Journal of Power Sources 286 (2015) 247–257

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Economics of vanadium redox flow battery membranes

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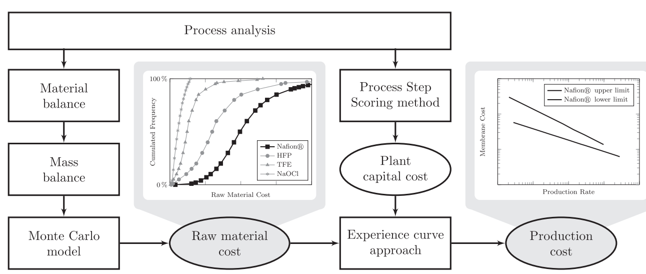
HIGHLIGHTS

- An analytical model of membrane production cost is proposed.
- Bottom price limits for different membrane materials are calculated and compared.
- Effects of production volume and raw material selection are investigated.
- Economic potentials for standard and innovative membrane materials are quantified.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 January 2015
Received in revised form
27 February 2015
Accepted 24 March 2015
Available online 26 March 2015

Keywords:
Redox flow battery
Membrane
Economic assessment
Technical cost model

ABSTRACT

The membrane is a key component of the vanadium redox flow battery (VRFB) in terms of electrochemical performance as well as costs. The standard material Nafion® is cost intensive and therefore several alternative materials are in the focus of research. In this paper a substantial analytical approach is presented in order to quantify bottom price limits for different types of membranes. An in-depth analysis of material and production cost allows statements concerning cost potentials of different ion exchange membranes (IEM) and nano filtration membranes (NFM). The final result reveals that expected costs of IEM and NFM at high production volumes differ by one order of magnitude. Moreover, an analysis of the current market situation is made to provide a framework for economic considerations at present.

1. Introduction

The vanadium redox flow battery (VRFB) is one of the most promising electrochemical storage systems for load levelling applications on an industrial scale [1]. VRFB systems are already commercially available, but there is still a need for research, especially on scale-up, cost reduction and performance of key components [2]. One important component of the VRFB is the membrane, which provides two essential functions. It serves as a physical separator for the positive and negative half-cells and in order to complete the electrical circuit it has to be semi-permeable for charge-balancing ions. This selective permeability causes high material requirements. A wide variety of membrane materials is object of research, while the standard material is Nafion® provided by E. I. DuPont De Nemours & Co. (DuPont) [3,4]. Nafion® is a high cost specialty material which makes the membrane also a key component in terms of system cost. Due to the fact that the VRFB is a relatively young technology, cost models are depending on many factors and are subject to considerable uncertainty. In general, a significant cost reduction is expected through the application of high production volumes.

In the present paper the economics of VRFB membranes are presented in a comprehensive way. A representative selection of materials in terms of costs includes ion exchange membranes (IEM) as well as nano filtration membranes (NFM). The present analysis is limited to the standard membrane material Nafion® (Section 3.1)

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http://dx.doi.org/10.1016/j.jpowsour.2015.03.144
0378-7753/

and sulfonated PEEK as a widely used alternative IEM material (Section 3.2). Furthermore, the considerable performance and cost potentials of different NFM are pointed out in Section 3.3. NFM may be used in innovative design concepts of VRFB cells. Material examples of those are polypropylene (PP) and a separator made of polyvinyl chloride (PVC) and silica.

For each material a detailed economic analysis is carried out. In order to identify a bottom price limit an analytical model of membrane production cost is developed. Production cost is defined as the sum of raw material and manufacturing cost. The corresponding methods are described in Section 2 in detail. The upper price limit is assessed in a market analysis. In conclusion, the results from these analyses are compared to cost objectives specified in corresponding literature. In this respect it is noted that the state of scientific knowledge regarding explicitly the economics of VRFB membranes is relatively low. It is therefore necessary to refer to studies on polymer electrolyte membrane fuel cells (PEMFC). Regarding this database the following questions are addressed in order to clarify the economics of VRFB membranes:

- To what extent is the data on membranes in PEMFC adaptable to VRFB systems?
- Are the ambitious cost and production objectives for Nafion® membranes achievable?
- Which perspectives in terms of costs are offered by alternative membrane materials?

The presented methodology reveals a reasonable range of membrane cost, along with an in-depth analysis of factors influencing membrane economics.

2. Methodology

In order to address the initial questions an economic analysis of technically suitable membrane materials is carried out. This involves both a market analysis to estimate upper price limits and an analytical production cost analysis to assess bottom price limits. The latter is based on the definition of production cost as the sum of raw material and manufacturing cost.

Profound analyses of membrane manufacturing processes form the basis for economic modelling and evaluation. As illustrated in Fig. 1 the assessment of raw material cost and manufacturing cost is carried out in parallel for each membrane type. The process analysis reveals both a material balance and an overview of relevant process steps. On the material side a mass balance is calculated, which provides the framework for a Monte Carlo model (Section 2.2). This model allows to calculate a probability distribution of membrane material cost when using statistical raw material price data as input (Section 2.1). On the manufacturing side the Process Step Scoring method (Section 2.3) is applied to membrane synthesis and forming processes. This method results in capital cost for a chemical production plant as a function of its production capacity. Finally, an experience curve approach (Section 2.4) using boundary conditions that consider the share of material and plant cost in relation to overall cost is applied. The final result is a projection of bottom price limits depending on production plant capacity. The methods used in this approach are described in detail below.

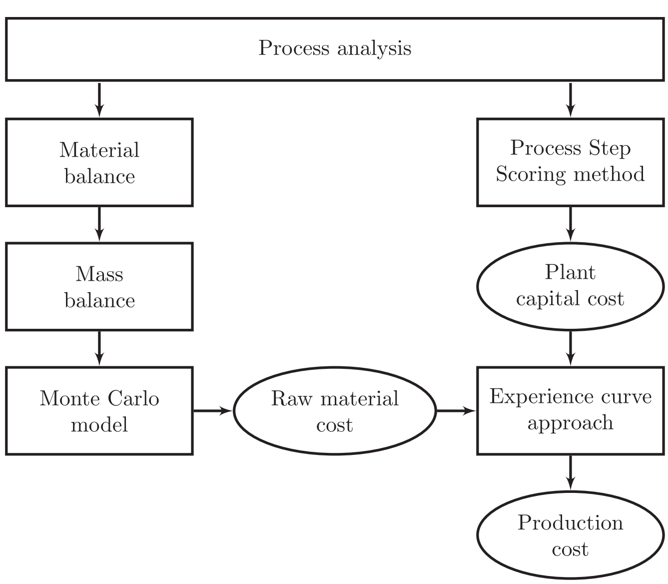

Fig. 1. Methodology for calculating production cost.

2.1. Preparation of statistical data

Many membrane materials are currently in their research phase. Thus, specialty substances or innovative processes with low production volumes may be used. Raw material prices are therefore depending on many complex factors, e.g. primary cost, purchase quantity or customer relationship. In order to use input data that is preferably independent from vendor inquiries prices for chemicals are collected from the PRODCOM database of the statistical office of the European Commission EUROSTAT [5].

The data retrieved from the PRODCOM database covers the period from 2007 to 2012. The geographical extent covers the EU-27 member states as constituted on January 1, 2007. For each year and state six indicators are considered: volume of production, import and export as well as monetary value of produced, imported and exported goods. A balance sheet value for production, import or export only results in case of the matching pair of quantity and value. Therefore, considering 27 states, 6 periods of time and 3 balance sheet values, the theoretical data volume for the price of a substance contains 486 data points. The so derived statistical data set is checked for consistency. The frequency distribution is documented in a histogram, whereas the corresponding totalizing function (cumulated frequency) contains complete information about the spread of values.

In case of insufficient data volume the probability distribution of raw material prices is generated in a mathematical model and wholesale inquiries are made where needed. For this purpose a triangular distribution is assumed which is described by only three variables. These are the lower limit a, the upper limit b and mode c, where $a \leq c \leq b$. A definition is given in Eq. (1).

$$f(x) = \begin{cases} \dfrac{2(x-a)}{(b-a)(c-a)}, & \text{for } a \leq x \leq c \\ \dfrac{2(b-x)}{(b-a)(b-c)}, & \text{for } c < x \leq b \end{cases} \tag{1}$$

With the described methods a probability distribution of prices for each raw material is generated. These distributions are processed in a further mathematical model to reveal value ranges of raw material cost for a specific membrane.

2.2. Monte Carlo model

Monte Carlo modelling is a stochastic method originating from nuclear technology research. It has been developed in the 1940s to predict movements of neutrons based on probability analyses. Since the 1980s this methodology is applied to economic problems [6]. Statistical methods are widely enabled in order to make