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Review article

Materials, system designs and modelling approaches in techno-economic assessment of all-vanadium redox flow batteries – A review

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HIGHLIGHTS

- Analysis of materials, cell geometry and techno-economic modelling frameworks.
- Representation of interconnections between studies and sources of cost data.
- Correlation of vanadium raw material prices, electrolyte and system costs.
- Impact of key components on system costs quantified.
- Framework and indication for realistic VFB system cost values.

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ABSTRACT

The vanadium redox flow battery (VFB) is one of the most promising stationary electrochemical storage systems. The reduction of system costs is a major challenge in the realization of its widespread application. The high complexity of this technology requires a close linking of technologic and economic aspects in system cost assessment. The present review provides an extensive literature analysis with a focus on techno-economic assessment of VFB. Considered materials, system designs and modelling approaches are assessed and compared in order to present and evaluate the current status of system cost assessment in a transparent way. Systems in a range of 2 kW–50 MW providing energy for up to 150 h are covered in literature resulting in an immense range of specific total system costs of 564–12931 € kW^{-1} or 89–1738 € $(kWh)^{-1}$. Based on the data from the reviewed studies, guide values of 650 € $(kWh)^{-1}$ and 550 € $(kWh)^{-1}$ for installed VFB systems in a power range of 10–1000 kW providing energy for 4 h and 8 h respectively are derived from literature. Moreover, the relevance of precision in the definition of scope and components for meaningful results of techno-economic assessments of VFB systems is pointed out.

1. Introduction

The vanadium redox flow battery (VFB) patented in 1986 is one of the most promising electrochemical storage systems for large-scale stationary applications [1]. Power and energy capacity of the system are scalable over a broad range making it suitable for a variety of applications. Redox flow batteries consist of a set of electrochemical cells in which electrical energy is converted into chemical energy. Energy storage is realized by fluid electrolyte solutions that are pumped through the cells and stored in external tanks. The energy capacity of the system scales with the volume of tanks, whilst the rated power is determined by the electrode area. The VFB has the advantage to use vanadium redox couples in both half cells eliminating cross contamination of electrolytes. Details on the technology and its development over time may be found in a review by Parasuraman et al. [2].

The VFB is already commercially available. Global installation figures of 2015 reveal 50 installed systems (commercial and demonstration projects) providing a total power of 23 MW. A major challenge in the realization of widespread application of VFB is the reduction of system costs [3].

Cost assessment in early technology phases is afflicted with uncertainties. Nevertheless, besides of rough estimates academic bottom-up capital cost assessments of VFB have been published since 2004. As indicated above VFB is a complex technology with numerous variants of system set-ups defined primarily by power and energy capacity. On a higher level of detail system set-ups are defined by many parameters,

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like cell voltage, current density, single cell area, vanadium concentration, material selection, etc. Therefore, a close linking of technologic and economic aspects is crucial for reliable statements on system costs.

In the present study available literature on techno-economic assessment of VFB is reviewed. Materials, system designs and modelling approaches are extracted from existing studies and critically analyzed. Besides of cost assessments in case studies modelling approaches aiming on scalable cost metrics for VFB are considered. Literature data on vanadium and cell component costs as well as capital cost results are prepared and presented for the purpose of documentation of the current status of techno-economic assessment of VFB. Furthermore, data is normalized in order to compare existing approaches and opinions. Finally, the extensive analysis allows drawing conclusions on the evaluation of system components and their cost reduction potential.

2. Methodology

In a literature review all available studies with a focus on techno-economic assessment of VFB are identified. The literature research is carried out in the online databases Science Direct and Web of Science using the following search strategies [4,5]:

Science Direct: TITLE-ABSTR-KEY (vanadium flow battery) and TITLE-ABSTR-KEY (cost assessment OR cost model OR techno-economic assessment).

Web of Science: TOPIC: (vanadium flow battery cost assessment) OR TOPIC: (vanadium flow battery techno-economic assessment) OR TOPIC: (vanadium flow battery cost model).

From the results lists all studies specifying the system costs of VFB for predefined battery configurations are considered. Publications that do not include an integrated consideration of technological and cost aspects are generally excluded, because the review focuses primarily on the techno-economic assessment of VFB. Since the databases used only issue results from 2010 onwards and the review is open to different types of documents (journal articles, technical reports, conference papers and theses), additional studies are taken from reference lists of the considered publications. Furthermore, the academic meta-search engine Google Scholar is used with the same search items (vanadium AND (flow battery OR cost model OR cost assessment OR techno economic)) in order to complete the list of relevant publications from 2000 to present.

The resulting set of relevant publications is analyzed concerning the modelling framework in each study. The studies are classified by their goals and scopes, e.g. assessment of capital cost, assessment of profitability and comparison of different storage technologies. Moreover, the technical configuration of the considered battery system is extracted from the studies. Key figures are

- Nominal power P in kW
- Energy to power ratio E/P in h
- Depth of discharge DOD
- Current density i in kA m^{-2}
- Single cell area A_{cell} in m^2
- Number of cells and stacks in a system
- Vanadium concentration in electrolyte c_V in mol L^{-1}

Those studies describing a detailed model for calculation of battery system costs can be classified by the applied cost assessment methodology. Furthermore, differences in the definition of system boundaries in each model can be identified. In the course of this analysis the interconnection of studies is evaluated and presented. This allows to illustrate the progress in techno-economic assessment of VFB in literature.

Besides the modelling framework the assessment of input data is as important. The qualitative and quantitative evaluation of input data focuses on the key components:

Table 1
Historical average exchange rates for base currency USD [6].

Year	EUR
2007	0.73082
2008	0.67971
2009	0.70001
2010	0.75416
2011	0.71815
2012	0.77834
2013	0.75320
2014	0.75350
2015	0.90190
2016	0.90389

- Vanadium electrolyte
- Membrane
- Bipolar plate
- Carbon felt electrode

The analysis includes material composition and geometry of cell components as well as prices and manufacturing costs. In order to compare figures from different sources normalization of data is necessary. First, the technical parameters are to be normalized and in addition the cost data which is stated in different currencies. Data on the energy related components vanadium and electrolyte are expressed as mass specific costs c_M in € kg^{-1} and energy specific costs c_E in € $(kWh)^{-1}$, respectively. Data concerning cell or power related components are expressed as area specific costs c_A in € m^{-2} and power specific costs c_P in € kW^{-1}. Literature values in USD are converted to EUR using historical average exchange rates (Table 1).

The results of system capital cost assessment in the reviewed studies are normalized analogously. There are studies providing specific cost rates for energy and power subsystem. These cost rates are specified as $c_{E,Sub}$ in € $(kWh)^{-1}$ and $c_{P,Sub}$ in € kW^{-1}, respectively. It has to be noted that these cost rates are different from the final results which are total costs of system related to either power or energy for reasons of comparability. Overall, three key figures are defined for final results:

- Costs of cell stacks related to nominal power $c_{P,Stack}$ in € kW^{-1}
- Total costs of system related to nominal power $c_{P,Sys}$ in € kW^{-1}
- Total costs of system related to energy capacity $c_{E,Sys}$ in € $(kWh)^{-1}$

The latter is the usual figure for comparison of capital costs of energy storage systems. Together with the other key figures and normalization of input data this method allows for correlations of component costs and system costs in a subsequent meta-analysis.

3. Results and dicsussion

3.1. Available studies

The literature search reveals 31 results in Science Direct, 38 results in Web of Science and 299 results in Google Scholar for the years 2000–2017. The analysis of results is carried out according to criteria described in the methodology. Finally, the literature analysis identifies a total of 23 available studies considering techno-economic assessment of VFB (journal article, technical report, conference paper and thesis) from 2004 to 2017. Relevant parameters of these studies are extracted and listed in Table 2.

3.2. Modelling framework in existing studies

3.2.1. Goal and scope

In Table 2 each study is labeled with a code indicating its scope. The first part of the code describes the focus of the model. 16 studies assess