



IEEE Guide for the Characterization and Evaluation of Flow Batteries in Stationary Applications

IEEE Power and Energy Society

Developed by the
Energy Storage and Stationary Battery Committee

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STANDARDS

IEEE Guide for the Characterization and Evaluation of Flow Batteries in Stationary Applications

Developed by the

Energy Storage and Stationary Battery Committee
of the
IEEE Power and Energy Society

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IEEE SA Standards Board

Abstract: Guidance for an objective evaluation of flow batteries by a potential user for any stationary application is provided in this document. IEEE Std 1679™-2020 is to be used in conjunction with this document. In a flow battery, the electrolyte is stored in one or two tanks, and pumps are utilized to deliver the electrolyte through the cells in order to recharge or discharge the battery. (When two electrolytes are used, they are often referred to as negolyte and posolyte). Technology descriptions, operating parameters, failure modes, safety information, battery architecture, and qualification and application considerations are provided in this document. Batteries that do not employ flowing electrolyte systems are not covered. Sizing, installation, maintenance, and testing techniques are not covered except insofar as they may influence the evaluation of a flow battery for its intended application.

Keywords: battery, energy storage, flow battery, hybrid flow battery, IEEE 1679.3™, redox flow battery, secondary, slurry flow battery, stationary application

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Introduction

This introduction is not part of IEEE Std 1679.3-2025, IEEE Guide for the Characterization and Evaluation of Flow Batteries in Stationary Applications.

Growing interest in long-duration energy storage has resulted in increased focus on flow batteries. Because of the unique characteristics of flow batteries and their different architectures, there is a need for objective information and suitable evaluation techniques. This document provides technology descriptions, information on failure modes, evaluation techniques, and regulatory issues for the major types of flow batteries for use in stationary applications.

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IEEE Guide for the Characterization and Evaluation of Flow Batteries in Stationary Applications

1. Overview

1.1 Scope

This document provides guidance for an objective evaluation of flow batteries by a potential user for any stationary application. This document is to be used in conjunction with IEEE Std 1679™-2020.⁶

In a flow battery, the electrolyte is stored in one or two tanks and pumps are utilized to deliver the electrolyte through the cells in order to recharge or discharge the battery. (When two electrolytes are used, they are often referred to as negolyte and posolyte).

The outline of IEEE Std 1679-2020 is followed in this document, with tutorial information specific to flow batteries provided as appropriate. Examples of tutorial information include technology descriptions, operating parameters, failure modes, safety information, battery architecture, and qualification and application considerations.

This document does not cover batteries that do not employ flowing electrolyte systems. Sizing, installation, maintenance, and testing techniques are beyond the scope of this document except insofar as they may influence the evaluation of a flow battery for its intended application.

1.2 Purpose

Flow batteries have been studied and tested since the 1970s and deployed in demonstration systems since the 1990s. They are now being offered on commercial terms for energy storage applications, and as such there is a need to evaluate their performance under various operating conditions related to these applications. End-users would benefit from having a guide to assist in evaluation of this technology for stationary applications.

Used with IEEE Std 1679-2020, this guide describes a format for the characterization of flow battery technologies in terms of performance, service life and safety attributes. This format will provide a framework for developers and manufacturers to describe their products. The resulting information will assist users, integrators, and servicing organizations in evaluating the possible use of these batteries in stationary applications and to provide objective criteria for comparative evaluation.

⁶ Information on references can be found in Clause 2.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{7,8}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 1679™-2020, IEEE Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications.^{9,10}

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. IEEE Std 1881™ [B21], or the *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.^{11,12} Other definitions may be found in IEC 62932-1 [B16].

bipolar plate: A flat conducting structure (e.g., a plate) that connects electrodes of opposite polarities on either face of the structure allowing current to flow between the electrodes.

flow battery: A rechargeable battery in which energy is stored in liquid electrolytes that flow through an electrode stack, forming positive and negative half cells that exchange ions during charge or discharge, typically through a membrane separator. *See also:* **hybrid flow battery**, **redox flow battery**, **slurry flow battery**.

flow battery stack: An arrangement of cells connected in series, with electrolyte flow through cells occurring in hydraulic parallel or series.

flow battery string: One or more stacks connected electrically in series.

⁷ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

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¹¹ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹² The numbers in brackets correspond to those of the bibliography in Annex A.

hybrid flow battery: A flow battery in which one or more of the electroactive components is deposited in solid form. *See also:* **flow battery, redox flow battery, slurry flow battery.**

membrane, flow battery: A thin, permeable sheet that allows ionic transfer while preventing transfer of electroactive species and minimizing transfer of solvent.

negolyte: The electrolyte that flows through the negative chamber of a conventional and hybrid flow-battery cell.

posolyte: The electrolyte that flows through the positive chamber of a conventional and hybrid flow-battery cell.

redox flow battery: A flow battery in which all the electroactive components are dissolved in the electrolytes. *See also:* **flow battery, redox flow battery, slurry flow battery.**

shunt currents: Parasitic current flow through manifolds when electrolyte is fed hydraulically in parallel to series connected cells in a flow battery stack.

slurry flow battery: A flow battery that uses particles suspended or fluidized in a solution, with the weight percentage of particles changing with state of charge. The solution is transferred between the tank and stacks to be charged and discharged. *See also:* **flow battery, hybrid flow battery, redox flow battery.**

3.2 Acronyms and abbreviations

AEGL	acute exposure guideline level
BMS	battery management system
CFR	Code of Federal Regulations
CPVC	chlorinated polyvinyl chloride
ESMS	energy storage management system
HDPE	high-density polyethylene
HVAC	heating, ventilation, and air-conditioning
IBC	intermediate bulk container
LCC	life-cycle costing
LDPE	low-density polyethylene
NRTL	Nationally Recognized Testing Laboratory
PAC	Protective Action Criteria (for Chemicals)
PCS	power conversion system
PPE	personal protective equipment
PVDF	polyvinylidene difluoride
RTE	round-trip efficiency
SDS	safety data sheet
SOC	state of charge
SSHA	subsystem hazard analysis

4. Document structure

Clause 5 through Clause 9 of this document refer to corresponding clauses of IEEE Std 1679-2020 that have the same clause headings but may differ in clause number. Throughout this guide there are references to the parent document for information that is general and applies to flow batteries without additional guidance. Additional subclauses have been added to this document that have no direct counterpart in IEEE Std 1679-2020, where additional guidance is required.

5. Technology description

5.1 General

Refer to Clause 5 of IEEE Std 1679-2020. A flow battery consists of one or more liquid or slurry electrolytes that are pumped through one or more stacks to produce electrical power. The process is reversible so that the electrolyte can be recharged. The components vary by technology. All flow batteries provide separation of energy from power.

5.2 Storage medium

5.2.1 General

Flow batteries can be grouped into three different categories, depending on the storage medium: conventional redox, hybrid and slurry. For the purposes of this guide, the focus will be on commercially available technologies at the time of this writing.

5.2.2 Conventional redox flow batteries

One example of a conventional redox flow battery is vanadium redox as shown in Figure 1. These batteries use vanadium materials for both electrolytes (V^{2+}/V^{3+} for the negolyte and V^{4+}/V^{5+} for the posolyte), with a mild sulfuric acid solution as supporting electrolyte. During a charge/discharge cycle, H^+ ions are transported across a hydrogen-ion-permeable cation exchange polymer membrane. The reaction at both electrodes corresponds to change of valence states of the vanadium ions, with no deposition at or stripping from the electrode surface.

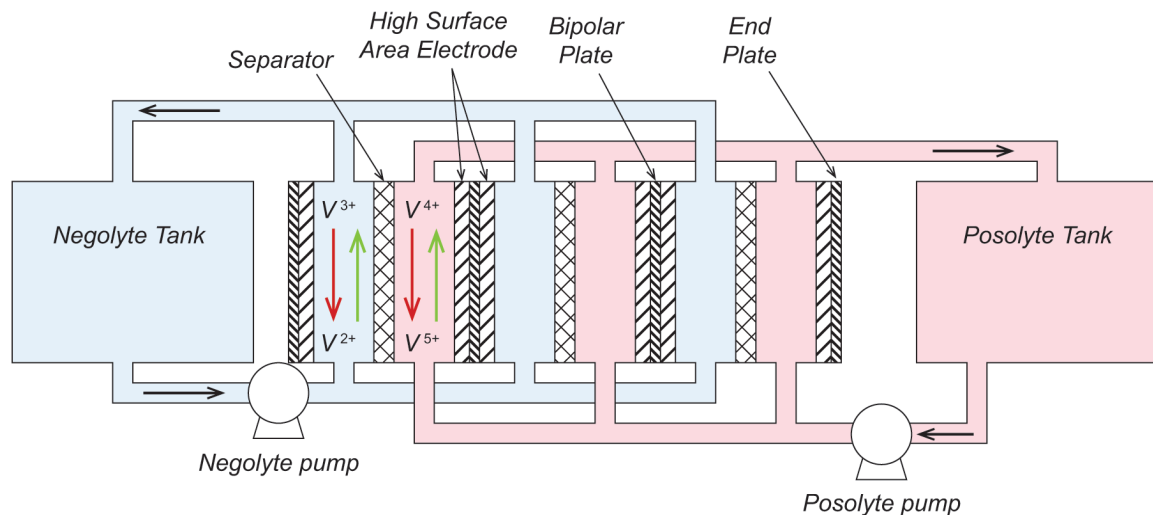


Figure 1—Schematic of a vanadium redox flow battery

5.2.3 Hybrid flow batteries

Hybrid flow batteries plate one or more active materials onto the cell electrode when the battery is recharged so that the energy of the negative active species is stored in the stacks, while the energy of the positive active species is stored in the posolyte. Examples of hybrid flow batteries include all-iron and zinc-bromine. In a zinc-bromine hybrid flow battery, zinc bromide electrolyte is circulated through both compartments. Metallic zinc is plated at the negative during charge, while bromine is evolved at the positive. The bromine is complexed and settles to the bottom of the posolyte tank. During discharge, zinc is stripped from the negative to form zinc ions, while bromide ions are generated at the positive, resulting in formation of zinc bromide. Conductive plastic bipolar plates with grooves on the negative side and carbon paper or felt bonded on the positive side are used as electrodes (see Swan [B37]). Figure 2 shows the schematic of a zinc-bromine battery.

The iron redox flow battery consists of an aqueous solution of FeCl_2 in the discharged state. The negolyte consists of ferrous chloride, with iron plating during charge. The posolyte consists of a mix of ferrous and ferric chloride, with Fe^{2+} oxidation to Fe^{3+} comprising the charge reaction.

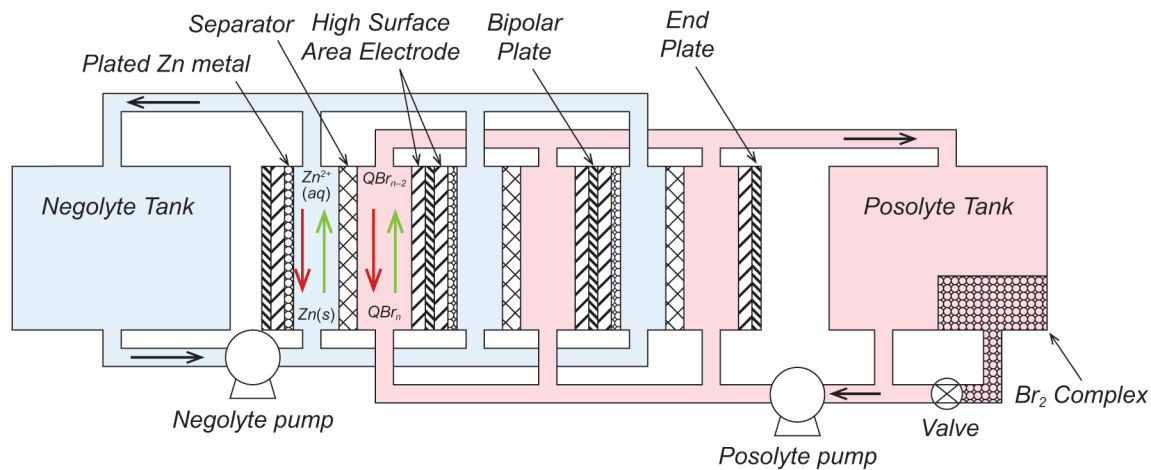


Figure 2—Schematic of a zinc-bromine flow battery

5.2.4 Slurry flow batteries

At the time of preparing this document, no slurry flow batteries had been commercialized. An example of one type of slurry flow battery is described in Annex C.

5.3 Intended applications

Flow batteries, due to their flexibility, can be used for power-intensive or energy-intensive applications. Since the stacks are a fixed cost for a fixed power rating, flow batteries are generally used in long duration applications where the fixed stack cost is spread over a larger energy capacity. Hence, these batteries are best suited for time shifting of renewable energy, typically with durations ranging from 6 h to 16 h, or more. With proper design and planning, flow batteries can be used in a suite of applications ranging from frequency regulation to peak shaving to time shifting of renewable energy. However, each flow battery type has advantages in each type of application.

For applications with frequent mode changes such as frequency regulation, conventional redox flow batteries can follow the signal well. However, since frequency regulation signals have an average absolute power of 10% to 20% of rated power, auxiliary power consumption can comprise 15% to 30% of the average power exchanged with the grid, resulting in low round-trip efficiency (RTE). See 5.6.4. This low RTE may be

overcome by superimposing the frequency regulation signal onto a constant charge or discharge power, with the absolute value of the maximum power for the frequency regulation set to the difference between rated power and the absolute value of charge or discharge power.

Frequent mode changes may contribute to non-uniform plating at the negative electrode during charge for hybrid batteries. Note that hybrid batteries can be subjected to varying discharge rates, as long as there are no frequent mode changes. This may limit them to a stacked use case where the frequency regulation signal is superimposed on a smoothly varying discharge power, such that the battery mode remains on discharge during the duration of the frequency regulation cycle. This may not apply for a superimposition on a smoothly varying charge power, since a rapidly changing charge power may not be conducive to uniform plating at the negative electrode.

For energy intensive applications such as peak shaving and time shifting, both flow battery types can be used.

These technologies can be used in standby applications, but some are more suitable than others because of the power required to maintain charged electrolyte at the stacks. Pumping continually results in wear and tear along with loss of energy. One option for standby application is to pair the flow battery with a short duration battery to allow ride through for up to a minute. Another option is to run the pump every 12 h to 48 h for a short duration sufficient to overcome self-discharge related losses, so that the stacks are ready to deliver or absorb power on demand. Note that the energy content of electrolyte in the stacks should be sufficient to support grid load and power needed to pump electrolyte through the stacks. For standby applications where the flow battery may be called upon very rarely, running the pump every 12 h to 48 h may result in significant auxiliary power consumption, hence the viability of this option should be assessed on a case-by-case basis. Use of a short-duration transition battery appears to be a reliable and cost-effective solution for standby applications.

It is important that the user verify with the battery supplier that the flow battery selected for use has been designed and is rated for that specific application.

5.4 Components and construction

5.4.1 General

The intent of this subclause is to provide the user with general knowledge of the types of components used in flow batteries. These components are used for battery management, thermal management, auxiliary systems for gas detection, leakage containment, communications, and control. A generic description for components used in flow batteries is provided in this section. Typically, fully integrated flow battery systems are supplied by the vendor, hence the user does not have to match the dc system with the corresponding ac hardware.

5.4.2 Stack

5.4.2.1 General

The stack consists of multiple cells connected in series by bipolar plates. The bipolar plates and membranes are housed within plastic frames, which have flow channels machined into them to supply electrolyte to the electrodes. The electrolyte is delivered to the plastic frames via manifolding. At the ends of each stack, there are current collectors and end plates, with the stack held in place via bolts/nuts torqued at the design pressure or by other means such as thermally welded plastic frames. Flow paths through the cell electrodes may be serpentine, parallel, interdigitated, or flow through (see [Figure 3](#)). For a) to c), red arrows denote flow along channels in the bipolar plate, and for d), they denote flow through the felt electrode. The blue arrows in c) denote flow out of the plane of paper from the inlet channels onto the felt electrode, flow across the felt electrodes, and back into the plane of paper to the outlet channels. Additional details are also found in 5.4.2 of IEEE Std 1679-2020.