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Techno-economic assessment of novel vanadium redox flow batteries with large-area cells

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HIGHLIGHTS

- Transparent cost model for megawatt size vanadium redox flow battery systems.
- Detailed technical configuration of VRFB systems with large-area cells.
- Techno-economic assessment of extruded large-area bipolar plate.
- Simple formula for system costs in specific power and energy capacity range.
- Cost reduction potential of key components identified in sensitivity analysis.

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ABSTRACT

The vanadium redox flow battery (VRFB) is a promising electrochemical storage system for stationary megawatt-class applications. The currently limited cell area determined by the bipolar plate (BPP) could be enlarged significantly with a novel extruded large-area plate. For the first time a techno-economic assessment of VRFB in a power range of 1 MW–20 MW and energy capacities of up to 160 MWh is presented on the basis of the production cost model of large-area BPP. The economic model is based on the configuration of a 250 kW stack and the overall system including stacks, power electronics, electrolyte and auxiliaries. Final results include a simple function for the calculation of system costs within the above described scope. In addition, the impact of cost reduction potentials for key components (membrane, electrode, BPP, vanadium electrolyte) on stack and system costs is quantified and validated.

1. Introduction

The vanadium redox flow battery (VRFB) is one of the most promising electrochemical storage systems for stationary applications. The principle of the redox flow battery allows to convert electrical energy into chemical energy in electrochemical cells and store it in fluid electrolytes in external tanks. Rated power and energy capacity can be designed independently. The system power scales with the cell area, whilst the energy capacity is determined by the electrolyte volume. The VRFB uses a solution of vanadium ions in sulfuric acid in both half-cells. The redox couple V^{2+}/V^{3+} operates in the negative electrolyte and the redox couple VO^{2+}/VO_2^+ (V^{4+}/V^{5+}) in the positive electrolyte. Main advantages are the high cycle life (270000 charge-discharge cycles demonstrated) and overall energy efficiency (80%) of the vanadium system [1].

VRFB are already commercially available [2]. Installation figures reveal 50 installed systems in 2015 with a total installed power of 23 MW (Fig. 1). The sharp increase of installation figures is due to the market entrance of Gildemeister energy solutions GmbH offering small modular container systems (Cellcube) with a rated power of 10 kW and an energy capacity of 100 kWh [3]. The sum of installed power is dominated by individual megawatt demonstration projects in Japan and China [4].

In order to allow large scale industrial applications two main challenges have to be met: Cost reduction of the system and enlargement of active single cell area. The cell area is currently limited to 0.1 m^2 by the size of the bipolar plate (BPP) due to manufacturing techniques [6]. Thus, the development of an innovative extrusion process aiming on novel large-area compound BPP

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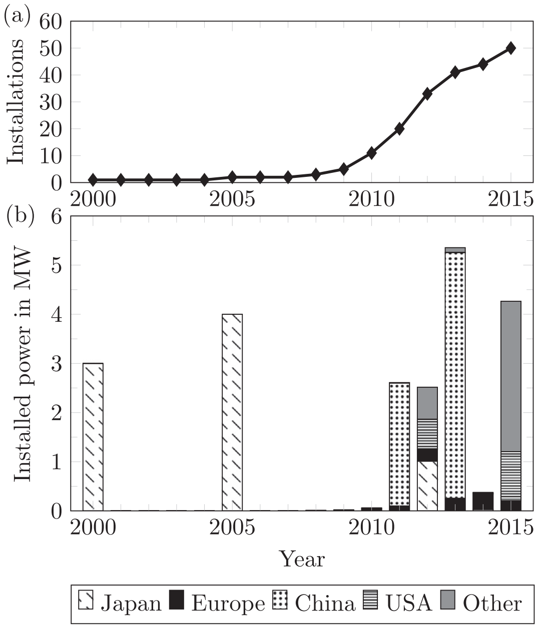

Fig. 1. (a) Installation figures of VRFB systems for stationary applications 2000 to 2015 (cumulative) and (b) installed power in selected regions [2–5].

with 2.7 m^2 is object of research and development. With a scale-up factor of 30 for the cell area megawatt VRFB can become commercial soon [7].

The present paper provides a techno-economic assessment of novel VRFB systems with large-area BPP. This approach has been developed in a comprehensive project on VRFB components and system design [2,5,6,8,9]. Object of consideration is a VRFB system with a single cell area of 2.7 m^2. Therefore, a detailed techno-economic analysis of extruded BPP is provided in a sub model. The technical configuration of the system is done for rated power in a range of 1 MW–20 MW. An applicable stack design following chlor-alkali electrolysis systems is proposed [7]. Two variations of the energy to power ratio (E/P) of the system are considered, namely 4 h and 8 h. Subsequent energy capacities are in a range of 4 MWh to 160 MWh. The comprehensive techno-economic model described in detail in section 2 combines the technical configuration of the whole system with resilient cost data on single components. In the conceptual approach the battery system is divided into a power subsystem and an energy subsystem in accordance with the cell area related to power and the electrolyte volume related to energy capacity. Analogously, cost functions are formulated identifying the specific costs of the power (c_{power}) and energy subsystem (c_{energy}). The intention of the present study is to identify system costs (sum of power and energy related costs) and cost potentials of novel large-scale VRFB.

2. Model

2.1. System definition and target function

The scope of the model is defined by rated power P in the range of 1 MW–20 MW and energy to power ratios (E/P) of 4 h and 8 h. The target function is a simple linear cost function describing the overall system costs C_{system} as sum of costs of power and energy subsystems (sections 2.4.1 and 2.5.1).

$$C_{system} = P \cdot c_{power} + E \cdot c_{energy} \tag{1}$$

with a cost rate of power subsystem c_{power} and a cost rate of energy subsystem c_{energy} calculated on the basis of the technical configuration (sections 2.4.2 and 2.5.2) and cost input parameters (sections 2.4.3 and 2.5.3).

2.2. Electrochemical model

A suitable operation point calculated in an electrochemical model serves as the basis for the design of VRFB systems. Target values are cell voltage and current density in charge and discharge mode. The simple model considers the linear part of the current-voltage characteristic described by Ohm's law (Eq. (2)) and does not include shunt current losses. All technical parameters are listed in Table 1.

$$U_{cell}(SOC) = OCV(SOC) - R \cdot A_{cell} \cdot i(SOC) \tag{2}$$

The cell voltage U_{cell} is dependent on the state of charge (SOC) defined by the concentrations c_i of vanadium species in the positive (VO^{2+}/VO_2^+) and negative (V^{2+}/V^{3+}) electrolyte:

$$SOC = \frac{c_{V^{2+}}}{c_{V^{2+}} + c_{V^{3+}}} = \frac{c_{VO_2^+}}{c_{VO_2^+} + c_{VO^{2+}}} \tag{3}$$

The open circuit voltage OCV is described by the Nernst equation:

$$OCV = E^\circ + \frac{RT}{F} \ln\left(\frac{c_{VO_2^+}\ c_{H^+}^2}{c_{VO_2^+}}\ \frac{c_{V^{2+}}}{c_{V^{3+}}}\right) \tag{4}$$

For simplification purpose the activity coefficients are equal to 1 and the formal potential is replaced by the standard potential $E^\circ = 1.255$ V. R is the universal gas constant and F the Faraday constant. The temperature is assumed with $T = 298$ K. The equilibrium voltage is determined by the SOC and the proton concentration which is dependent on the concentration of the sulfuric acid (see Ref. [10]). For subsequent processing the value at SOC = 0.5, OCV = 1.4 V, is used.

The equivalent ohmic resistance of a cell is assumed with $R = 0.058$ mΩ (1.556 Ω cm^2) based on experimental data. The current density i is negative in charge mode and positive in discharge mode. On the basis of this current-voltage characteristic (Eq. (2)) a suitable operation point is calculated. The calculation is based on assumed voltage and coulombic efficiencies of 80% and 99%, respectively [1,10–13]. Voltage efficiency η_V and coulombic efficiency η_C of the cell are defined as the ratio of discharge and charge voltage and charge, respectively. The resulting energy efficiency η_E is 79% according to Eq. (5).

$$\eta_E = \eta_V \cdot \eta_C \tag{5}$$

Table 1
Parameters for technical configuration of large-scale VRFB systems.

	Symbol	Unit	Value
Temperature	T	K	298
Open circuit voltage (SOC = 0.5)	OCV	V	1.4
Cell voltage (discharge)	U	V	1.2
Current density	i	kA m^{-2}	1.0
Active cell area	A_{cell}	m^2	2.7
Minimum state of charge	SOC_{min}		0.2
Maximum state of charge	SOC_{max}		0.8
Depth of discharge	DOD		0.6
Vanadium concentration	c_V	mol l^{-1}	1.6
Sulfate concentration	c_{H2SO4}	mol l^{-1}	4.0