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Research Article

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A Comparison of the Capital Costs of a Vanadium Redox-Flow Battery and a Regenerative Hydrogen-Vanadium Fuel Cell

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Abstract

The capital costs of a Regenerative Hydrogen-Vanadium Fuel Cell and a Vanadium Redox-Flow Battery are compared for grid level energy storage. The bulk of the capital costs for a Vanadium Redox-Flow Battery lie in the costs of the vanadium electrolyte, while the Regenerative Hydrogen-Vanadium Fuel Cell presents a potential for savings by eliminating the need for half of the vanadium electrolyte required by a Vanadium Redox-Flow Battery. It was found that the Regenerative Hydrogen-Vanadium Fuel Cell would cost $57 less per kWh than the Vanadium Redox-Flow Battery, with savings garnered from the elimination of half of the electrolyte somewhat mitigated by the costs of the catalyst and air compressor required. If the capital costs are annualized through straight line depreciation, and the operation costs are included, the Vanadium Redox-Flow Battery is $5 per kWh less per year than the Regenerative Hydrogen-Vanadium Fuel Cell.

Keywords: Flow battery; Economics; Regenerative hydrogen-vanadium fuel cell; Capital costs comparison

Introduction

The goal of this paper is to estimate and compare the capital cost of a regenerable hydrogen-vanadium battery (RHVB) with an all-vanadium redox-flow battery (VRB) for grid-scale applications [1,2]. As more and more renewable power production is added to the grid the need increases for large-scale storage alternatives. The potential of the redox flow battery (RFB) for use in grid scale energy storage is well documented [3-6]. Revenue streams for RFBs are somewhat complex, including peak shaving, load leveling, energy reserve and grid stabilization capabilities to improve the performance of the utility grid and deferral of investments for additional generation capacity [7]. In a series of papers Banham-Hall and others establish the technical viability of these potential revenue streams for VRBs integrated into a system of renewable power generation [7-9]. Using grid-based prices and other relevant information, Fare and others showed the value of VRBs for frequency regulation to be about $1500/kW [10]. The combination of renewable energy production and energy storage enables the system to behave more like a conventional power generation systems [7-9]. The all-vanadium redox flow battery (VRB) is currently the leading battery alternative. For bulk energy storage the Vanadium Redox-Flow Battery (VRB) has a distinct advantage over other types of flow batteries. Vanadium cations have four different oxidation states, allowing vanadium to be used in both the anolyte and the catholyte. This is advantageous because any cross contamination of ionic species through the membrane does not present major difficulties. Vanadium, however, is more expensive that many other electrolyte sources for flow batteries and represents a significant portion of the capital costs of building a VRB [2]. A possible solution to this is to create a hybrid battery/fuel cell, designing the anode half-cell to function as in a fuel cell, and the cathode half-cell to function as in a flow battery. The chemical equations are [1]:

$$\text{Cathode: } 2VO_2^+ + 4H_3O^+ + 2e^- \rightarrow 2VO^{2+} + 6H_2O$$

$$\text{Anode: } H_2 + 2H_2O \rightarrow 2H_3O^+ + 2e^-$$

$$\text{Overall: } 2VO_2^+ + 2H_3O^+ + H_2 \rightarrow 2VO^{2+} + 4H_2O$$

This concept was demonstrated with a regenerative hydrogen-vanadium battery (RHVB) by Yfit et al. [1]. A RHVB has the potential for lower capital costs by eliminating the need for half of the vanadium required in a VRB. In addition, since the electrolyte is only required for the reaction in the cathode half-cell, metal ions with only 2 oxidation states may be used as an alternative. Metal ions that provide 2 or more moles of electrons for every mole of ions when they are oxidized could further reduce the required capital cost.

In this paper the capital cost of a RHVB is estimated and compared with a VRB. The contributions to the total capital costs of a VRB can be seen in Figure 1. The relevant information about the RHBV can be found in Tables 1 and 2. In this costing study it is assumed that there is little difference in the stack components between the RHVB and the VRB. The differences in the stacks are in the reactions taking place in the anode half-cell, the electrical potential generated by the reactions in each cell, and the need for a catalyst in the regenerative battery. The VRB requires two liquid tanks for the anolyte and catholyte, and 2 pumps to move the electrolyte solutions. The RHVB battery requires just one tank and pump but also requires storage for the hydrogen as well as a compressor.

Methods

The stack component costs in the EPRI report *Vanadium Redox Flow Batteries: An In Depth Analysis* were largely used for this analysis [5]. With the addition of cost of a catalyst ink and Application of $65/$m^2$ from James et al. [11]. Using the design details in the EPRI report for the total electrode area needed for a 1 MW, 6 MW hr battery, the number of cells required for the battery was calculated. This was then multiplied by the cost per cell component provided by the report. The voltage efficiency used was calculated from data provided by Che-Nan Sun in experiments conducted at Oak Ridge National Laboratory on a VRB [12]. This efficiency was used for both the RHVB and the VRB for simplicity purposes. The flow rates of the vanadium electrolyte and the

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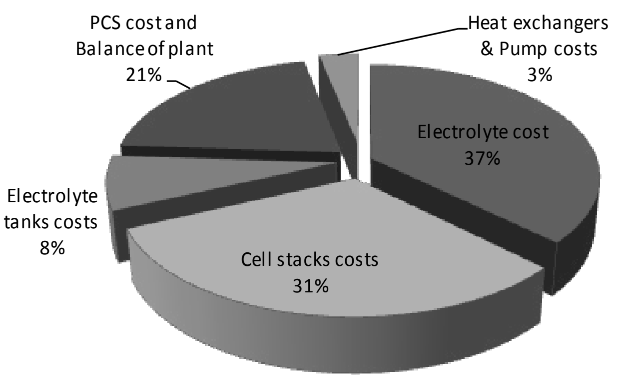

Figure 1: The Capital Costs of the Base Case VRB.

hydrogen were estimated by calculating the moles of electrons oxidized per second by one cells, then multiplied by the number of cells in the stacks. This estimate is the molar flow rate and molar concentration required, and is used to estimate the size of the pumps and the compressor required using the methods found in a textbook by Ulrich and Vasudevan [13]. The pressure drop of the vanadium electrolyte through the cell stacks was estimated by using an empirical correlation in "Understanding Vanadium Redox-Flow Batteries" by Blanc and Rufer that uses a hydraulic resistance calculated from computer simulations using the finite element method [14]. It was assumed that there is no loss to the power produced by the batteries due to species depletion as the electrolyte and the hydrogen flows through the stack.

The volume of vanadium required was estimated by multiplying the previous calculation of moles of electrons oxidized per time of the entire stack by the charge or discharge time. The method of hydrogen storage is assumed to be with the use of an adsorbent. It is important to note that the capital costs of this storage method used here are from the USDOE FreedomCAR targets [15]. The 2010 target is $133 per kg of hydrogen, the 2017 target is $67 per kg of hydrogen, and the cost used to calculate the capital cost for this paper was $100 per kg hydrogen. While the use of adsorbent storage reduces the need for high pressure storage of hydrogen, it is still necessary to use a pressurized vessel, albeit at a lower pressure than without an adsorbent. A compressor is then necessary for the hydrogen exiting the stacks during the charging process. Heat is required to desorb the hydrogen, and at steady state operation it is possible that the heat generated by the cell stacks or the compressor could be used. An external source of heat would be required at start up, however. During the charge cycle the hydrogen flowing from the stacks contains water, requiring that this water be removed from the stream or that a method of removing the water from the storage tank be found. The capital cost calculations in this paper do not reflect the costs associated with heating the adsorption materials or removing the water for the hydrogen stream or the tank. The costs of the power conditioning system and the control system for both systems were assumed to be the same and were taken from the EPRI report [3].

The annual operational costs associated with the fixed capital can be seen in Table 3. These costs are $42.77 per kWh for a RHVB and $51.02 per kWh for a VRB. Other operation costs are assumed to be the similar for the two battery systems with the exception of the costs to run the pumps and compressors. The cost of electricity is assumed to be $0.10 per kWh, and it is also assumed that the battery runs a full cycle a day (charge and discharge) 328 days a year. With these assumptions, the costs of electricity annually for the RFB are $0.79 per kWh while the costs of electricity annually for the RHVB are $16.80 per kWh.

Results

The results of the capital cost analysis can be seen in Tables 4 and 5. The total cost per year, using straight line depreciation for the capital costs over a 20 year lifespan, would be about $70 per kWh for the VRB and $75 per kWh for the RHVB. The precious metal catalyst required for the RHVB constitutes the difference in the capital cost between the cell stacks. In addition, the higher electrical potential available to the vanadium battery cells allowed for an overall smaller stack size than the RHVB, reducing costs. The VRB uses two pumps, while the RHVB uses a pump for the vanadium electrolyte and a compressor for the hydrogen. The capital cost of the compressor is much greater than the costs of the pumps, adding to the costs of the RHVB in comparison to the VRB. In addition, the costs for the electricity to run the compressor are much greater than the costs for running the pumps. The savings in the capital costs associated with the regenerative battery is for the vanadium and its storage, the regenerative battery only requiring vanadium as a catholyte, while the VRB requires vanadium for the anolyte as well. Because of the lower electrical potential of the cells in the regenerative battery, a higher current is required to sustain the power requirement of 1 MW. This necessitates the use of more electrolytes in the regenerative battery, mitigating some of the savings in the purchase costs of vanadium.

Conclusion

Overall the VRB is about $5 per kWh per year cheaper than the RHVB. The capital costs are for batteries with the specific energy and power capacities detailed in Figure 1. A sensitivity analysis by Zhang et al. for a VRB can be used to determine how these costs will change when the energy and power capacities are adjusted [16]. With a fixed energy capacity (stored electrical energy) a VRB has a power capacity sensitivity index of 0.4881, which represents the rate of change of the capital costs with respect to the power capacity. This rate of increase in the capital costs would be higher with a RHVB as the power capacity is determined by the size of the stacks, which has a higher cost in the RHVB due to the catalyst. If the power capacity is held constant

Category	Value
Stoichiometry	Cathode: $2VO_2^+ + 4H_3O^+ + 2e^- \leftrightarrow 2VO^{2+} + 6H_2O$ Anode: $H_2 + 2H_2O \leftrightarrow 2H_3O^+ + 2e^-$
Power Capacity	1,000 kW
Energy Capacity	6,000 kWh
Overall Efficiency	0.73
Open Circuit Electrical Potential per Cell	1.1 Volts
Cross Sectional Area of Cell	236 cm^2
Current Density	604 mA/cm^2

Table 1: Design Details for Hydrogen-Vanadium Regenerative Battery.

Component	Value
Stoichiometry	Cathode: $2VO_2^+ + 4H_3O^+ + 2e^- \leftrightarrow 2VO^{2+} + 6H_2O$ Anode: $V^{2+} \leftrightarrow V^{3+} + e^-$
Power Capacity	1,000 kW
Energy Capacity	6,000 kWh
Overall Efficiency	0.73
Open Circuit Voltage per Cell	1.3 Volts
Cross Sectional Area of Cell	1 m^2
Current Density	604 mA/cm^2

Table 2: Design Details for the Vanadium Redox-Flow Battery.

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Capital-related cost item	Fractions of fixed capital
Maintenance and repairs	0.06
Operating supplies	0.01
Overhead, etc.	0.03
Taxes and insurance	0.03
General	0.01
Total	**0.14**

Table 3: Annual Expenses Proportional to Fixed Capital.

Component	Cost
Total Cost of Stack	$9.00
Pump Costs	$4.11
Cost of Compressors	$50.00
Cost of Electrolyte Tank	$30.00
Cost of Adsorption Tank	$1.64
Cost of Vanadium	$59.18
Fuel Cell Balance of Plant	$97.42
PCS, Transformer, etc.	$54.12
Total Cost	$305.47

Table 4: Capital Costs of RHVB in $/kWh.

Component	Cost
Total Cost of Stacks	$4.92
Pump Costs	$8.23
Cost of Electrolyte Tanks	$60.00
Total Cost Vanadium	$139.76
Fuel Cell Balance of Plant	$97.42
PCS, Transformer, etc.	$54.12
Total Costs	$364.44

Table 5: Capital Costs of VRB in $/kWh.

the sensitivity index for capital costs due to cycle time (representing total energy capacity) and vanadium costs are 0.6101 and 0.3337, respectively, for a VRB. These rates of change for the capital costs would be less for a RHVB because the main driving force for these costs is for the vanadium, with the RHVB using half the mass of vanadium as a VRB.

In order for the RHVB to be more cost effective than the VRB more cost reductions must be found. Possibilities for cost reductions are:

1) Eliminating the need for the catalyst by operating the battery at higher temperatures

2) Reducing the pressure in the H_2 storage tank

3) Replacing vanadium with a lower cost redox material

It would be necessary to ensure that the vanadium does not precipitate from the solution at high temperatures, however. For the purposes of this study the costs of the compressor and pressurized tank were only calculated for a hydrogen storage pressure of 10 bar, a more thorough analysis may provide a cost savings in this regard. A more affordable electrolyte could significantly reduce the costs of the regenerative battery. Because of the need for a metal with only 2 oxidation states and a reduced chance of cross contamination through the membrane, it is possible a number of other metals would present a cost savings over vanadium.

References

1. Yfit V, Hale B, Matian M, Mazur P, Brandon NP (2013) J Electrochem Soc 160: A56.
2. Moore M, Counce R, Watson J, Zawodzinski T, Kamath J (2012) A Step-by-Step Design Methodology for a Base Case Vanadium Redox-Flow Battery. Chem Eng Ed 46: 239-250.
3. Weber AZ, Mench MM, Meyers JP, Ross PN, Gostick JT, et al. (2011) Redox flow batteries: a review. J Appl Electrochem 41: 1137-1164.
4. Skyllas-Kazacos M, Chakrabarti MH, Hajimolana SA, Mjalli FS (2011) Progress in Flow Battery Research and Development. J Electrochem Soc 158: R55-R79.
5. Eckroad S (2007) Vanadium Redox Flow Batteries: An In-Depth Analysis. EPRI, Palo Alto, CA.
6. Kear G, Shah AA, Walsh FC (2012) Development of the all-vanadium redox flow battery for energy storage: a review of technological, financial and policy aspects. Int J Energy Res 36: 1105-1120.
7. Banham DD (2012) Flow Batteries for Enhancing Wind Power Integration. IEEE Trans 27: 1690-1697.
8. Banham-Hall DD, Taylor GA, Smith CA, Irving MR (2011) Frequency control using Vanadium redox flow batteries on wind farms. IEEE Power and Energy Society General Meeting 1-8.
9. Banham-Hall DD, Smith CA, Taylor GA, Irving MR (2012) International Universities Power Engineering Conference, UPEC, IEEE Computer Society.
10. Fares RL, Meyers JP, Webber ME (2014) A dynamic model-based estimate of the value of a vanadium redox flow battery for frequency regulation in Texas. Appl Energy 113: 189-198.
11. James BD, Kalinoski JA, Baum KN (2010) Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications. Directed technologies, Arlington VA.
12. Sun CN, Mench M, Zawodzinski T (2013) Comparing Limits of Performance in Aqueous and Non-aqueous Redox Flow Batteries. 224th ECS Meeting.
13. Ulrich G, Vasudevan P (2004) Process (Ulrich) Publishing. Durham, NH.
14. Blanc C, Rufer A (2010) Understanding the Vanadium Redox Flow Batteries, Paths to Sustainable Energy. InTech
15. He C, Dansai S, Brown G, Bollepalli S (2005) Electrochem Soc Interface 31.
16. Zhang M, Moore M, Watson J, Zawodzinski T, Counce R (2012) Capital Cost Sensitivity Analysis of an All-Vanadium Redox-Flow Battery. J Electrochem Soc 159: A1183-A1188.