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The Economic Potential of the All-Vanadium Redox Flow Battery With a Focus on State of Charge

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Abstract

The purpose of this study is to assess the economic potential of an all-vanadium redox battery. The battery was evaluated on a base case and on two cases where the state of charge was varied. The base case state of charge was 10%-90% and the varied states were 45%-55% and 25%-75%.

The economic potential was assessed using the outline laid out in J.M. Douglas's paper "Conceptual Design of Chemical Processes." The level 2 design evaluates based on the electron flow in and out of the cell. After a level 2 analysis, all 3 cases were still economically feasible. The level 3 design evaluates based on the power capacity. In these cases, the designs were economically feasible at upwards of 300 cycles. The level 4 analysis is based on the solution capacity. The base case and the 25%-75% case were feasible after upwards of 450 cycles, while the 45%-55% case was not. The level 5 analysis is based on the operating costs for the plant. After this analysis, none of the cases were economically feasible. The level 6 analysis was a base case capital cost estimate. At this case, it cane be determined that the solution costs are 14% of the total cost, and the stack costs were 67% of th total cost. The level 7 analysis was an operating cost analysis.

From this study, it can be determined that much must be done in order to make the all-vanadium redox battery feasible. The biggest changes that need to be made are in the cost of the vanadium solution and the ion exchange membranes. The vanadium solution cost could be brought down by using a less pure vanadium solution. The ion exchange membranes are patented and would need to be brought down through negotiation with the company.

Section 1: Introduction

The purpose of this study is to design a base case all-vanadium battery for electrical storage. An all-vanadium battery stores energy in the form of oxidation-reduction reactions. There are two half-cells. In the positive half-cell during discharge, vanadium oxide ions in the +5 oxidation state are converted to vanadium oxide ions in the +4 oxidation state. In the negative half cell during discharge, vanadium ions in the +2 oxidation state are converted to vanadium ions in the +3 oxidation state. Vanadium batteries have a large capacity to store energy; this ability makes them useful to store energy from highly variable power sources, such as solar or wind power. The use of vanadium batteries was first suggested by NASA scientists in 1978, but the vanadium redox battery was first successfully implemented in 1985 by Maria Skyllas-Kazacos and her team at University of New South Wales.

This project is necessary because fossil fuels are a limited resource. The vanadium redox battery could be effectively used to store energy from green sources, such as solar and wind power, to reduce fossil fuel use. However, the battery has a fairly low charge to size ratio, so batteries need to be large to be effective as storage units of energy.

The objective of this study is to analyze a base case for the Vanadium Redox battery. Design objectives are as follows. First, cell current density will be optimized. Second, cell resistance, current density, and state of charge will be calculated and used to estimate efficiency. In this objective, the work of You, et al., will be used as a reference. Results will be determined for vanadium concentrations between 10% to 90% in each redox state. Specific design parameters are included below.

The battery is designed to have an energy charge/discharge rate of 1 MW and energy storage capacity of 8 MW-hr. The study is in 2010 U.S. dollars and culminates in the estimation of capital and operating costs and an estimate of profitability. The Che Index used is 558.2. The electrical energy discharged will be sold during peak demand hours, such that the base-case cost per kilowatt-hour is \$0.45. The study also presents results of an investigation of an important design variable. The design variables examined in this report are the fraction of the V affected in each cycle (state of charge, SOC), the number of cycles per year, and the current density. For this project, a current density of 40mA/cm2 was chosen, and the other possibilities disregarded.

This report will provide an analysis of the given base case. The analysis will be done in seven levels. Level 1 will be on an input-output level. Level 3 will analyze the power capacity of the battery. Level 4 will analyze the energy capacity of the battery. Level 5 will set up the control system for the battery. Level 6 will be a cost estimation of the battery design. Level 7 will be a cost estimate of the operation of the battery. This process was outlined by J. M. Douglas in the paper "A Hierarchical Decision Procedure for Process Synthesis."

Section 2: Synthesis Information for Process

The use of vanadium batteries was first suggested by NASA scientists in 1978, but the vanadium redox battery was first successfully implemented in 1985 by Maria Skyllas-Kazacos and her team at University of New South Wales. You, et al, developed a model of a single all-vanadium redox battery that particularly studies the effects of applied current density, electrode porosity and local mass transfer coefficient on the cell performance. The work of Ponce de Leon, et al can be used as a reference for redox flow batteries.

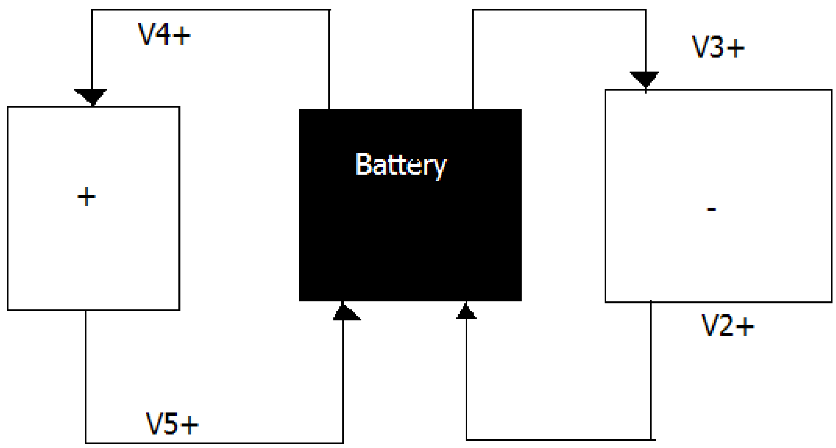

Figure 1: a basic schematic of the process design

The input information for the base case is:

1. 1M V and 5M sulfuric acid
2. 1000 kW (1MW) system
3. 8000 kW-hr system
4. cooling or temperature adjustment as flow enters the stack
5. $500/m^2 of membrane
6. off-peak power cost of $0.045/kW-hr, peak power cost of $0.45/kW-hr
7. cell current density of 40 mA/cm^2
8. a cycle between 10%-90% of V in each redox state
9. 100 cells in one stack

For this case, the design variable is the state of charge (parameter 8). This will be changed to include a range from 25%-75% to 45%-55% (that is, larger V redox swings and at smaller redox swings). This will affect the amount of Vanadium solution needed.

The Vanadium redox battery uses the following charge/discharge reaction in order to collect power:

The positive cell reaction for charging is: $2(VO)SO_4 + 2\ H_2O \rightarrow (VO_2)_2SO_4 + H_2SO_4 + 2\ H^+ + 2\ e^-$
$(V^{4+} \rightarrow V^{5+})$

The negative cell reaction for charging is: $V_2(SO_4)_3 + 2e^- + 2\ H^+ \rightarrow 2\ VSO_4 + H_2SO_4$
$(V^{3+} \rightarrow V^{2+})$

Table 1: Important Properties

Property	**Value**
Temperature	25C
[Vanadium]	1M
[H_2SO_4]	5M
Density of Vanadium Solution	1287 g/L
Power Capacity	1000 kW
Energy Capacity	8000 kW-hr
Minimum State of Charge Considered	0.1
Maximum State of Charge Considered	0.9
Enthalpy of Reaction to Positive Tank	-1155 kJ/mol
Enthalpy of Reaction to Negative Tank	-747 kJ/mol

The Vanadium battery to be discussed will have a cell of 1 m^2, a current density of 40 mA/cm^2(You, et al), and 548 cycles per year 548 cycles per year is the absolute amount an 8 hour charge/discharge cycle can have if it is run 24 hours per day 365 days per year. The battery will have heat exchangers and tanks attached to it. These pieces will be designed out of high-Nickel steel or PVC, depending on cost and durability. These materials must be used due to the high acidity of Sulfuric Acid.

The costs for the raw materials and their specifications are outlined in the table below:

Table 2: Raw Material Costs and Specifications

Material	**Cost**	**Specification**
Vanadium	$2.10/gram	1 Molar
Sulfuric Acid	$0.04/kilogram	5 Molar
Ion-Exchange Membrane	$500/m^2	1/cell
Current Collectors	$80/m^2	1/cell
Carbon Felt	$50/m^2	1/cell

The AC/AC efficiency is calculated using information from EPRI Report #1014836 and the work of You, et al:
Transformer Efficiency = E^2_t = 99.5%
Power control system = E^2_{pcs} = 97.0% (estimated)
Efficiency of DC power to chemical energy and reverse = E_{ec}
E_{ec} = f (current density)

Efficiency of DC power to chemical energy and reverse (E_{ec}) for one cell will be the same as the whole stack.

Thinking in terms of series processes for charge and discharge:
$E_c = E_t * E_{pcs} * E_{ec}$
$E_c = (0.995)^{1/2} * (0.970)^{1/2} * E_{ec}$
$E_d = E_t * E_{pcs} * E_{ec}$
$E_d = (0.995)^{1/2} * (0.970)^{1/2} * E_{ec}$
$E_{oa} = E_c * E_d$
The overall efficiency is 76.8%.

The next step in this design will be first to finish Level 2 analysis by completing input-output analysis. Following that, Level 3 will analyze the power capacity of the battery. Level 4 will analyze the energy capacity of the battery. Level 5 will set up the control system for the battery. Level 6 will be a cost estimation of the battery design. Level 7 will be a cost estimate of the operation of the battery.

Section 2.1: Input-Output Level Analysis

Level two analysis is based on electron flow into and out of the cell stack. It is a very basic analysis. Kilowatts go into the cell stack charged and come out discharged after use by the cell stack.

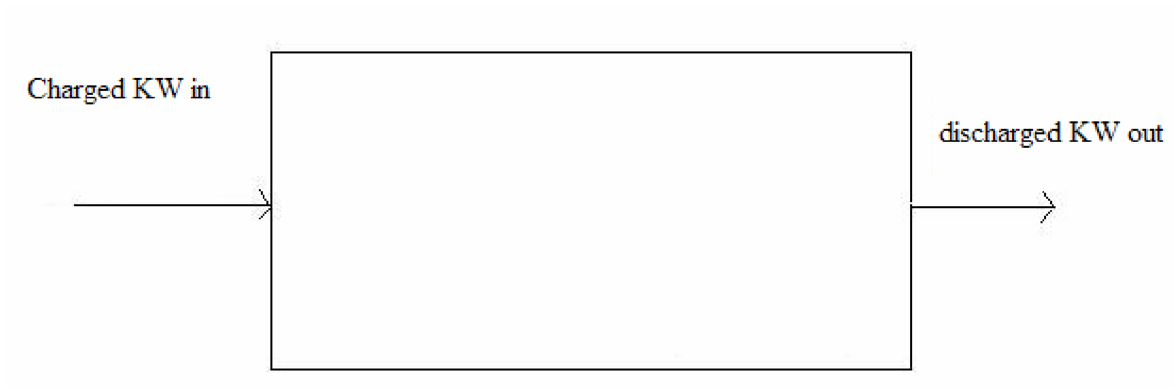

Figure 2: Level Two Input/Output Diagram

The molar and mass flow rates for each stream were calculated

The equation above gives the total electron flow through the cell stack. The total vanadium flow is also equal to this. The total electron flow is 0.08 e-/s

Level two analysis is based solely on energy. The battery efficiency was calculated in Section 2 as 76.8%. The level 2 calculation is:

EP2 = profit-cost
income = kwhr*efficiency*# of cycles*0.45
cost= kwhr/efficiency*0.045*# of cycles

The level two economic potential for one cycle is \$2296.05. The economic potential was calculated for cycles per year ranging from 1 to 548 (max cycles per year).

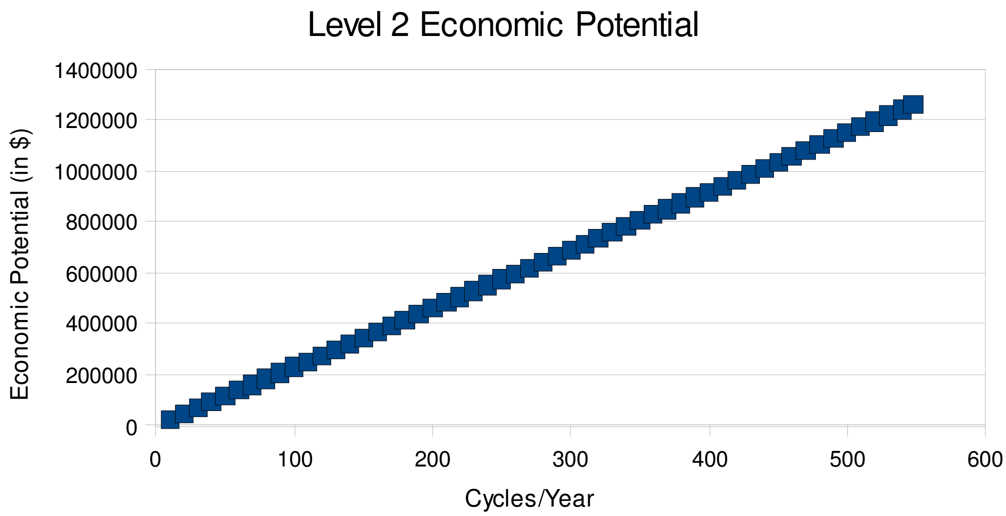

Figure 3: A graph of the level two economic potential for different numbers of cycles per year

Section 2.2: Level 3 Analysis

Level 3 analysis is based on the power capacity, rather than the energy capacity. The power capacity is based on the pumps, heat exchangers, cell stack, the ion exchange membranes and the carbon felt. The molar flow rate was calculated at 0.08 mol/s in Section 2.1.

Much of the equipment choices are made by the nature of the system. The 100 cells require 101 current collectors, 202 carbon elements (carbon felt), and 100 ion exchange membranes. The cost of the equipment is listed in Table 3. A stack is $1m^2$, and there are 100 cells in a stack. There are approximately 20 stacks in a battery.

Table 3: Costs of stack elements

Ion-Exchange Membrane	\$500/m^2	1/cell
Current Collectors	\$80/m^2	1/cell
Carbon Felt	\$50/m^2	1/cell
Pump		2/battery
Heat Exchanger		2/battery

The level 3 economic potential is the annualized cost subtracted from the level 2 economic potential. The annualized cost is found via the formula:

$$A = 1.18*f_o*C_{a,bm}$$

$$EP3 = EP2-A$$

fo is found as a function of the fixed capital The values are listed in Table 4. These values are from

Chemical Engineering Process Design and Economics by Ulrich.

Table 4: fo components

Maintenance and repair	0.06
Operating supplies	0.01
overhead	0.03
Tax and insurance	0.03
depreciation	1/service life = 1/10 years
general	0.01

f_o is 0.24.

$C_{a,bm}$ includes the Cp for the heat exchangers, pumps, collectors, carbon felt elements, and ion exchange membranes. They must all be calculated separately and then added together to get an overall $C_{a,bm}$

The heat exchanger area is calculated by: Area= $q/U\Delta T$
The Cp for the heat exchanger is calculated using Figure 5.36 and 5.38 in Ulrich.
The values used to calculate Cp for the heat exchangers are found in Table 5.

Table 5: Heat Exchanger Variables.

q	29811.44 J/s
U	900 J/m^2-s-K
ΔT	10C
Area	3.31 (~3.5) m^2
Fm (Ni/Ni)	3.8
Fp	1
Fa,bm	7
Cp (1 HEX)	$1100
Cp (2 HEX)	$2200

The pump cost is calculated using the flow rate of the Vanadium solution, which was calculated in section 2.
The volumetric flow rate is calculated via: $X= \rho * C_p * \Delta T/[V] * \Delta H$
The shaft power is calculated via: Ws = Volumetric Flow Rate * pressure * efficiency
Cp is calculated using Figures 5.49 and 5.51 in Ulrich.
The values used to calculate the Cp for the pumps are found in Table 6.

Table 6: Pump Variables

X (conversion)	0.05 (gives a temperature change of 10C)
ρ	1287 g/L
ΔT	10C
ΔH	178 x 10^3 cal/mol
[V]	1 M
Cp for Sulfuric Acid	0.7 cal/g-C
Pump efficiency	0.5
Volumetric Flow Rate Calculated	1 L/s
Volumetric Flow Rate Used	2 L/s (doubled because there are 2 pumps)
Shaft Power	800 W ~ 1 kW
Fp	1
Fm (high Ni alloy)	3.5
Fa,bm	7
Cp (one pump)	$4000
Cp (two pumps)	$8000

The Cp for the collectors, carbon felt elements and ion exchange membranes are found in a much simpler way. The total number of stacks is 20 (20m^2 of stack). This total cost for the three element types is 70% of the total Cp.

Table 7: Element Variables

101 Collectors	$80/m2	$161,600.00
202 Carbon Felt Elements	$50/m2	$202,000.00
100 ion exchange membranes	$500/m2	$1,000,000.00
70% of Cp	Total for elements	$1,363,800.00
Cp	(total for elements)/0.7	$1,948,285.71

Table 8 summarizes the base module cost, Ca,bm, calculations for the elements, heat exchangers and pumps:

Table 8: Base Module Cost and Annualized Cost

Ion Exchangers, Carbon Elements and Collectors	1.2*Cp	$2,337,942.86
Heat exchangers	Fa,bm*Cp*558.2/400	$21,490
Pumps	Fa,bm*Cp*558.2/400	$78,148
Annualized Cost	A = 1.18*0.24*(total Cp)	$690,322.90

Figure 4 is the graph of the economic potential with respect to cycles per year. Since the economic potential is lower, at cycles below approximately 300 per year, the economic potential is below 0.

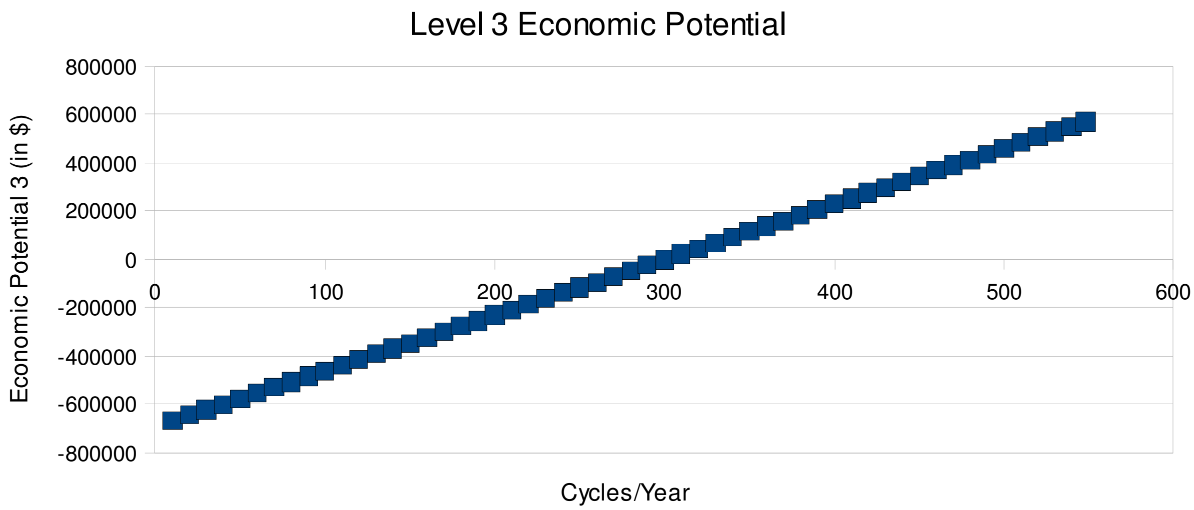

Figure 4: Economic Potential Level 3

Section 2.3: Level 4 Analysis

Level 4 analysis is based on the solution capacity. This is based on the tank size and the solution costs. In this level, the state of charge variable comes in.

Figure 5 shows the input-output diagram for Level 4.

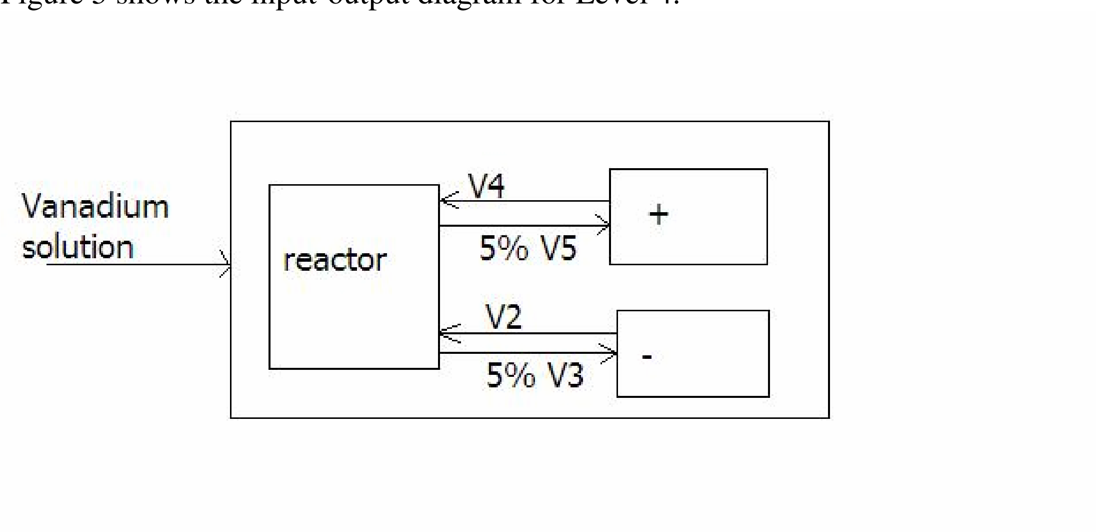

Figure 5: Input-Output Diagram for Level 4

The economic potential for level 4 is calculated by subtracting the solution and tank base module costs from the level 3 economic potential.

$$EP4=EP3-Cbm(solution)-Cbm(tanks)$$

The base module cost for the tanks is calculated similarly to how the base module costs for the heat exchangers and pump were calculated in the previous section.

For the tank, fiberglass must be used due to the acidity of the Vanadium/H2SO4 solution. The tank volume is found by finding the total Vanadium solution the tank will be required to hold. The calculations must be done three times-once for the base case of 10%-90% SOC, once for the case of 25%-75% SOC, and once for the case of 45%-55% SOC. All three are described on the same tables in this section.

Table 9 describes the variables needed to find the tank volume.

Table 9: Tank Volume Variables

Variable	Base Case (20% excess)	25%-75% SOC (50% excess)	45%-55% SOC (90% excess)
Vanadium needed	2880 molV	4608 molV	23040 molV
[V]	1 mol/L	1 mol/L	1 mol/L
Tank Size	4 m^3	6 m^3	25 m^3

Cbm for the tank is calculated via: Cbm = Fbm*Cp*558.2/400. Figure 5.61 in Ulrich is used to do these calculations. Table 10 describes the variables needed to calculate Cbm.

Table 10: Tank Base Module Cost

Variable	Base Case	25%-75% SOC	45%-55% SOC
Cp (0-10 barg tank)	$6,000.00	$8,000	$11,500.00
Fbm (for fiberglass)	3.3	3.3	3.3
Cbm (one tank)	$27,261.90	$36,841.20	$52,959.23
Cbm (two tanks)	$55,261.90	$73,682.40	$105,918.45

There are 3 solutions whose cost must be taken into account for level 4. These are Vanadium, H2SO4 and water.
The base module cost for the solutions is found via: Cbm = 1.118*f_o*total L of solution*(Cp/Liter)
Table 11 describes the variables needed to calculate Cp and Cbm for the solutions.

Table 11: Solution Variables

[V]	1 mol/L
Cost per gram of Vanadium	$2.20
ρ of solution	1.288 g/cm^3
[H_2SO_4]	5 mol/L
Cost per kilogram of Sulfuric Acid	$0.04
Cost per gram of Water	$0.000245
[water]	53 mol/L

Cp for the solutions is calculated very simply, by converting the concentration to grams and multiplying by the cost per gram. Table 12 below describes Cp and Cbm.

Table 12: Capital Cost and Base Module Cost for Solutions

Variable	Base Case	25%-75% SOC	45%-55% SOC
Vanadium Cp/Liter	$112.07/L	$112.07/L	$112.07/L
Sulfuric Acid Cp/Liter	$0.02/L	$0.02/L	$0.02/L
Water Cp/Liter	$0.23/L	$0.23/L	$0.23/L
Cp/Liter	$112.32	$112.32	$112.32
fo	0.24 (calculated in Level 2)	0.24 (calculated in Level 2)	0.24 (calculated in Level 2)
Total liters of solution	2880 L	4608 L	23,040 L
Cbm	$61,922.89	$139,326.50	$650,190.34
Cbm for 2 tanks	$173,593.17	$277,749.07	$1,388,745.33

The level 4 economic potential graph shows the potential for the base case, the 25%-75% (50%) case and the 45%-55% (10%) case in figure 6.

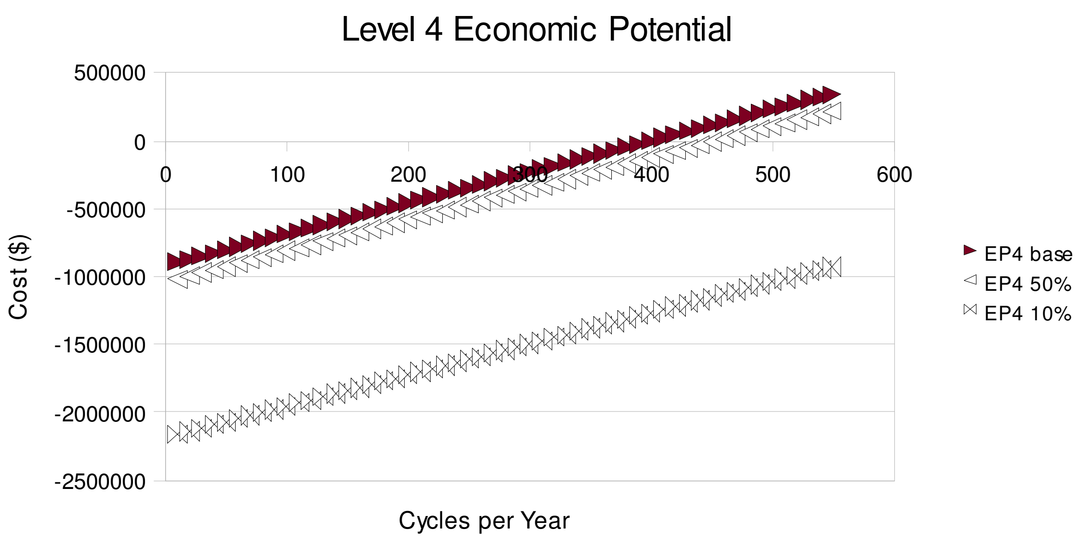

Figure 6: Level 4 Economic Potential

Section 3.0: Level 5 Analysis

Level 5 economic potential involves the operating costs and building costs of a plant. The operating costs are the power and energy capacity of the battery. The building costs are based on EPRI's calculations. These costs can be found in *Vanadium Redox Flow Batteries: An In-Depth Analysis.* EPRI, Palo Alto, CA: 2007. 1014836. They are also found in Table 12. Level 5 economic potential is calculated by:

EP5 = EP4 – building costs(2011) – Control System Costs – Remaining Costs

Table 15: Operating and Building Costs

Building Costs (2007)	$900/m^2
Inflation rate	3%
Building Costs (2011)	$1013/m^2
Facility Size	500m^2/MW
Control System Costs	$22,510
Remaining Costs	$56/kW

Figure 7 shows the level five economic potential.

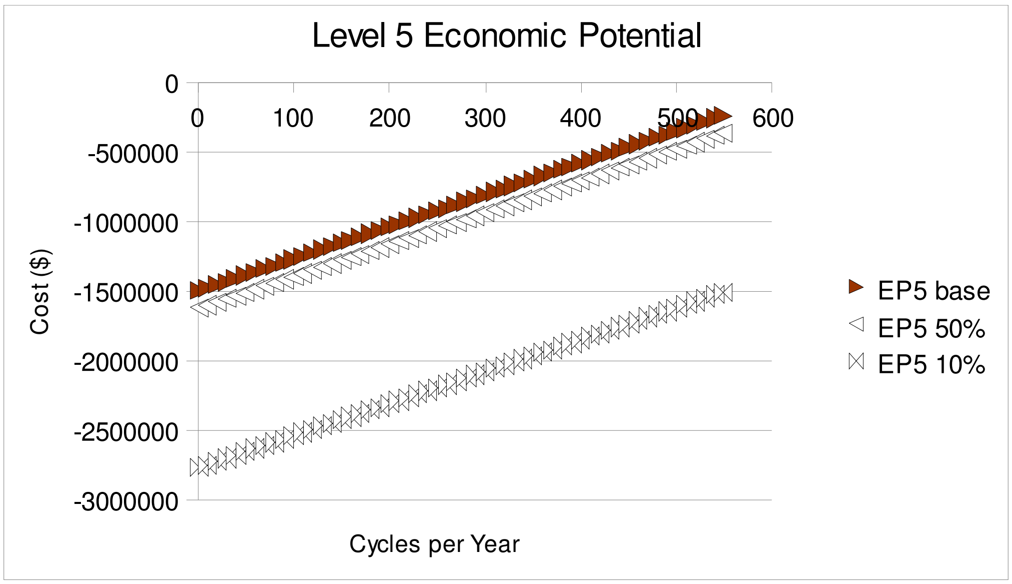

Figure 7: Level 5 Economic Potential

Section 4.0: Capital Cost Estimate

Level 6 of the design is a capital cost estimate using the costs that were found in the previous five levels. Table 16abc below shows the capital cost estimate for the three cases.

Table 16a: Base-Case Capital Cost Estimate

Equipment ID	Capacity	Cost	Material Factor	Base Case Cost
Stacks	20 stacks	$2,337,942.86	1.2	$2,805,531.43
Vanadium Solution	2880L	$646,963.20	1.1	$711,659.52
Tanks (2)	4m3 tanks	$16,746.00	3.3	$55,261.80
Heat Exchangers (2)	3.5 m2, High Nickel Steel	$3,070.10	7	$21,490.70
Pumps (2)		$11,164.00	7	$78,148.00
Control System,	1 MW	$22,510.00	1	$22,510.00
Balance of Plant Costs		$506,500.00	1	$506,500.00
Total Cost		$3,544,896.16		$4,201,101.45

Table 16b: 50% Case Capital Cost Estimate

Equipment ID	Capacity	Cost	Material Factor	50% Cost
Stacks	20 stacks	$2,337,942.86	1.2	$2,805,531.43
Vanadium Solution	4608 L	$1,035,141.12	1.1	$1,138,655.23
Tanks (2)	6m3 tanks	$22,328.00	3.3	$73,682.40
Heat Exchangers (2)	3.5 m2, High Nickel Steel	$3,070.10	7	$21,490.70
Pumps (2)		$11,164.00	7	$78,148.00
Control System,	1 MW	$22,510.00	1	$22,510.00
Balance of Plant Costs		$506,500.00	1	$506,500.00
Total Cost		$3,938,656.08		$4,646,517.76

Table 16c: 10% Case Capital Cost Estimate

Equipment ID	Capacity	Cost	Material Factor	10% Cost
Stacks	20 stacks	$2,337,942.86	1.2	$2,805,531.43
Vanadium Solution	23040L	$5,175,705.60	1.1	$5,693,276.16
Tanks (2)	25m3 tanks	$32,096.50	3.3	$105,918.45
Heat Exchangers (2)	3.5 m2, High Nickel Steel	$3,070.10	7	$21,490.70
Pumps (2)		$11,164.00	7	$78,148.00
Control System,	1 MW	$22,510.00	1	$22,510.00
Balance of Plant Costs		$506,500.00	1	$506,500.00
Total Cost		$8,088,989.06		$9,233,374.74

Section 5.0: Base-Case Operating Cost Estimate

Level 7 of the design is an operating cost estimate. These are estimated using Ulrich's text. The operating costs include the operator salary and the utilities cost. The operator salary is illustrated in Table 17. Power costs (utilities) were calculated in Level 5 as $56,000. Supervision and maintenance are also included in the operating costs. Table 18 illustrates the base case operating cost.

Table 17: Operator Salary

Operator Salary		
Equipment	Number	Operators/Unit
Pumps	2	0
Heat Exchang	2	0.05
Tanks	2	0
Reactor	1	0.3
Total		0.35
# Shifts		5
Salary for one operator		52697.63539
Salary for total operators		92220.86193

Table 18: Operating Costs

Operating Costs		
Operating Labor	In Table 15	$92,220.86
Utilities	via Level 5	$56,000.00
Supervision Labor	15% of operating	$13,833.13
Maintenance	6% of Fixed Capital	$107,852.99
Total Operating		$269,906.98

Section 6.0: Investigation of Selected Design Variable

The variable examined in this project was the state of charge. We considered three different cases: ranges from 10%-90% (the base case), 25%-75%, and 45%-55%. The state of charge affects the economic potential because it changes the amount of vanadium solution needed. For the base case, 2880 mol V are needed, for the 50% SOC (25%-75%), 4608 mol V are needed, and for the 10% SOC (45%-55%), 23040 mol V are needed. Since different amounts of vanadium are needed, different tank sizes are needed for each case. For the base case, a 4 m^3 tank is used, for the 50% SOC case, a 6 m^3 tank is used, and for the 10% SOC case, a 25 m^3 tank is used.

Section 7.0: Results and Conclusions

According to this design, changing the state of charge beyond the 10%-90% base case results in no betterment in the economic potential. In fact, changing the state of charge actually worsens the economic potential. The main points of cost was the cost of Vanadium. The cost of Vanadium not only increased the overall solution cost but also the tank cost. The solution was 17% of the total cost in the base case. While this is not a huge amount, this amount would drastically increase in the 50% and 10% cases. In fact, in the 50% case, the solution is 25% of the total cost, and in the 10% case, the solution is 62% of the total cost. It is also the second most costly item in the designs for the base case and the 50% case. It is the most costly item in the 10% case. Another huge point of cost was the cost of the ion exchange membranes. At $500/m2, they were extremely expensive. The total cost of the ion exchange membranes, carbon elements and collectors were 67% of the total cost of the base case, 60% in the 50% case and 30% in the 10% case. These were the most costly item in the design for the base and 50% cases. The main conclusion that can be drawn from this project is the battery cannot be economically feasible unless changes are made. These possible changes are addressed in Section 8.0.

Section 8.0 Recommendations

The main recommendation that can be drawn from this study is that it needs to be determined if less pure Vanadium can be used. Laboratory grade Vanadium Pentoxide was used for this design. Perhaps less pure Vanadium can be used. This would greatly reduce the cost. Likewise, the ion exchange membrane costs need to be addressed. Since the membranes are owned by only one company, this cost cannot be lowered until other companies begin to make the ion exchange membrane. Likewise, more research needs to be done to see if another ion exchange membranes works just as well. The main problem with this design is the ion exchange membranes. If this can be addressed, the battery could become more economically feasible at all 3 states of charge.

Section 9.0 References

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Nomenclature

SOC State of Charge
M Molar
L Liter
Mol moles
kW kilowatts
kW-hr kilowatt-hour
MW megawatt
W watt
kJ kilojoules
m meter
E_t transformer efficiency
E_{pcs} power control system efficiency
E_{ec} efficiency of DC power to chemical energy and reverse
E_{oa}, E overall efficiency
EP2 economic potential level 2
f_o fixed capital function
A annualized cost
Cbm, $C_{a,bm}$ base module cost
EP3 economic potential level 3
Cp capital cost
q heat
U heat transfer coefficient
Fm material factor
Fp pressure factor
Fa,bm base module installation factor
Delta_T change in temperature
X conversion
Rho density
Delta_H enthalpy
Cp heat capacity
EP4 economic potential level 4
[V] concentration of Vanadium
Cp/L capital cost per liter

Appendix
Calculations are described in this section.

Efficiency Calculations:
The efficiency of the battery must be calculated for a 40 mA/cm^2 current density. The voltage was calculated by You, et al:
40 mA/cm^2
Cell voltage ~= 1.225 V
Eeclcharge = 1 – (1.45-1.225)/1.45 = 0.845
Eecldischarge = 1 – (1.30-1.225)/1.30 = 0.942
$E_c = (0.995)^{1/2} * (0.970)^{1/2} * 0.845 = 0.830$
$E_d = (0.995)^{1/2} * (0.970)^{1/2} * 0.942 = 0.925$
$E_{oa} = 0.830 * 0.925 = 0.768$
Level One Calculations:
Flow rate of electrons is equal to:
1000kW*1000W/kW*1 V-A/W*1 cell/1.255V*1/100 cell*1C/s/A*e-/1.6E-19C*mol/6.022E23 e-
Flow rate = 0.08 mol/s
Level Two Calculations:
EP2 = profit-cost
profit = kwhr*efficiency*# of cycles*0.45
cost= kwhr*0.045*# of cycles
example for one cycle:
profit = 8000 * . 45 * 1
cost = 8000 * .045 * 1
EP2 = profit – cost = $2764.80

Level 3 Calculations:
EP3 = EP2-A
A = 1.18*fo*Ca,bm

1. Heat Exchanger Cp

   Area= q/UΔT

q=0.08 mol/s*(178x10^3cal)/(2mol)*4.187J/cal

U is determined to be 900 J/m^2-s-K, which is the value of U for a salt water-water heat exchanger. This is used because it is a good approximation for the heat exchanger that will be used. This value is from Ulrich.

The temperature change needs to be very small, around 10C in order to keep the heat down.

The total heat exchanger area is: 3.31 m^2, which is rounded to 3.5 m^2

Fm is 3.8 for a Ni/Ni heat exchanger. A Ni/Ni heat exchanger must be used because sulfuric acid will corrode other metals. Fp is 1 for less than 7 bar. Fa,bm needs to be found using figure 5.38 in Ulrich for a conventional heat exchanger. (Fa,bm=7)

The Cp for the heat exchanger is found using Figure 5.36 in Ulrich. It is found to be $1100 for a spiral tube heat exchanger.

2. Pump Cp

The pump cost is calculated using the flow rate of the solution. The flow rate is 0.08 mol/s, but to be used to calculate pump cost, this needs to be in volume. The conversion is needed, and it is found via: $X= \rho * Cp * \Delta T/[V] * \Delta H$

The ΔH is $178x10^3$ cal/mol. The Cp used is the Cp for sulfuric acid (0.7 cal/g-C), since the solution is mostly sulfuric acid.

Assuming a conversion of x=0.05, which is what is obtained with a temperature change of 10C, the volumetric flow rate is 1 L/s. Since the flow is in and out, the flow rate needs to be doubled to 2 L/s. The efficiency of the pump is taken to be 0.5. Based on this flow rate, the shaft power need to be calculated:

$$0.002\ m^3/s*2\ bar*10\ Pa/bar*0.5 = 800\ W \sim 1\ kW$$

The pump's Fa,bm value is found from Figure 5.51 in Ulrich. Fp is 1 and Fm is 3.5 for a high Ni alloy. This gives a Fa,bm value of 7.

Using this value and the shaft power, figure 5.49 in Ulrich must be used to calculate Cp, which is $4000 for a centrifugal pump. There are 2 pumps, so Cp is $8000.

3. Element Cp

The elements' costs accounts for 70% of their total Cp.

The total number of stacks is calculated:

$40mA/cm^2 = 400A/m^2$

Total m^2 of stack = (1000W/battery * 1000 W/kW * 1V-A/W * 1 cell/1.255 V * battery/100 cell)/$400A/m^2 = 19.9\ m^2$

There is $1m^2$ in a stack → there are 20 stacks in this design.

The total cost of the elements is calculated:

Cost of collectors = $\$80/m^2 *101*20m^2 = \$161,600$

Cost of carbon elements = $\$50/m^2 *202*20m^2 = \$202,000$

Cost of ion exchange membranes = $\$500/m^2*100*20m^2 = \$1,000,000$

Total cost of all elements types = $1,363,800

Total Cp = $1,363,800/0.7 (since the total cost is 70% of the total Cp for the elements) = $1,948,285.71

4. Base Module Cost

For the collectors, elements and membranes Cbm is 1.2*Cp = 1.2*1,948,285.71 = $2,337,942.86

For the heat exchangers, Cbm is Cp*Fa,bm * 558.2/400 = $2200*7*558.2/400 = $21490.70

For the pumps, Cbm is Fa,bm*Cp*558.2/400=$8000*7*558.2/400 = $78148

Therefore, A is 1.18*0.24*(2337942+21490.70+78148) = $690,322.90

EP3=EP2-$690,322.90

Level 4 Calculations:

EP4=EP3-Cbm(solution)-Cbm(tanks)

1. Tank Calculations

Vfound = (0.08 mol V/s)(8 hr)(3600 s/hr) = 2304 mol V (total amount of Vanadium going through the system at any time)

Base Case: (a SOC of 10%-90%) =Vtotal=Vfound/0.8 = 2880 mol

2880 mols V*L(0.001 m3/L)/1molV ~= 4 m3 (tanks should be 10% more than the needed moles)

From Figure 5.61 in Ulrich (tank 0-10 barg),
Cp=$6000
Fbm=3.3 for fiberglass
Cbm=Fbm*Cp*558.2/400
Cbm= $27,630.90
There are two tanks, so total Cbm is $55,261.90

For SOC of 25%-75%: Vtotal = Vfound/(0.5) = (2304 mol V)/(0.5) = 4608 mol V
4608 molV*L(.001m3/L)/1molV ~= 6 m3
From Figure 5.61, Cp = $8000
Fbm= 3.3 for fiberglass
Cbm=Fbm*Cp*555.2/400
Cbm= $36,841.20
There are two tanks, so total Cbm is $73,682.40

For SOC of 45%-55%: Vtotal = Vfound/(0.1) = (2304 mol V)/(0.1) = 23040 mol V
23040molV*L(.001m3/L)/1molV ~= 25 m3
From Figure 5.61, Cp = $11500
Fbm=3.3 for fiberglass
Cbm=Fbm*Cp*555.2/400
Cbm= $52,959.23
There are two tanks, so total Cbm is $105,918.45

2. Solution Calculations

There are 3 solutions whose cost must be taken into account for level 4. These are Vanadium, H2SO4 and water.

[V] = 1 mol/L
$2.10 $/gV
ρ of vanadium solution=1.288 g/cm3
[H2SO4] = 5 mol/L
$0.04/gH2SO4

Cost of Vanadium = (1 mol/L)*(50.9415 g/mol)*($2.20/g) = $112.07/L
Cost of H2SO4 = (5 mol/L)*(98.0791 g/mol)*($0.04/1000g) = $0.02/L
Cost of H2O = (53 mol/L)*(18.02g/mol)*($0.000245/g) = $0.23/L
Cp/Liter= $112.07/L + $0.02/L + $0.23/L = $112.32/L
Total L of solution:

Base case: 2880L mol*1 mol/L = 2880 L
25-75%: 4608 mol * 1 mol/L = 4608 L
45-55%: 23040 mol * 1 mol/L = 23040 L

2* Cbm = 2 * 1.118*0.24*total L of solution*Cp/Liter. Cbm is multiplied by 2 because there are 2 tanks.

Base Case = 1.118*0.24*2880L*$112.32/L = $173,593.17
25-75% = 1.118*0.24*4608L*$112.32/L = $277,749.07
44-55% = 1.118*0.24*23040L*$112.32/L = $1,388,745.33

Level 5 Calculations
EP5=EP4-Building Cost-Control System Cost-Remaining Costs
2011 Building Cost: 1.3*(2007 Building Cost) = 1.3*900 = $1013/m2
Building Cost = $1013/m2*500m2/MW*1MW = $506,500
Remaining Cost =$56/kW*1000kW = $56,000
Control System costs are given by S. Eckroad's EPRI Report as $22510

Base Case Calculations
The majority of the calculations for the base case cost were calculated in Levels 2-5. The cost for the Vanadium was found and multiplied by 2. It was multiplied by 2 because there are 2 tanks:

2880L*$112.32/L*2 = $711,659.52
4608L*$112.32/L*2 = $1,305,141.12
23040L*$112.32/L*2 = $5,175,705.60

Below is the data collected by doing the calculations described in the appendix.

Cycles/year	EP2	EP3	EP4 base	EP4 50%	EP4 10%	EP5 base	EP5 50%	EP5 10%
1	2296.05	-688026.85	-916881.82	-1039458.31	-2182690.63	-1501891.82	-1624468.31	-2767700.63
10	22960.5	-667362.4	-896217.37	-1018793.86	-2162026.18	-1481227.37	-1603803.86	-2747036.18
50	114802.5	-575520.4	-804375.37	-926951.86	-2070184.18	-1389385.37	-1511961.86	-2655194.18
100	229605	-460717.9	-689572.87	-812149.36	-1955381.68	-1274582.87	-1397159.36	-2540391.68
150	344407.5	-345915.4	-574770.37	-697346.86	-1840579.18	-1159780.37	-1282356.86	-2425589.18
200	459210	-231112.9	-459967.87	-582544.36	-1725776.68	-1044977.87	-1167554.36	-2310786.68
250	574012.5	-116310.4	-345165.37	-467741.86	-1610974.18	-930175.37	-1052751.86	-2195984.18
300	688815	-1507.9	-230362.87	-352939.36	-1496171.68	-815372.87	-937949.36	-2081181.68
350	803617.5	113294.6	-115560.37	-238136.86	-1381369.18	-700570.37	-823146.86	-1966379.18
400	918420	228097.1	-757.87	-123334.36	-1266566.68	-585767.87	-708344.36	-1851576.68
450	1033222.5	342899.6	114044.63	-8531.86	-1151764.18	-470965.37	-593541.86	-1736774.18
500	1148025	457702.1	228847.13	106270.64	-1036961.68	-356162.87	-478739.36	-1621971.68
548	1258235.4	567912.5	339057.53	216481.04	-926751.28	-245952.47	-368528.96	-1511761.28