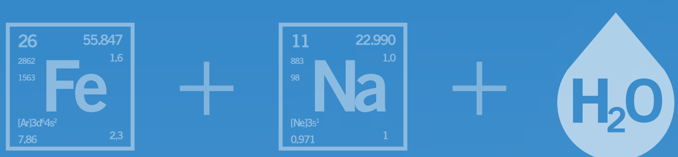
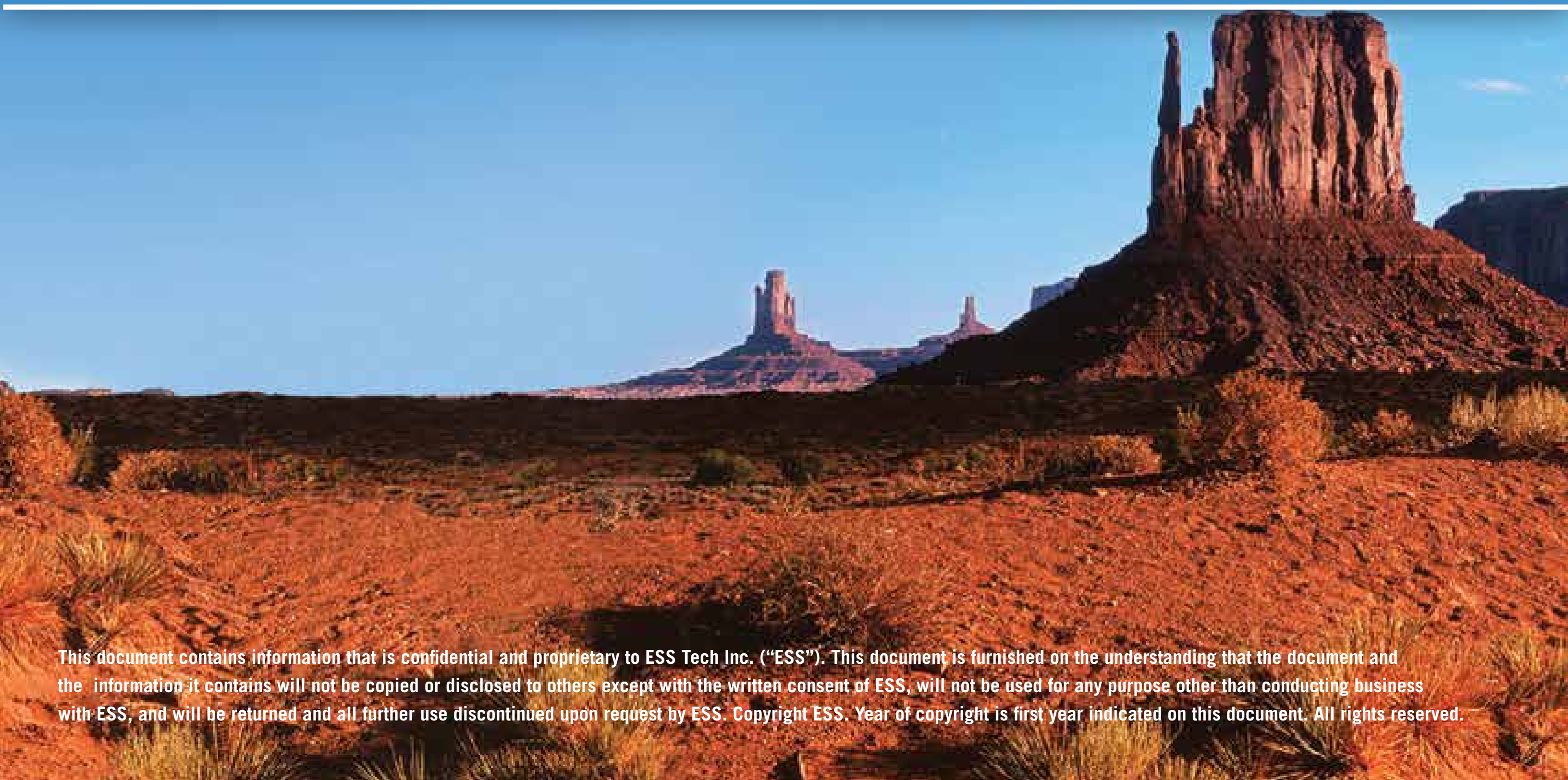
TECHNICAL WHITE PAPER

All-Iron Flow Battery – Overview





A reduction-oxidation (redox) flow battery is an electrochemical storage device which stores energy in a chemical form. Redox, a contraction of reduction (a gain of electrons) and oxidation (a loss of electrons), is a chemical reaction in which electrons are transferred between chemical species. Using the same element on both sides eliminates cross-contamination issues.

The stored chemical energy is converted to an electrical form via spontaneous reversible redox reactions. To restore the dispensed chemical energy, an electrical current is applied to induce the reversible redox reaction. Hybrid flow batteries deposit one or more of the electro-active materials as a solid layer on an electrode. Hybrid flow batteries include a chemical that forms a solid precipitate plate on a substrate at a point throughout the charge reaction which may also be dissolved throughout the discharge reaction. During the charge reaction, the chemical may solidify on the surface of the substrate forming a plate near the electrode surface. The chemical is regularly a metallic compound. In hybrid flow battery systems, the energy stored by the redox battery may be limited by the amount of metal plated during charge and may accordingly be determined by the efficiency of the plating system as well as the available volume and surface area to plate. Unlike typical batteries that are packaged as fixed cells or modules, a flow battery allows the battery's power (th e rate of electricity flow) to be decoupled from the battery's capacity (the total amount of energy held). As a result, users are free to tune the battery's specifications to their specific needs.

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One example of a hybrid redox flow battery is the all-iron redox flow battery (IFB) developed by ESS. The IFB technology uses iron as an electrolyte for reactions including a negative electrode where plating occurs, herein also referred to as the plating electrode, and a positive electrode where a redox reaction occurs, herein also referred to as the redox electrode. The performance of an IFB battery can be broken down to its plating electrode performance (negative electrode), redox electrode performance (positive electrode), and ohmic resistance loss. On the plating electrode, the ferrous (Fe^{2+}) ion gains electrons and plates as solid iron on the substrates during charge, as shown in Figure 1 below, and the solid iron dissolves as ferrous ions and releases two electrons during discharge. The equilibrium potential for the iron plating reaction is -0.44V. On the redox electrode, the redox reaction between ferrous and ferric (Fe^{3+}) ions occurs during charge and discharge. On the positive electrode, two Fe^{2+} ions lose two electrons to form Fe^{3+} ions during charge, as shown in Figure 1 below and two Fe^{3+} ions gain two electrons to form Fe^{2+} during discharge. The equilibrium potential between ferrous and ferric ions is +0.77V. Thus, the reaction in an IFB redox flow battery is reversible.

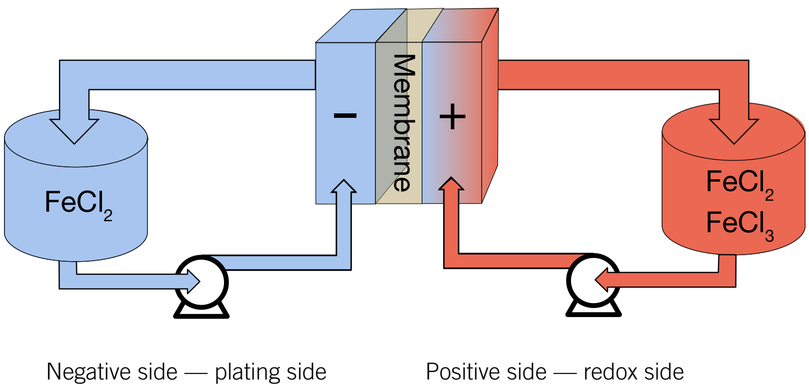

Figure 1: Principle of IFB Technology

Charge:		**Discharge:**	
$Fe^{2+} + 2e^- \rightarrow Fe^0$	Negative Electrode	$Fe^0 \rightarrow Fe^{2+} + 2e^-$	Negative Electrode
$2Fe^{2+} \rightarrow 2Fe^{3+} + 2e^-$	Positive Electrode	$2Fe^{3+} + 2e^- \rightarrow 2Fe^{2+}$	Positive Electrode

ESS has cracked the code to keeping traditional iron chemistry stable for thousands of deep charge and discharge cycles with no degradation.

The ESS team has innovated upon this simple yet elegant electrochemistry and enabled this traditional IFB technology to operate much more efficiently (US20140065460). Our patented battery design combines plentiful and extremely cost effective materials with an innovative cell design that dramatically increases power density and enables a smaller, less costly power stack. ESS IFB users can expect over 20,000 cycles at over 80% depth of discharge during a 25-year life, with minimal maintenance.
ESS has cracked the code to keeping traditional iron chemistry stable for thousands of deep charge and discharge cycles with no degradation. ESS' patent electrode designs allow you to operate at high flow-battery efficiency levels (US20140272493, US20140363747, US20150255824). In addition, ESS has scaled up and validated its unparalleled battery technology from Watts to Multi-kW power modules (Figure 2) and from a single power module to fully-integrated, multi-power module, turnkey systems (Figure 3).

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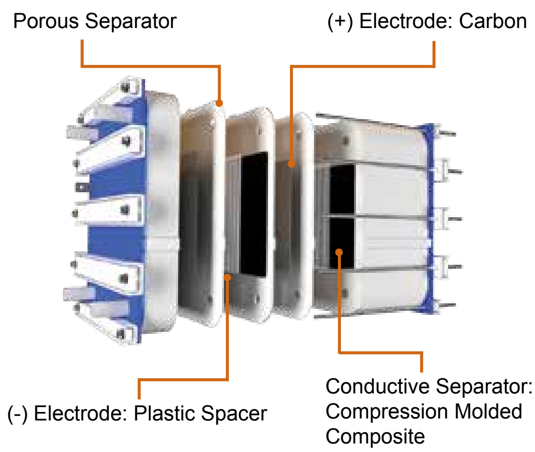


Figure 2: ESS subscale and multi-kW IFB modules

Figure 3: ESS IFB System

Table 1 compares the effectiveness of various types of energy storage technologies in regards to integration with renewable generation sources such as solar and wind. Currently there are seven primary categories of energy storage technologies - pumped hydropower, compressed air energy storage (CAES), electrochemical batteries, supercapacitors, flywheels, superconducting magnetic energy storage (SMES) and thermal energy storage. Each type of storage technology varies in terms of power and energy and has its preferred market and applications. For example, pumped hydropower is preferable for applications of high system power (> 100MW) and long discharge time (in hours). Furthermore, this technology is capital intensive and geographically limited. Flywheels can readily scale from 10kW up to hundreds of kW of energy storage, but it typically stores seconds' worth of energy. Batteries are easier to implement and have a wide range of performance ratings depending on the type of batteries and their cost and performance.

	Flywheels	Lead Acid Batteries	Li-ion Batteries	Trad, Flow Batteries	ESS Iron Flow Batteries
Cost	Good	Good	Medium	Medium	Good
Energy Density	Good	Poor	Good	Poor	Poor
Energy Capacity	Poor	Poor	Medium	Medium	Good
Installation	Poor	Poor	Medium	Medium	Good
Cyce Life	Good	Poor	Poor	Good	Good
Depth of Discharge	Medium	Poor	Good	Good	Good
O&M	Medium	Poor	Medium	Medium	Medium
Response	Good	Medium	Medium	Good	Good
Environment	Good	Poor	Poor	Medium	Good

Good Medium Poor

Table 1 - Distributed Energy Storage Technology Comparison

Bloomberg New Energy Finance predicts that by 2024 cost of energy storage will have reached significant levels of grid penetration in many key utility markets, from 29% in Germany to 39% in California.

The primary barriers for commercializing flow battery technologies are cost for energy storage in terms of $/kWh, cost for the power capacity in terms of $/kW, and battery performance in cycle life and round trip energy efficiency. However, no other technology can match the advantages of ESS' All-Iron Redox Flow Battery. The IFB leads competitive technologies in low cost per kWh and unlimited deep cycles, as well as with an environmentally friendly electrolyte, 20-plus year system life, turnkey installation and fast electrical response time. The ESS IFB technology differentiates from any other battery technologies and fulfills the targeted energy storage performance and cost requirements for the renewable industry because:

1) The cost of energy storage ($/kWh) is driven by the commodity price of the raw electrolyte materials. The ESS IFB system utilizes earth abundant $FeCl_2$ as its electrolyte and the electrolyte costs <$20/kWh, making it cheaper than the chemicals used in most other battery technologies. Our non-corrosive electrolyte enables the use of plentiful and extremely cost effective materials with an innovative cell design that dramatically increases power density and enables a smaller, less costly power stack.

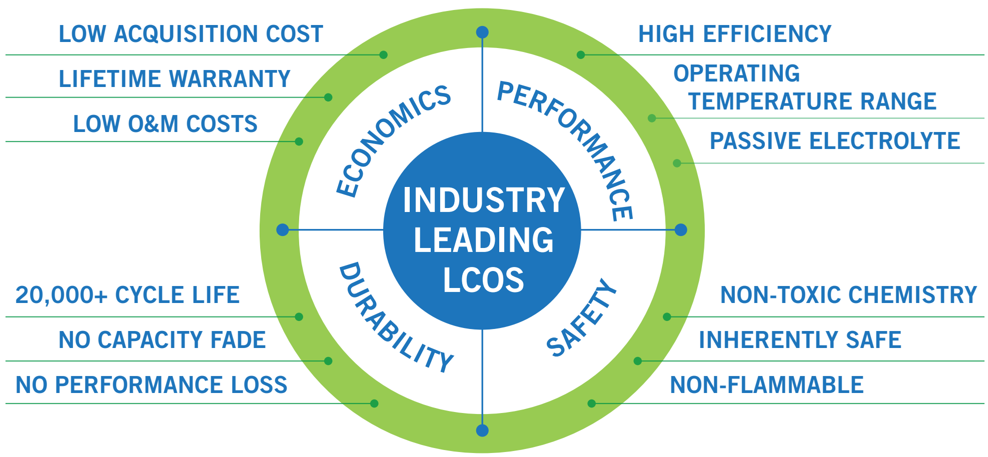
2) The cost of power module ($/kW) is driven by the cost of repeat and non-repeat parts in the power module. ESS' patent power module design (US20140065460) utilizes low cost materials and has demonstrated 5X higher power density than comparable battery technologies. The higher the power density, the fewer number of batteries are required for the same system power requirement. This equates to less material and lower cost.

3) >97% round trip columbic efficiency and >76% DC energy efficiency has been demonstrated on ESS' IFB modules for over 10,000 cycles at over 80% depth of discharge with no performance degradation. Because the IFB electrolyte operates within a benign pH range of 1 to 4 and the electrode reaction potential is less than carbon corrosion potential of 0.8V, there is minimal material or electrode degradation during operation.

4) Safety and sustainability – ESS' IFB electrolyte is composed of $FeCl_2$, table salt and water and operates between a pH range of 1 and 4. With a non-toxic, non-corrosive, non-flammable and 100% recyclable iron-based electrolyte, the IFB sets a high bar for safe, reliable, and environmentally conscious energy storage. With these unique operating characteristics, the IFB can be safely installed indoors or out, and in populated or sensitive areas.

5) Modular, scalable and dispatchable design – Housed in a rugged ISO container, that can meet both distributed and grid scale integration requirements, the IFB is easily transported pre-assembled and permitted in the field. By adding available potable water when the system arrives, the weight that has to be moved is 70% less than other flow and traditional batteries. When installed, the IFB systems can be combined into multi-MW energy storage projects.

6) Fully integrated and Turnkey solution – ESS team offers a fully packaged energy storage solution to our customers including 8 hours of energy storage capacity, 480 V_{ac} 3-phase power and a communications interface for remote monitoring and real time control capabilities.



Ideal requirements when evaluating the levelized cost of storage (LCOS) of electrical LDS

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