodium Tetrasulfide Solution	\$234,654
Annualized Cost of Sodium Tetrasulfide Solution	\$56,317
Sodium Tetrasulfide Storage Tank Size	1,346,731L
Total Cost of Sodium Tetrasulfide Storage Tank	\$179,739
Annualized Cost of Sodium Tetrasulfide Storage Tank	\$43,137
Level 4 Total Annualized Capital Cost	\$187,537

Level 5 Capital Costs	
Size of Facility	500m^2/MW
Cost of Building and Site Preparation	$1,107
Total Cost of Building and Site Preparation	$3,874,102
Annualized Cost of Building and Site Preparation	$929,785
Total Cost of Control System	$24,596
Annualized Cost of Control System	$5,903
Remaining Costs	$61.19
Total Remaining Costs	$428,349
Annualized Remaining Costs	$102,804
Level 5 Total Annualized Capital Cost	$1,038,491

Capital Cost Summary

Equipment ID	Capacity/Specifications	Purchase Cost	Installation Factor	Actual Cost	Annualized Cost
Cell Stacks (109 cells/stack)	200 stacks	$2,786,988	1.4	$3,901,783	$936,428
Sodium Bromide Pump	centrifugal, cast iron, 0.8kW shaft power, 0.5barg	$5,135	3.5	$17,974	$4,314
Sodium Tetrasulfide Pump	centrifugal, cast iron, 3.25kW shaft power, 0.5barg	$8,559	3.5	$29,957	$7,190
PCS	7,000kW	$1,085,000	1	$1,085,000	$260,400
Sodium Bromide Solution	244,860L	$251,947	1.1	$277,141	$66,514
Sodium Bromide Storage Tank	269,346L, floating roof, carbon steel	$42,795	2.1	$89,870	$21,569
Sodium Tetrasulfide Solution	1,224,301L	$213,322	1.1	$234,654	$56,317
Sodium Tetrasulfide Storage Tank	1,346,731L, floating roof, carbon steel	$85,590	2.1	$179,739	$43,137
Balance of Plant Costs		$4,327,048	1	$4,327,048	$1,038,491
Total Cost		$8,806,384		$10,143,165	$2,434,360