Estimating the system price of redox flow batteries for grid storage

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Abstract

Low-cost energy storage systems are required to support extensive deployment of intermittent renewable energy on the electricity grid. Redox flow batteries have potential advantages to meet the stringent cost target for grid applications as compared to more traditional batteries based on an enclosed architecture. However, the manufacturing process and therefore potential high-volume production price of redox flow batteries is largely unquantified. We present a comprehensive assessment of a prospective production process for aqueous all vanadium flow battery and nonaqueous lithium polysulfide flow battery. The estimated investment and variable costs are translated to fixed expenses, profit, and warranty as a function of production volume. When compared to lithium-ion batteries, redox flow batteries are estimated to exhibit lower costs of manufacture, here calculated as the unit price less materials costs, owing to their simpler reactor (cell) design, lower required area, and thus simpler manufacturing process. Redox flow batteries are also projected to achieve the majority of manufacturing scale benefits at lower production volumes as compared to lithium-ion. However, this advantage is offset due to the dramatically lower present production volume of flow batteries compared to competitive technologies such as lithium-ion.

Keywords: redox flow battery; grid storage; lithium-ion battery; manufacturing cost; production volume;

1. Introduction

The integration of renewable sources of energy with the electricity grid has increased dramatically over the last 10 years. However, the desire to obtain large fractions of electrical energy (>10% of total demand) from renewable energy resources has encountered challenges arising from wind and solar power's intermittency and poor predictability.[1-4] Over the same period, new developments in electrochemical energy storage technology have brought forward the possibility that the very problems renewables introduce, storage may solve. Of particular interest are redox flow batteries which are rechargeable electrochemical energy storage devices that utilize the oxidation and reduction of soluble electroactive species for charging and discharging.

Comprehensive reviews of flow battery systems for grid electricity have been reported.[5-8] Compared with ubiquitous enclosed batteries (e.g. lead-acid or lithium-ion battery); flow batteries store at least one of the electrode's active materials externally from the electrode. This architecture allows independent scaling of the battery's rated power and energy. The characteristics of the reactor (i.e. reaction sites, membrane, and current collectors) determine the battery power and the volume of the tank which stores the active material determines the battery energy. However, this independent scaling requires the use of facile reactions and efficient mass transport so that high power densities may be reached, thus minimizing the expense of the reactor and capturing the benefit of the flow architecture. Applications requiring hours of energy storage are particularly well suited to flow batteries. To increase the energy content of a flow battery, the system only requires additional active material and an inexpensive tank. Conversely, expanding the energy content of traditional enclosed architectures requires the

procurement of both materials for energy and materials for the reactor, even if additional power is not demanded from the battery.

The cost target of grid energy storage for widespread adoption is very challenging. The Department of Energy's (DOE) Office of Electricity Delivery and Energy Reliability proposed cost targets of \$250 per kWh by 2015, falling to \$150 per kWh in the future for a fully integrated distributed energy storage system providing 4 h of storage.[9] Our previous work[10] investigates electrochemical systems capable of economically storing energy for the grid and presents an analysis of the relationships among technological performance characteristics, component cost factors, and system price for established and conceptual batteries. From this study, reductions in non-materials costs are identified as the single largest cost-savings opportunity for today's battery-based storage options. These cost factors associated with capital equipment, sales, and administration are forecasted to reduce as production volumes increase and efficiencies are realized. Thus, the associated timing of increasing implementation and/or existence of widespread commercialization of redox flow batteries will depend upon the availability of cost-competitive manufacturing. Therefore, manufacturing cost modeling can provide value by projecting cost curves as a function of production volume.

Extensive materials cost analysis has been reported for aqueous redox flow batteries, [11-19] using top-down and bottom-up approaches. Cost analysis was done for the Fe-Cr system with cost breakdown for various stack components and chemicals.[12] A high-level analysis was completed for an all vanadium system with 1MW, 8MWh capability.[13] Materials cost for vanadium flow battery was analyzed with a focus on stack components, i.e., bipolar plate, carbon felt, and ion exchange membrane.[14] Viswanathan et al. developed an open-source cost and performance model that takes into account shunt current and pumping losses for all vanadium

and Fe-Cr flow batteries with a focus on material cost.[15] While these models simulate electrochemical performance and materials cost, they have not examined in detail the capital equipment, labor, and overheads of the assembly process. In comparison, comprehensive manufacturing cost estimates, though limited in number, have been reported for lithium-ion (Li-ion) batteries and proton exchange membrane fuel cells.[20-24]

The goal of this paper is to estimate the manufacturing costs and resulting system price of flow batteries for grid energy storage. To achieve this goal, we focus in this work on estimating the unit price less material costs for flow batteries. By this, we mean all of the contributions to system price other than purchased goods that are assumed to be manufactured elsewhere by a firm specializing in their production. Figure 1 illustrates a system price breakdown, not including installation, for a flow battery energy storage system. As detailed later in the analysis, these values are for the vanadium redox flow battery with materials and purchased item prices reported for 2014 and an assumed annual manufacturing production rate of 20,000 batteries each capable of delivering 100 kWh of useable energy at a continuous power of 20 kW. The membrane, carbon felt, redox active material, and electrolyte are all examples of purchased materials. The heating and cooling system, pumps, and power conditioning system are examples of purchased items that we term balance of plant (BOP). The remaining contributions of depreciation, labor, overhead, profit and warranty are named the unit price less materials and are the focus for this work.

To estimate the unit price less materials, we created a detailed bottom-up model that captures production volume, manufacturing process, and associated overheads, enabling comparison of different flow battery technologies. We focus on vanadium redox (VRFB) and lithium polysulfide (LiPS). VRFB is one of the few aqueous flow batteries that have been tested

at the utility scale and is the subject of intense commercialization efforts. As an alternative to aqueous VRFB, LiPS was selected as a representative non-aqueous hybrid or semi-flow RFB using lithium metal as an anode and a flowing positive electrolyte consisting of solubilized polysulfide.[25, 26] Analysis of this immature chemistry allows for a deeper understanding of the manufacturing cost differences between Li-ion and aqueous redox flow batteries. This paper begins by describing the stack design and performance of each system. This is followed by a detailed discussion of the assembly process and the dependence of equipment cost, labor, and required plant area as a function of production volume. Finally, high-volume production estimates of Li-ion, VRFB, and LiPS are compared to evaluate the relative contributions to total battery price, benefit of manufacturing scale and consequences for market penetration.

2. Model Description

2.1. Approach

This work presents a comprehensive unit price less materials analysis of VRFB and LiPS flow battery systems suitable for grid storage and comparison with enclosed Li-ion. Site installation costs for the energy storage system, though very important, are not estimated in this work. The approach taken for the flow batteries is detailed within this manuscript. The Li-ion projections were taken from a peer-reviewed bottom-up battery performance and cost (BatPaC) model available free of charge (www.cse.anl.gov/batpac).[20, 21] Additional cost factors of a power condition system and heat exchanger for thermal management are added to the values produced by BatPaC. The annual production volume requirements for stack components are determined by the design information generated in modeling the cell and battery stack performance.

The unit price less materials for the designed battery stack are scaled from a baseline plant. The baseline plant accounts for the size, speed, number of units, direct labor, and the capital equipment cost for each processing step. The capital equipment cost is adjusted based upon the required features of the part and the cycle time it takes to generate those features in a typical machine of the appropriate type. In the case of stack components not widely used at present, the manufacturing process is analyzed to determine the probable high-volume price. The process expenses are summed with the additional costs of operating the manufacturing facility. These costs include launch costs, working capital, variable overhead, general, sales, administration (GSA), research and development, depreciation, and profit.

The basis for this unit price less materials model is an assumed future state where the electrochemical energy storage devices analyzed in this work are subject to high-volume production, vigorous market competition, and engineering advances commonplace to technology maturation. Essentially, the model treats the product as being produced in an established and mature industry much like large scale automotive manufacturing. These conditions do not exist for flow batteries and are only beginning to take shape for large format Li-ion energy storage systems. The future state baseline manufacturing plant is designed for an annual production rate of 100,000 battery stacks providing a continuous stack power of 20 kW and useable energy of 100 kWh. We note that many applications for grid storage require orders of magnitude more power than 20 kW. We envision these 20 kW stacks as building blocks to be combined in parallel and series to reach much higher power ratings. Cost analysis was performed for mass-manufactured stacks at production rates of 20-500% of the baseline rate. Stack performance and design is invariant with production rate. As the large scale manufacture of flow

batteries does not yet exist, this stack design does not reflect the design of any one manufacturer but are composites of the base elements from a number of designs.

Materials and purchased item costs are an important and often examined portion of the system price. As shown below, the contributions of these costs are used to scale the contributions for some factors that contribution to the unit price less materials. The purchase price for materials will depend on volume consumed in the market and the fraction of that volume purchased by the manufacturer of the energy storage system. We examine both near and long-term costs to evaluate a sensitivity between current material costs and those that may be reached in an established market. The materials and purchased items costs reported for 2014 and for the assumed future state are taken from Darling et al.[10] and are restated in the Appendix. In that work, the VRFB values are largely taken from Viswanathan et al. [15]

2.2. Cell and Battery stack design

In a flow battery architecture, the serial stacking method using bipolar plates, which resemble the method used in fuel cells, is employed as illustrated in Figure 2a. The cell components include the porous electrodes, separator, the bipolar plates, and a frame/gasket. For LiPS, the stack is using stationary negative electrode of Li-metal instead of porous carbon felt electrode for VRFB. To provide a specific manufacturing process for the model, a prismatic cell in a stiff-pouch container was selected for Li-ion and the polymer electrolyte fuel cell was benchmarked for flow batteries. Figure 2b illustrates Li-ion stack design.

2.3. System performance and operation

Table 1 shows performance characteristics for Li-ion, VRFB, and LiPS. The technology performance characteristics are taken from Darling et al.[10] The representative Li-ion chemistry

is taken to be a graphite (Gr) anode coupled with a LiFePO_4 (LFP) cathode. The continuous discharge power density is determined by the area specific resistance (ASR), voltage efficiency, $\varepsilon_{v,d}$, and average open circuit potential, U . The resultant power density determines the active area used in the stack geometry to meet the target power of 20kW. The flow battery designs are benchmarked from previously demonstrated systems. Current cell areas of flow batteries for grid storage range from 0.1 to 0.8 m^2 for kW-class stacks.[27, 28] We apply an additional constraint that the stack current should be less than 200 A to allow for standard power electronic components. Thus, the area of a single cell is designed to be 0.1 m^2 and 0.5 m^2 for VRFB and LiPS, respectively. With the cell area set, the number of cells in a 20 kW stack is determined by the power density. For flow batteries, a stack is composed of multiple stacked unit cells in series. The number of cells in a stack is 75 and 200 for VRFB and LiPS, respectively. The stack voltage is calculated by multiplying average open circuit potential of unit cell by the number of cells. Though the reactor stack of VRFB and LiPS are similar in design, the active area required to meet the rated power differs by an order of magnitude. The higher power density of the aqueous VRFB compared to LiPS is attributed to higher aqueous electrolyte conductivity and that LiPS is limited in current density by the lithium metal negative electrode. Thus, the hybrid nature of LiPS system prevents it from capturing all of the benefits available to a true flow battery.

While power density determines cell count for the flow batteries, the number of cells for a Li-ion battery is determined by the energy requirement and designed system voltage. The stack dimensions for Li-ion follows the BatPaC model.[21] Mirroring Li-ion electric vehicle batteries, we take an average system voltage of 370 V. The battery achieves this voltage and energy content by connecting 2 cells in parallel and 14 cell groups (28 cells) in series in each of the 8

series connected modules. A single cell has a nominal cell voltage of 3.3 V. The low continuous power density of the Li-ion results in a stack area approximately 200 times larger than the VRFB. This is offset to some degree by the low cost of separator and current collectors in Li-ion as compared to VRFB (i.e., $\sim \$5/\text{m}^2$ as compared to $\sim \$500/\text{m}^2$). However, this difference in active area will manifest in the form of higher production costs as discussed later.

2.4. Baseline manufacturing plant

To establish a frame of reference for future state baseline production volume, we calculate the annual production volume for flow batteries if used to store 1% of the electricity produced worldwide for 5 hours each day. This equates to 2 GW and 10 GWh of new energy storage production annually. The model's baseline plant is designed to produce 100,000 baseline battery stacks per year to reach this power and energy total. Thus, the baseline battery stack is providing total stack power of 20 kW and total energy of 100 kWh. Figure 3 illustrates the flow of materials through the plant and the processing steps. The overall manufacturing rate of baseline is achieved by operating for 3 shifts at the equivalent of 300 days per year of fully effective production. This is equivalent to saying the factory is operating 360 days per year at 83% efficiency. Most of the operations are carried out with normal factory atmosphere, but the manufacturing and assembly processes associated with Li-metal are completed in a dry room atmosphere.

2.5. Cost components of the unit price less materials model

The unit price less materials in this paper consists of plant investment costs and unit costs for battery pack. The investment costs are defined as those directly related with building and operating the plant. Each cost item for the battery under design is adjusted from the estimate of the baseline plant.

The unit costs include variable costs such as direct labor and variable overhead, GSA, R&D, depreciation, profit, and warranty. The model scales the plant investment costs based on baseline plant, and thus financial overhead to match the design and production volume of the battery considered. The descriptions of cost components are summarized in Table 2, and we modified the BatPaC model for the calculation method.[21] In the development of the financial structure for the flow battery price, we first applied the exact approach used in the BatPaC model. This methodology scaled most of the financial structure towards a return on capital investment and protection of the depreciating asset. However, the low capital expenditure required for flow batteries resulted in an unrealistic charge for GSA, R&D, and profit as a percentage of the entire system price. Thus, we modified the allocation formulae to rely on the costs of goods manufactured (COGM) to scale the financial structure. Here, we define COGM to include materials, labor, variable overhead, and depreciation. COGM is similar to the financial balance sheet term cost of goods sold (COGS), but does not account for changes in inventory and thus is not equivalent to COGS. To the first order, they can be considered equivalent. The percent of COGM allocated to profit or GSA was scaled to match a similar fraction of the total battery price as predicted for the baseline case of the peer-reviewed BatPaC model. Tabulation of these values for mature industries averaged across many companies is available elsewhere.[29]

2.6. Adjustment of cost for varying production volumes

The unit price less materials depend on the production volume. We employed power law methods to estimate the unit price less materials from the baseline production rate to another.[29] The capital cost of individual item of equipment depends on scale and can be correlated by the approximate relationship:

$$C = C_0 \left(\frac{R}{R_0} \right)^P \quad [1]$$

where,

C_0 : capital cost of an installed equipment item;

R_0 : baseline processing rate;

P : power factor

The power factor, P is usually between 0.3 and 1.0 for many manufacturing process steps. [30] For process steps requiring the addition of many identical pieces of equipment for scale up, such as bipolar plate manufacturing or formation cycling of battery cells, the value of P may be as high as 0.9, and is unlikely to reach 1.0 because the equipment cost includes installation. The exponential method should be used to scale a capital cost estimate up or down within a factor of five, based on capacity for its accuracy because the exponent is itself a function of scale.[30] The capital and labor costs of various production rates estimated for the polymer electrolyte fuel cell were examined to estimate values of P for flow battery manufacturing and assembly.[20, 22, 23, 31] Similar method has been applied for determining the effect of processing rate on the annual hours of labor and the plant area required for a manufacturing step.[20] For our calculations, cost components for manufacturing are taken from published literature on polymer electrolyte fuel cells and engineering estimates. The manufacturing process of polymer electrolyte fuel cells has received considerable attention over the previous decade. When utilizing engineering estimates, we employed a comparison to similar high volume products and/or a bottom-up rationalization to determine high-volume values.

3. Result and Discussion

3.1. Manufacturing and Assembly

The analysis of the unit price less material in this work assumed the separator and felt electrodes for stack assembly will be purchased. This could result in slightly higher stack cost compared to the use of in-house production of these materials. However, these parts are manufactured using complex, highly specialized, multi-step processes. Consequently, start-up costs and quality issues of in-house production facilities could result in costs that are higher than the manufacturer's purchase price. In mature manufacturing plants, some items which are assumed to be purchased in this study might be internally manufactured from raw materials. However, the net effect would be a small change to the overall unit price less materials of the battery stack.

The cost factors for the individual manufacturing steps in the baseline plant are summarized in Table 3 and more detailed discussion is provided in following sections.

3.1.1. End plates

The purposes of end plates in a flow battery stack are providing uniform compressive loads across the stack and protecting the stack. An end plate made from a compression-molded composite is strong enough to withstand the required compressive loading, while also being a good electrical insulator.[22, 23] Compression molding is similar to injection molding, except the machine is somewhat simpler. The cavity must be fairly simple in shape so that the plastic will flow nicely under the ram pressure. Machine cost of compression molding is approximately 1/2 that of the basic injection molding cost guideline.[31] The detailed machine cost analysis for injection molding is discussed in the section that follows.

3.1.2. End gaskets

The end gaskets are sandwiched between the last bipolar plate and the end plate and are needed with only two per stack. The screen-printing for end gasket manufacturing has benefits in both cycle time and cost efficiency. In the process, the bipolar plate is fed into the machine by conveyor, and then a precision emulsion screen is placed over the plates, allowing a wiper to apply the sealing resin. After application, the resin is UV cured to ensure adequate sealing. The capital cost includes the cost of the screen printer, a UV curing system, and plate feeding equipment. [22, 23]

3.1.3. Bipolar plates

Each stack consists of 75 and 200 active cells for VRFB and LiPS, respectively. For VRFB, the anode and cathode flow field sides of the bipolar plates have identical flow patterns. Consequently, one bipolar plate has identical flow fields on both sides. The total number of plates in a stack is therefore $(75 \text{ active cells} * 1 \text{ plates per cell} + 1 \text{ end bipolar plate per stack})$. For LiPS, each cell needs one bipolar plate with flow field on cathode side only. The total number of plates in single LiPS stack is $(200 \text{ active cells} * 1 \text{ plates per cell} + 1 \text{ end bipolar plate per stack})$.

Two different manufacturing processes were examined for the bipolar plate: injection-molded carbon powder/polymer and stamped stainless steel.[22, 23] The injection-molded carbon/polymer bipolar plate was selected for VRFB because an acidic solution is used as the electrolyte in VRFB and the bipolar plates in contact with the electrolyte should be resistant to acid. Stamped stainless steel plates were selected for LiPS as stainless steel is stable in the proposed nonaqueous cell, utilizes an inexpensive raw material, and has a high conductivity.

Injection molding requires relative expensive tooling. For this reason, injection molding is suited for large production volumes. The capital cost of injection molding equipment is mainly driven by equipment size and cycle time. The equipment cost depends on the projected area of the part and the depth needed. The molding cycle time consists of the injection time and the cooling time. The cooling time usually dominates and it can be estimated by the heat transfer equations.[31] Although composite materials have been successfully molded to form bipolar plates for fuel cell use, technical challenges likely exist to achieve adequate electrical conductivity using the injection molding process.

Metal stamping is an alternate method for the production of bipolar plates.[22, 23] In stamping process, coils of sheet metal are fed into stamping presses having a series of die station, each one sequentially imparting one or more features (flow fields, manifolds, etc.) into the part. The machine costs are determined by the size of the machine, the required shearing force. The stroke speed is correlated with press size: a small press is capable of higher sustained operating speeds than a large press. Machine cost and press speed are estimated according to the stamping machine cost model.[31]

3.1.4. Frame/Gasket for MEA

The frame/gasket for the membrane electrode assembly (MEA) is produced by insertion molding.[22, 23] The frame/gasket is molded around the roll-pressed separator and electrodes. The purposes of frame/gasket are providing sealing and proper manifolding around the periphery of the MEA. They also impart a rigid structure to the MEA.

3.1.5. Cutting and slitting

The rolls of roll-pressed separator and electrodes are fed through slitters and cutters to trim to the desired dimensions for insertion-molding machine of a frame/gasket. The input roll is

slit into ribbon streams of the appropriate width. The streams continue through to the cutters, which turn the continuous material into individual rectangles.[22, 23]

3.1.6. Stack assembly

Stack assembly costs are based on the workstation costs and the estimated times to assemble cells.[22, 23] The primary rate factor that determines the cost in stack assembly is the number of cells assembled per year. For cell stacking, an additional cost factor is the cell active area. Large cells usually require a more capable and thus more expensive stacking machine.

3.1.7. Conditioning / Formation cycling

The conditioning for VRFB and formation cycling for LiPS occur after stack assembly step. VRFB stacks conditioned at the manufacturing facility for quality assurance purposes and to shorten the start-up time at the installation site. A series of conditioning steps are modeled based on a regulation scheme of fuel cell.[22, 23] The Li-metal electrode in LiPS is assumed to also require formation cycling for quality assurance purposes and perhaps to modify the solid electrolyte interphase that forms spontaneously on Li-metal in the presence of a nonaqueous electrolyte. The capital cost of the cycling equipment is primarily a function of the annual number of stacks to be tested. The cycling duration for both VRFB and LiPS is adjusted based on their current densities.[20-23]

3.1.8. Stack housing

The plastic stack housing encases the stack and provides protection from physical damage as well as protection from electrical shorting contacts.[22] In this step, the assembled stack is slid into the container, connections are made for flow pathways and then the shell is sealed. For LiPS, an air-tight container is considered because electrode material is more air sensitive than that of VRFB.

3.2. Comparison of calculated unit price less materials

Darling et al. reported the largest decrease in system price between 2014 values and the assumed high volume future state occurred in the additional contributions to price factor (i.e. unit price less materials) that captures manufacturing and assembly cost. A comparison of the unit price less materials contributions calculated for Li-ion, VRFB, and LiPS is shown in Figure 4 for the baseline annual production rate of 100,000 stacks with 20 kW continuous power and 100 kWh of useable energy. For these high volume projections, both VRFB and LiPS are shown to have significantly smaller unit price less materials values than enclosed Li-ion. The smaller depreciation, labor, and variable overhead costs result from the simpler stack design and assembly process of flow batteries than enclosed batteries. In addition, these costs for VRFB are lower than LiPS as a consequence of simpler assembly process (e.g., no need for a dry room) and smaller equipment scale due to smaller cell and stack area. We note that the low unit price less materials of VRFB manufacturing is comparable with values reported for fuel cell manufacturing.[22, 23]

The unit price less materials has several factors that are a function of the materials and purchased items costs as detailed in Table 2. For the cases considered in Fig. 4 and 5, the materials costs detailed in the Appendix are those based on the future state assumption of a high volume, competitive market place. For these values, the materials and purchased items cost for Li-ion, VRFB, and LiPS coincidentally all fall within a very similar range of \$14,400 to \$14,800 per battery that produces 20 kW and 100 kWh. Thus differences seen in Fig. 4 and 5 result predominately from the manufacturing process used to assemble the energy storage system. The 2014 reported materials and purchased items cost for VRFB and Li-ion are also very close in

value. However, the LiPS material costs are significantly higher as its state of development is immature compared to even VRFB.

Figure 5 illustrates the unit price less materials trends for the 20kW VRFB and LiPS stacks in comparison to Li-ion batteries as a function of designed plant production volume. All batteries have downward trend by production volume, and the unit price less materials of Li-ion decrease significantly between 20,000 and 100,000 of annual production volume. However, unit price less materials of Li-ion is projected to be more expensive than one based on flow architectures when compared at equivalent production volumes. This difference results from the much larger required cell area and complicated manufacturing processes such as electrode coating. The unit price less materials for flow batteries is projected to be low at annual production volume of 20,000 units. For example, the unit price less materials for VRFB and LiPS decrease by 10 and 13 % respectively by increasing production from 20,000 to 200,000 units. Conversely, Li-ion decreases by 31%. Most components in a flow battery stack such as bipolar plate and gaskets are repeating parts made from simple processes. This means mass-manufacturing techniques of those parts remain appropriate even at the lowest production volume of 20,000 stacks/year. The investment costs for establishing the baseline plants are \$1,300MM, \$600MM, and \$930MM for Li-ion, VRFB, and LiPS respectively. Therefore, redox flow batteries have a comparatively low investment cost entry barrier as compared to Li-ion batteries. The challenge for flow batteries is that Li-ion already enjoys a significant production volume with future facilities planned for the production rate of the magnitude here-in discussed.[32, 33]

Estimates of the total battery system price are shown in Fig. 6. The top panel utilized materials and purchased items costs reported in 2014. The bottom panel assumes lower values

for the future state based on published forecasted learning curves or conversations with industry experts. The materials and purchased items costs used are detailed in the Appendix. VRFB is shown to be the lowest cost energy storage system for all cases; however, the uncertainty in the price estimation is larger than the difference in high volume estimates between Li-ion and VRFB. The uncertainty for VRFB system price was previously estimated at $\pm 28\%$ for 95% confidence intervals.[10] The largest source of variation for VRFB is the commodity price of vanadium. The BatPaC model reports an uncertainty of $\pm 10\%$ for 95% confidence intervals based on uncertainties in the top 8 cost contributors.[21] In addition to minimal existing production capacity, the attractive low investment costs of flow batteries is tempered, modestly, by the strong dependence of the product prices of ion-exchange membranes and carbon felt electrodes to manufacturing volume reflected in Fig. 6 by the difference in values used for 2014 and the future state.[22, 23, 34] The high cost of the ion-exchange membrane and carbon felt is an important obstacle in the broader deployment of the flow battery technology. Interestingly, the materials contribution to system price will decrease as production volumes increase. This trend holds even as the system price itself decreases. For example, the materials used in the reactor (i.e. power component to cost) are 16% of the total VRFB price for 2014 materials cost and 20,000 stacks produced per year. Higher production volume for VRFB, such as those in our calculated future state, is estimated to reduce the cost of the reactor to 6% of the total price.

Li-ion is in the process of entering new, high-volume markets after completely taking over the consumer electronics market and being employed in transportation applications. The steep cost curve and high performance of Li-ion batteries are enabling their use in early stationary energy storage applications. The estimated minimum price in 2014 without installation for a lithium-ion grid energy storage system for five hours of storage is reported to be

\$500/kWh.[10] The gap between the reported \$500/kWh and \$340/kWh estimated here is attributed to several factors. First, the BatPaC model designs a factory to produce a single type of battery in a facility that is fully utilized. At the time of this publication, most large format Li-ion factories are operating below rated capacity thus resulting in higher prices. Additionally, while Li-ion energy storage system installations are increasing, they are still produced in modest numbers resulting in higher inefficiencies than what is possible. If market penetration for energy storage is successfully achieved for long-duration applications, the market size will grow tremendously resulting in further price reductions in line with those projected in this study.

In comparison, VRFB is still in its infancy. Recently, the development of VRFB has benefitted tremendously from parallel efforts in fuel cells. For the high volume competitive market place projections, VRFB is shown to have moderately lower system price than Li-ion. The unit price less materials calculated for the 2 GWh annual production volume is less than \$35 kWh⁻¹ compared to an estimated \$63 kWh⁻¹ for Li-ion. At the time of this publication, a commercial LiPS system does not exist. However, research efforts are underway to improve the stability of the lithium electrode and flow cathode electrode design.[26] It is unclear at this time that the nonaqueous LiPS system represents a potentially lower cost system than other more established chemistries.

The values estimated in this analysis are subject to uncertainties associated with forecasting a manufacturing process that is not yet established. Moreover, our estimates of the benefits from manufacturing scale are also limited by using a continuous function rather than the discrete reality of purchased equipment. The greatest value of this work is in the qualitative comparison of one technology platform to another, rather than an exact quantitative prediction.

We also note that site installation costs are an important factor in the total energy storage system capital cost. However, installation costs are location specific and beyond the scope of this work.

4. Conclusion

A comprehensive bottom-up manufacturing model was created to enable the calculation of the system price for redox flow batteries. This work presents a comprehensive production process for flow batteries and calculates the resulting investment and variable costs as a function of annual production volume between 0.4-10 GW year⁻¹ (2-50 GWh year⁻¹). The calculated unit price less materials is identified as a key gap in current knowledge for flow batteries. Through the analysis of the unit price less materials, we show that both VRFB and LiPS benefit from simple manufacturing processes and thus lower additional contributions over materials costs. The unit price less materials for a 2 GW year⁻¹ (10 GWh year⁻¹) production facility are \$158 kW⁻¹, \$173 kW⁻¹, and \$237 kW⁻¹ and estimated to be 18%, 19%, and 25% of the total system price for VRFB, LiPS, and Li-ion. Flow batteries are found to have orders of magnitude lower area normalized production rates due to higher areal power densities. Additionally, flow batteries employ simpler methods of manufacture compared to Li-ion. These differences enable flow batteries to capture the majority of benefits of production volume at much lower rates than Li-ion. If niche applications for energy storage allows for early market penetration, the system price estimated for flow batteries in this publication would suggest extensive cost-effective deployment may be possible with only moderate levels of production (e.g., 20,000 20-kW batteries per year).

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Appendix

Future state and 2014 material and purchased items costs used in the analysis. The mean value is used when a probabilistic range was provided by the reference.

a. Li-ion

Material	Year 2014 Cost	Reference	Future state Cost	Reference
Negative (Graphite), \$ kg ⁻¹	18	[10]	12 (9-15)	[10]
Positive (LiFePO ₄), \$ kg ⁻¹	15	[10]	10 (8-12)	[10]
Electrolyte (1 M LiPF ₆ in carbonate-based solvent), \$ kg ⁻¹	15	[10, 20]	10 (5-15)	[10, 20]
Current collector, separator, and packaging \$ m ⁻²	6	[10]	3.5 (2-5)	[10, 20]
Balance of Plant, \$ kW ⁻¹	550	[10]	263 (200-325)	[10]

b. VRFB

Material	Year 2014 Cost	Reference	Future state Cost	Reference
Negative (Vanadium), \$ kg ⁻¹	29	[10]	22 (7-37)	[10]
Positive (Vanadium), \$ kg ⁻¹	29	[10]	22 (7-37)	[10]
Electrolyte (4M H ₂ SO ₄), \$ kg ⁻¹	0.1	[10]	0.1	[10]
Graphite for flow field plate, \$ kg ⁻¹	7	[22]	7	[22]
Carbon-fiber felt electrodes, \$ m ⁻²	70	[15]	20 (10-30)	[22, 23]
Fluorinated ion-exchange membrane, \$ m ⁻²	500	[15]	50 (25-75)	[22, 23, 34]
Gaskets, seals, and manifolds total, \$ m ⁻²	6	[10]	2 (1-3)	[10]
Balance of Plant, \$ kW ⁻¹	410	[10]	203 (145-260)	[10]

c. LiPS

Material	Year 2014 Cost	Reference	Future state Cost	Reference
Negative (Lithium metal), \$ kg ⁻¹	200	[10]	100 (60-140)	[10]
Positive (Sulfur), \$ kg ⁻¹	10	[10]	2 (1-3)	[10]
Electrolyte (1 M LiTFSI in ether-based solvent), \$ kg ⁻¹	15	[10]	5 (3-7)	[10]
Stainless-steel for flow field plate, \$ kg ⁻¹	4	[24]	4	[24]
Carbon-fiber felt electrodes, \$ m ⁻²	70	[15]	20 (10-30)	[22, 23]
Polyolefin nanoporous separator, \$ m ⁻²	10	[15]	2 (1-3)	[10]
Gaskets, seals, and manifolds total, \$ m ⁻²	6	[10]	2 (1-3)	[10]
Balance of Plant, \$ kW ⁻¹	360	[10]	173 (115-230)	[10]

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Table and Figure Captions

Table 1. Chemistry and design characteristics for Li-ion, VRFB, and LiPS. Performance values are for 5h continuous discharge

Table 2. Contribution to unit price less materials

Table 3. Baseline plant for VRFB

Table 4. Baseline plant for LiPS

Figure 1. VRFB system price breakdown for materials and purchased items costs reported for 2014 and a simulated annual production rate of 20,000 stacks/year.

Figure 2. Schematic of (a) Flow batteries reactor stack and (b) Li-ion

Figure 3. Baseline flow battery manufacturing process, (a) VRFB and (b) LiPS

Figure 4. Comparison of financial structure of the unit price less materials

Figure 5. Unit price less materials as a function of annual production rate based on future state materials and purchased items

Figure 6. System price as a function of annual production rate using materials costs reported for (top) 2014 and (bottom) those estimated for the assumed future state.

Table 1. Chemistry and design characteristics for Li-ion, VRFB, and LiPS. Performance values are for 5h continuous discharge

Architecture:		Enclosed	Flow	Hybrid
Chemistry:		Li-ion Gr/LFP	VRFB V²⁺/V⁵⁺	LiPS Li/Li₂S₈(Li₄S₈)
Power (Continuous)	kW	20	20	20
Active cells	-	224	75	200
Cell area	m ²	6.6	0.1	0.5
Stack area	m ²	1478	7.5	100
ASR	Ω-cm ²	60	0.5	20
U_{cell}	V	3.3	1.4	2.3
Stack voltage	V	370	105	460
ε_{v,d} t_d=5h	-	0.99	0.92	0.95
Power density (Continuous)	kW m ⁻²	0.014	2.7	0.2

Table 2. Contribution to unit price less materials

Investment costs	Description	Calculation method
Capital equipment	Equipment costs including installation	Estimates of costs for each processing step at baseline rates, adjusted for actual rates
Plant floor space	Space includes aisles and space for equipment plus land and utility costs	Estimates of costs for each processing step at baseline rates, adjusted for actual rates
Launch costs	Plant start-up, training, out-of-spec product	10% of direct labor plus variable overhead and 5% of materials and purchased items
Working capital	Cash to meet payroll, receivables, inventories of unfinished and finished product, minus payables	15% of total annual variable costs (including materials and purchased items)
Variable costs		
Direct labor	Labor costs for operations and immediate supervision	Estimates of costs for each processing step at baseline rates, adjusted for actual rates
Variable Overhead	Indirect materials, labor, utilities, plant maintenance	40% of direct labor cost plus 20% of depreciation
Fixed expenses		
General, Sales, and Administration (GSA)	Plant office, taxes on income and property, cost of sales and insurance expenses	4% of the cost of goods manufactured
Research and Development	On-going research needed to upgrade product and maintain competitive position	3% of the cost of goods manufactured
Depreciation	Provides funds for new investments to replace those in current equipment and plant	16.7% of capital equipment cost plus 5% of plant floor space cost
Profit	Return on invested capital after taxes	5% of the cost of goods manufactured
Warranty	Funds set aside for reimbursing customers for battery pack failures	5.6% added to price based on present worth of projected payments

Table 3. Baseline plant for VRFB

Process	Cap. Equipment				Direct labor		Plant area		
	Annual production rate	Machine cost ^[22, 23, 31]	Number of machines	Cycle time ^[22, 23, 31]	Scale factor ^[22, 23]	Labor per line ^[22, 23]	Scale factor ^[20]	Area	Scale Factor ^[20]
		\$millions		second				m ²	
End plate	200,000 (parts)	0.8	2	1300	0.86	1	0.75	30	0.8
End gasket	200,000 (parts)	1.8	1	40	0.32	1	0.4	2.5	0.8
Bipolar plate (injection molding)	3,100,000 (parts)	1.9	2	96	1	1	1	80	0.8
Roll pressing	750,000 (m ²)	1.7	1	0.17 (per cell) 1 (linear rate ,m/s)	0.6	1	0.4	15	0.6
Cutting & slitting	750,000 (m ²)	1.6	1	0.20 (per cell) 0.85 (linear rate ,m/s)	0.6	1	0.4	15	0.6
Frame/gasket	3,000,000 (part)	1.2	12	630	1	1	1	280	0.6
Cell stacking	3,000,000 (cells)	1.6	1	175 (per stack)	0.9	1	0.9	10	0.8
Stack conditioning	100,000 (stacks)	3.7	15	5 (hours per stack)	0.6	0.5	0.9	350	0.6
Stack housing	100,000 (stacks)	0.5	1	15 (per stack)	0.8	1	0.4	5	0.6

Table 4. Baseline plant for LiPS

Process	Cap. Equipment				Direct labor		Plant area		
	Annual production rate	Machine cost ^[20, 22, 23, 31]	Number of machines	Cycle time ^[20, 22, 23, 31]	Scale factor ^[20, 22, 23]	Labor per line ^[20, 22, 23]	Scale factor ^[20]	Area	Scale Factor ^[20]
		\$millions		second				m ²	
End plate	200,000 (parts)	4.0	3	1600	0.86	1	0.75	90	0.8
End gasket	200,000 (parts)	9.0	1	48	0.32	1	0.4	5	0.8
Bipolar plate (stamping)	20,100,000 (parts)	1.5	3	3	0.91	1	1	60	0.8
Roll pressing	10,000,000 (m2)	2.3	1	0.26 (per cell) 0.9 (linear speed, m/s)	0.6	1	0.4	30	0.6
Cutting & slitting	10,000,000 (m2)	2.3	1	0.31 (per cell) 0.77 (linear speed, m/s)	0.6	1	0.4	30	0.6
Frame/gasket	20,000,000 (parts)	5.4	19	770	1	1	1	760	0.6
Cell stacking	20,000,000 (cells)	2.6	6	1540 (per stack)	0.9	1	0.9	60	0.8
Formation cycling	20,000,000 (cells)	5.0	10	500 (cells per cycle)	0.8	8	0.7	282	0.6
Stack housing	100,000 (stacks)	0.8	1	15 (per stack)	0.8	1	0.4	5	0.6
Dry room & control	3,000 (m2)	1.9	1		0.6	0.5	0.4	122	0.4

Cell with multi-layer

Module

Pack

Li-ion factory 10 GWh(2GW) per year
Unit price less materials = \$237per kW

VRFB factory 10 GWh(2GW) per year
Unit price less materials = \$158per kW

LiPS factory 10 GWh(2GW) per year
Unit price less materials = \$173per kW