



Cost-driven materials selection criteria for redox flow battery electrolytes



Rylan Dmello ^{a, b, 1}, Jarrod D. Milshtein ^{a, c, 1}, Fikile R. Brushett ^{a, d}, Kyle C. Smith ^{a, b, *}

^a Joint Center for Energy Storage Research, USA

^b Department of Mechanical Science and Engineering and Computational Science and Engineering Program, University of Illinois at Urbana-Champaign, Urbana, IL, 61801, USA

^c Department of Material Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA

^d Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA

HIGHLIGHTS

- We develop a techno-economic model for redox flow battery (RFB) electrolytes.
- Electrolyte costs account for redox active material, salt, and solvent components.
- Reactor, balance-of-plant, and additional costs are considered.
- Design maps to build \$100 kWh⁻¹ RFBs guide electrolyte materials selection.
- Multiple pathways to decreasing RFB electrolyte costs are proposed.

ARTICLE INFO

Article history:

Received 27 June 2016

Received in revised form

10 August 2016

Accepted 30 August 2016

Available online 13 September 2016

Keywords:

Redox flow battery

Electrolyte

Techno-economic model

Energy storage

ABSTRACT

Redox flow batteries show promise for grid-scale energy storage applications but are presently too expensive for widespread adoption. Electrolyte material costs constitute a sizeable fraction of the redox flow battery price. As such, this work develops a techno-economic model for redox flow batteries that accounts for redox-active material, salt, and solvent contributions to the electrolyte cost. Benchmark values for electrolyte constituent costs guide identification of design constraints. Nonaqueous battery design is sensitive to all electrolyte component costs, cell voltage, and area-specific resistance. Design challenges for nonaqueous batteries include minimizing salt content and dropping redox-active species concentration requirements. Aqueous battery design is sensitive to only redox-active material cost and cell voltage, due to low area-specific resistance and supporting electrolyte costs. Increasing cell voltage and decreasing redox-active material cost present major materials selection challenges for aqueous batteries. This work minimizes cost-constraining variables by mapping the battery design space with the techno-economic model, through which we highlight pathways towards low price and moderate concentration. Furthermore, the techno-economic model calculates quantitative iterations of battery designs to achieve the Department of Energy battery price target of \$100 per kWh and highlights cost cutting strategies to drive battery prices down further.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Grid-scale energy storage technologies are becoming increasingly critical to promoting sustainable electricity generation. First,

energy storage can alleviate the intermittency of renewable energy technologies (i.e., wind, solar), facilitating broad implementation [1]. Second, storage can also improve the cost-effectiveness of the existing fossil fuel infrastructure, decreasing electricity costs via load-leveling and price arbitrage operations [2]. Third, grid-scale storage can provide high value services such as back-up power, frequency regulation, and voltage support [2]. Redox flow batteries (RFBs) provide a promising technological pathway towards low-cost grid-scale energy storage devices due to decoupled capacity and power, long lifetimes, and facile thermal management [3–8].

* Corresponding author. University of Illinois at Urbana-Champaign, Department of Mechanical Science and Engineering, 105 S. Matthews Ave., Urbana, IL, USA.

E-mail address: kcsmith@illinois.edu (K.C. Smith).

¹ These authors contributed equally to this work.

Current RFB prices, however, are too high for market penetration [9–11]. According to the Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability, decreasing RFB system price to \$120 kWh⁻¹ in the near term will enable widespread adoption for 4 h discharge grid-scale energy storage applications [3,9]. In comparison, the DOE's Advanced Research Projects Agency - Energy (ARPA-E) suggests a long-term energy storage battery price target of \$100 kWh⁻¹ for 1 h of discharge [12]. In 2014, RFB prices exceeded \$500 kWh⁻¹ [9,10]. Despite the existing high prices, recent work has established that both aqueous and nonaqueous RFBs can meet the desired \$100 kWh⁻¹ battery price target by appropriately decreasing RFB reactor and materials costs contributions [9].

To achieve the price target, the price-to-energy ratios of aqueous and nonaqueous RFBs can drop by following different cost reduction pathways that optimize their fundamentally different reactor and materials characteristics [9]. Aqueous RFBs (AqRFBs) leverage inexpensive electrolytes, utilizing water as the solvent and typically a low-cost inorganic salt (e.g., H₂SO₄, KOH, and NaCl), while exhibiting high power density due to low cell resistance. The typical electrochemical stability window of water (less than 1.5 V), however, limits the maximum achievable AqRFB electrolyte energy density. In contrast, nonaqueous RFBs (NAqRFBs) employ nonaqueous solvents with wide electrochemical stability windows (3–4 V) and can thus enable electrolytes with greater energy density as compared to aqueous systems. Despite attractive voltage capabilities, NAqRFBs suffer from relatively expensive nonaqueous solvents (e.g., nitriles, glymes, and carbonates) and fluorinated salts (e.g., tetrafluoroborates, hexafluorophosphates, and bis(trifluoromethylsulfonyl)imides), as well as low power density due to low membrane conductivities. Considering the advantages and drawbacks of each system, AqRFB cost cutting efforts should maximize cell voltage, while NAqRFB design should decrease electrolyte cost and improve power density.

Redox-active materials for both families of RFBs require continued research and development for widespread adoption. Inorganic non-metallic (e.g., polysulfide-bromine) and transition metal (e.g., all-vanadium) redox-active materials have traditionally been at the forefront of AqRFB development, although metal coordination complexes have also been explored [7,13,14]. AqRFBs utilizing certain inorganic, non-metallic redox-active materials, such as bromine, have failed to penetrate the market due to their corrosive and toxic nature, making the practical design of flow fields, pumps, storage tanks, and pipes difficult [15]. Additionally, transition metal based AqRFBs have struggled to achieve the battery price targets due to the high cost and limited abundance of the redox-active material [6]. Early investigations into NAqRFBs employed metal coordination complexes as redox-active materials that suffer from low solubility, poor stability, or expensive precursors [16–19]. A significant portion of recent RFB progress beyond vanadium RFBs, arguably the current state-of-the-art systems, has aimed at identifying low-cost redox-active materials such as abundant inorganic species [20,21] and tailored organic molecules [22–34]. Organic redox-active molecules are particularly attractive for use in both aqueous and nonaqueous RFBs; organic molecules are comprised of earth abundant elements (e.g., hydrogen, carbon, oxygen, sulfur) and offer a broad design space, allowing for rational control of molecular weight, solubility, and redox potential by molecular functionalization [35].

RFB price relates to experimentally measurable chemical properties, electrochemical performance, and cost parameters that serve as critical inputs towards developing RFB cost projections via a techno-economic (TE) model. TE models have quantified the price performance of transportation [36,37] and grid-scale [9–11,38–40] energy storage devices. In 2014, Darling, Gallagher, and co-workers

developed a comprehensive TE model (hereafter referred to as the DG model) to compare the price performance of aqueous and nonaqueous RFBs [9]. The DG model defined benchmark values for redox-active material concentration, molecular weight, cell voltage, and area-specific resistance (ASR), for both families of RFBs, to reduce battery price to \$100 kWh⁻¹. Although instrumental in elucidating future RFB prices, the DG model focused on a single set of benchmarks but did not explore alternative design iterations. A recent investigation into separator performance characteristics for RFBs considered the tradeoffs among cell voltage, ASR, and reactor cost [41], but no such sensitivity analysis has accounted for the relative cost contributions from the electrolyte constituent materials: solvent, salt, and redox-active compounds.

The present work addresses the lack of RFB design strategies by exploring the materials space mapped by an electrolyte-centric TE model, which identifies new RFB price reduction strategies. A detailed electrolyte cost model, explicitly accounting for redox-active species, salt, and solvent cost contributions, combined with the existing DG model, enables a sensitivity study of aqueous and nonaqueous RFB prices to various material and cost parameters. We explore the available RFB design space and investigate the sensitivity of both aqueous and nonaqueous RFBs to pertinent electrolyte constituent cost variables, cell voltage, and ASR. Further, maps of the available design space translate abstract price targets into quantitative performance targets, bridging the TE model to prototype guidelines. As such, this paper demonstrates tradeoffs in RFB constituent costs and performance to achieve a \$100 kWh⁻¹ battery price. While previous modeling efforts have highlighted cost performance challenges with specific RFB chemistries (e.g. all-vanadium, zinc-bromine) [9–11,40], our analysis culminates in a set of design maps to aid in selecting materials for new RFB electrolytes. We also suggest research pathways to most easily achieve the near-term target battery price (\$100 kWh⁻¹) and lower. This electrolyte-centric analysis can guide future research efforts in the development and selection of new, promising materials for use in economically viable RFB prototypes.

2. Methodology

2.1. Model definitions

Redox flow battery price is defined as the RFB's future-state battery price P_0 (excluding power conditioning systems) per unit discharge energy E_d , delivered over a time t_d . The present TE model (which builds on the DG model [9]) separates RFB price into four major cost contributions from the reactor $C_{Reactor}$, electrolyte $C_{Electrolyte}$, additional $C_{Additional}$, and balance-of-plant (BOP) C_{BOP} :

$$\frac{P_0}{E_d} = C_{Reactor} + C_{Electrolyte} + C_{Additional} + C_{BOP} \quad (1)$$

Table 1 provides variable definitions for all cost equations, as well as benchmark values and units. Here, a series of design maps are presented in which certain model parameters vary. In addition, the supplementary information contains a MATLAB script that generates the design maps presented here. The parameters that do not vary in the design maps assume benchmark values (Table 1), unless otherwise explicitly stated. In these design maps, thin dotted black lines denote benchmark values from the original DG model.

This work builds on the reactor, additional, and BOP cost descriptions from the DG model. In the DG model [9], the reactor cost (in \$ kWh⁻¹) depends on the reactor cost per unit area c_a , which incorporates the costs associated with bi-polar plates, membranes, and seals; the cost of each reactor hardware component is detailed in Ref. [9]. Additionally, the reactor cost varies with area-specific

Download English Version:

<https://daneshyari.com/en/article/5150250>

Download Persian Version:

<https://daneshyari.com/article/5150250>

[Daneshyari.com](https://daneshyari.com)