GridStar®
ENERGY SOLUTIONS

Flow Batteries for Flexible, Long-Duration Energy Storage

ADVANTAGES OF COORDINATION CHEMISTRY TECHNOLOGY

LOCKHEED MARTIN

As the grid evolves toward a distributed model, energy storage can play a vital role in providing stability, reliability and capacity. In the earlier stages of energy storage, lithium-ion chemistry emerged as a dominant design for short-duration frequency regulation and renewables integration. Soon, lithium-ion became the most widely deployed electrochemical battery technology for stationary applications. However, as the market has since evolved to two-hour demand charges and four hour capacity, it is clear the industry is continuously moving towards energy storage with longer and longer duration.

Growing market applications such as transmission and distribution deferral and renewables shifting require long-duration energy storage. In general, requirements for energy storage on the grid are becoming more challenging – requiring batteries with not only longer duration, but higher flexibility. Currently the dominant technology in the energy storage industry, lithium-ion has proven to have significant durability, flexibility, and cost limitations for long-duration storage. Technologies beyond lithium-ion can provide long-duration storage the market increasingly needs.

This paper examines what's driving the need for long-duration, high-durability storage and compares the capabilities of each approach. Finally, the paper finds clear advantages of redox flow batteries and details the ideal architecture and application for optimal results. We'll look at:

- The storage market opportunity, focusing on the opportunity for long-duration energy storage solutions;
- Current long-duration storage systems, comparing their relative strengths and weaknesses;
- Characteristics of the best redox approach to utility-scale applications that ensure the most durable, scalable and cleanest energy storage system.

WHAT IS LONG-DURATION?

We define long-duration as discharge of more than six hours. Two important characteristics relate to sizing and operation for energy storage: power (kW) and energy (kWh). Ancillary services applications, such as frequency regulation, require a rapid discharge time – seconds to minutes. Smoothing and short peaking shifting require 1-4 hours duration.

Other applications require substantially longer durations still - 6, 8, 10, or even more than 12 hours of storage availability.

WHERE LONG-DURATION PLAYS...

Many growing market applications require long-duration (>6 hours) energy storage, including:

Transmission and Distribution Infrastructure Deferral

Energy storage can be built as an alternative to transmission and distribution infrastructure investments, which are **projected** to reach $351 billion per year globally by 2026.[1] Properly placed on an electric grid, energy storage can defer or replace the need for new wires and substation equipment required to address load growth and congestion, replace aging equipment or improve grid reliability in the face of rising distributed energy resources. These types of projects can require energy storage with durations of >6 hours.

Wind Time-Shifting and Solar Time-Shifting

Energy storage can be used for smoothing out intermittency for solar and wind generation – an important factor for these resources, which are projected to increase from 12 percent to 46 percent of global generation over the next 17 years. Increasing penetrations of solar (e.g. Hawaii and California) and wind (e.g. Texas) often exceed demand, causing renewable generation to be curtailed for increasingly long periods, wasting valuable resources and creating steep evening demand ramps, requiring large, flexible assets to meet load. Long-duration storage can help address challenges related to high penetration of intermittent renewables.

Bulk shifting of >6 hours of energy from solar and wind installations can address renewable curtailment, and enable higher levels of renewables as part of the generation mix.

Islanded and Military Microgrids

Energy storage can enable microgrids, including islanded and military microgrids, to improve reliability, reduce fuel costs from expensive diesel fuel and integrate renewable energy generation. Recently, the Department of Defense instructed military bases to develop a strategy to be self-sufficient for at least 14 days without outside power, water and other utilities. These types of stand-alone grids require storage that can bridge many hours of operation, stand fully charged and cycle deeply on a daily basis.

LIMITATIONS OF CURRENT STORAGE TECHNOLOGIES

A range of technologies can address the long-duration, high-durability energy storage challenge.

Lithium-Ion

Lithium-ion batteries are growing rapidly in deployment as technology has improved and prices have declined due to scale-ups in the electric vehicle and consumer electronics industry. Lithium-ion systems are disadvantaged, however, for applications that require frequent cycling, high rest state-of-charge, low energy capacity degradation and operations in extreme temperature environments or places where temperature is not tightly controlled.

Disadvantages include:

- Capacity degradation due to cycling frequency, depth of discharge, high rest state-of-charge, and calendar degradation;
- Temperature sensitivity;
- Marginal cost flat-lining after 3-4 hours. Marginal cost doesn't improve for cell-based systems like Li-ion.

As a result, the economic and technical benefits of lithium-ion systems weaken considerably for applications that require more than four hours of duration and high flexibility.

Pumped Hydro

Another approach to energy storage is the pumping of water uphill to a reservoir then releasing it back downhill to generate electricity. This technology has a very long project life (greater than 30 years) and can offer low cost energy storage; however, new pumped hydro systems are exceedingly difficult to site and permit, as they require unique geological sites, are large civil works projects and are often subject to public opposition.

There is a large opportunity for long-duration energy storage technology that can meet the following characteristics:

- >6 to over 12 hours charge/discharge duration
- Minimal degradation with usage, time and temperature
- Long project life (30 years)
- Low total cost of ownership
- Modular and scalable
- Quick-to-build, easy to site and permit

Flow Batteries

Unlike sealed batteries, where electrodes, electrolyte, and wiring are completely packaged in individual sealed containers (typically cylindrical or prismatic cells), a flow battery deconstructs this architecture and greatly increases its scale by separating the individual components. In a flow battery, the electrolyte is stored in large tanks and pumped through cell stacks, which either charge the electrolyte using electrical energy from the grid or convert energy from the electrolyte to electricity sent back to the grid. NASA was the first to develop a redox flow battery in 1973, and today there is a strong use case for these long-duration technologies.[2]

UNLOCKING REDOX FLOW BENEFITS:

Architecture and Advantage for Optimal Impact

Redox flow batteries have the potential to address many of the limitations of existing battery chemistries, like lithium-ion, by offering a number of critical advantages: separation of power and energy; low marginal cost of energy capacity; low degradation under high cycling and greater operational flexibility with limited impact on system performance; and low total cost of ownership.

Redox flow batteries differ from sealed batteries (e.g., lead acid, lithium-ion) in that they separate the power (MW) and energy (MWh) portions of a battery system and allow each to be independently sized. **This decoupling of power and energy, is key to cost-effective long-duration storage.** It reduces the marginal cost of stored energy and can allow flow batteries to achieve low first costs at long discharge times. As system duration increases, the cost of the power equipment is amortized over the nameplate energy capacity, so the cost per watt-hour is reduced. From an applications standpoint, this ability to independently specify power and energy improves asset utilization. Since energy is stored within the electrolytes, the energy capacity (or duration of charge/discharge) is limited only by the amount of electrolyte, and can be increased by adding more electrolyte.

Flow batteries, if properly designed, can result in systems with high-cycle life. This is due to the ability to perform full charge-discharge cycles and operate multiple deep discharge cycles without capacity degradation. Sealed batteries, in contrast, suffer structural changes which limit cycle life when deeply discharged. In practice, this means that sealed battery deployments must be oversized and/or augmented during the project life to compensate for capacity loss. Since the electrolytes are stored away from the stacks, flow batteries experience relatively little self-discharge. Additionally, unlike sealed batteries, flow batteries can store energy at high states-of-charge without accelerating degradation.

Flow battery technologies currently on the market today include Vanadium Redox, Zinc Iron, and Zinc Bromine.

- **Vanadium Redox,** the most common redox flow battery technology on the market, uses the oxidation states of vanadium. Vanadium redox batteries are limited by the high cost of vanadium and by the acidic nature of the electrolyte which makes these systems higher cost, hard to site, and subject to accelerated degradation.
- **Zinc Iron** batteries are a hybrid design where zinc is plated and de-plated on the electrode surface during charging and discharging. They are not true redox flow batteries, limiting their ability to operate for durations >4 hours. These systems must periodically be taken out of service to strip excess metal off electrodes, reducing system availability and electrical efficiency.
- **Zinc Bromine** batteries, like Zinc Iron batteries are limited in their ability to operate at durations >4 hours and by the plating of zinc. Additionally the use of highly toxic bromine increases system costs and makes these batteries hard to site.

Existing flow technologies have failed to deliver on the promise of the flow architecture due to:

- High cost, high corrosivity, and/or toxicity of electrolytes
- High cost balance of plant – e.g., due to high corrosivity of electrolytes
- Inefficient systems – e.g., due to low current density, active material cross-over

COMPARING PROJECT LIFETIME COSTS

Valuing and comparing energy storage technologies and projects can be complex. Energy storage comparison and valuation requires a project-level analysis because value depends on project size, market conditions and energy storage system utilization. Energy storage system performance depends on a combination of key economic and technical attributes.

Key metrics for selecting energy storage systems include:

1. **COST**
   Levelized cost of storage (LCOS), total cost of ownership (TCO) and CAPEX or first cost
2. **POWER TO ENERGY RATIO**
   Power (W), energy (Wh), and duration
3. **LIFECYCLE USAGE**
   Footprint, build time, ease of siting, permitting, installation, use, disposal/recyclability
4. **USAGE PERFORMANCE**
   Efficiency, response time, degradation
5. **ENVIRONMENTAL, HEALTH AND SAFETY IMPACTS**

Tips for Evaluating Long-Duration Energy Storage Systems

- What is the total cost of ownership, including the installation costs?
- Does the system easily allow future additions?
- Is the system backed by a reliable warranty from a reputable company that will be around for the lifetime of the system?
- Is the system certified to 3rd party standards? E.g., UL certification
- Does the company supplying the system focus on continuous product innovation?

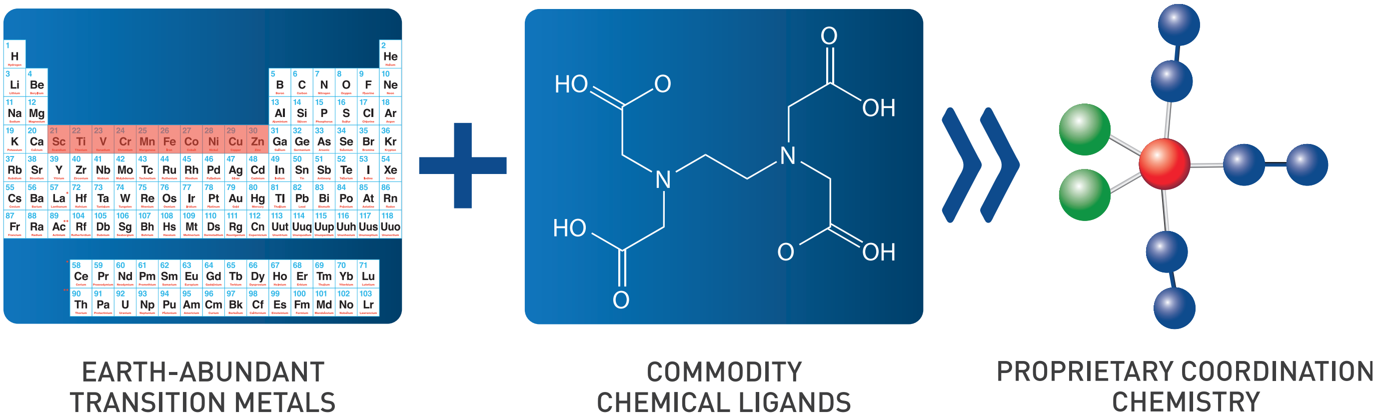
When considering overall project economics, project developers, customers, owners and investors should contemplate not just the first costs, but overall costs of an energy storage system over a project lifetime.

BREAKTHROUGH TECHNOLOGY: COORDINATION CHEMISTRY FLOW BATTERY

For long-duration energy storage applications, a new class of flow battery can enable flexible, durable, high-value, long-duration energy storage for utility-scale projects. Currently being commercialized by Lockheed Martin Energy as GridStar® Flow, the Coordination Chemistry Flow Battery (CCFB) technology delivers a fully-integrated energy storage system designed to serve 1 MW to >100 MW utility applications.

Unlike other flow batteries, GridStar® Flow is based not on one set chemistry (e.g., Vanadium or Zinc-Bromine), but on a patented coordination chemistry framework – offering a new electrochemistry consisting of engineered electrolytes. This provides the basis

Figure 1: GridStar® Flow Chemistry

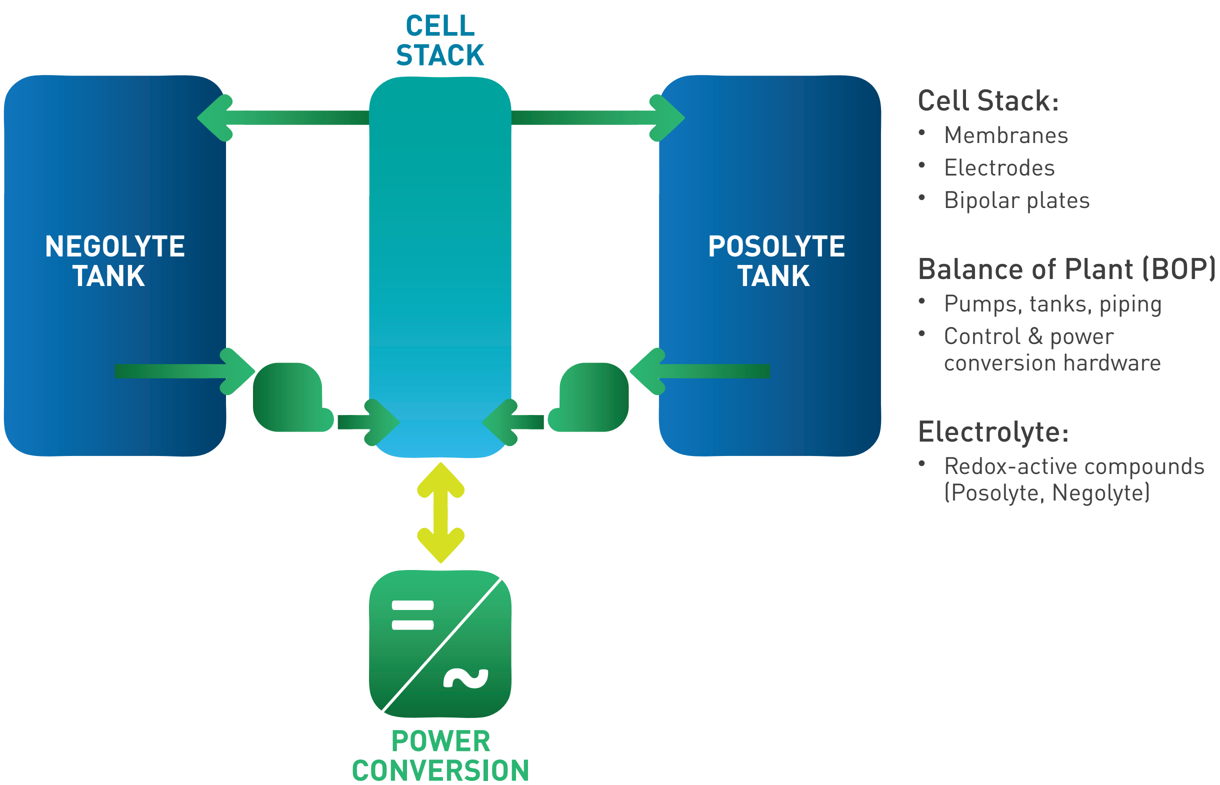


for tailoring the physical and electrochemical properties of the battery to achieve many desirable product attributes simultaneously. The physical and electrochemical properties of the electrolytes have been designed to optimize battery performance and total cost of ownership.

BENEFITS OF GRIDSTAR® FLOW, COORDINATION CHEMISTRY FLOW BATTERY

- **Long-Duration, High-Cycle Requirements and High Rest State-of-Charge**
  While it can operate at short charge-discharge durations, the system is optimized for applications requiring six or more hours of duration, high annual cycle requirements and a high rest state-of-charge.

Figure 2: Diagram of GridStar® Flow Battery



- **Robust, Reliable System**
  Factory-assembled power components combined with field assembly of electrolyte tanks achieves 100 MWh scale energy storage with a reduced number of components compared with other systems. This simplifies installation and maintenance, with a goal of improving quality and safety.

- **Durability**
  Designed to be durable for more than 20 years, the GridStar® Flow meets the requirements of long-duration use cases.

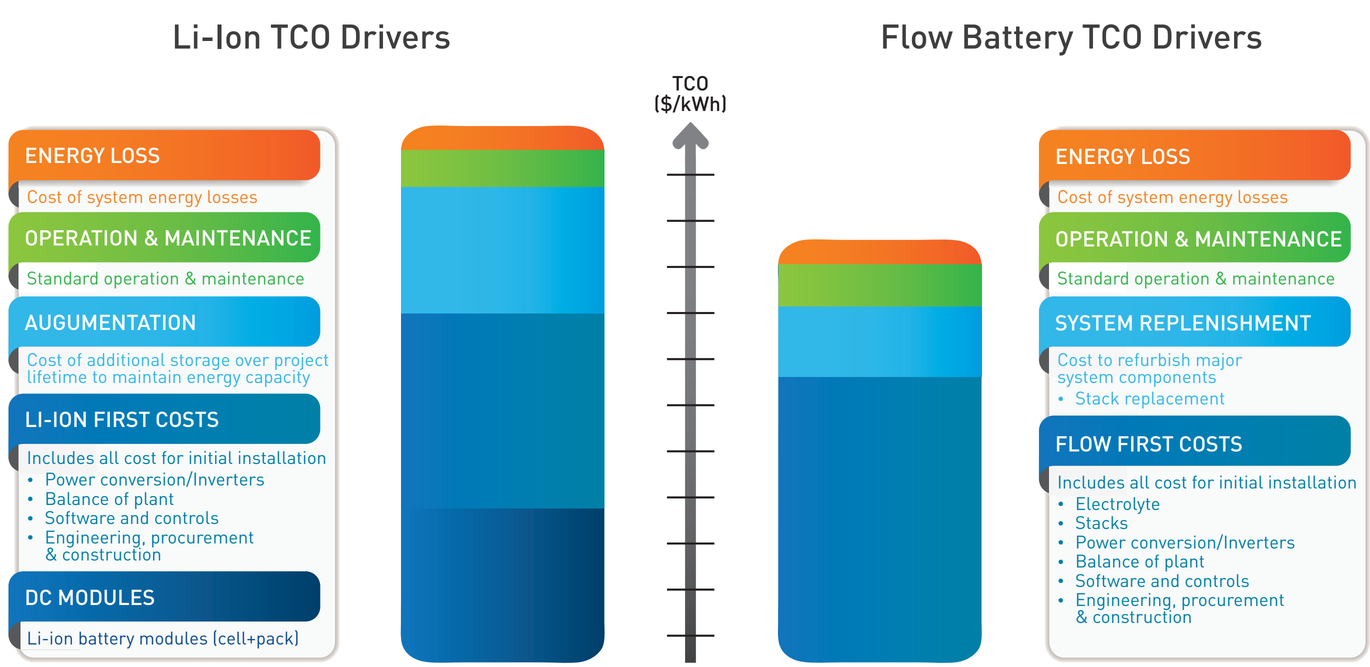
- **Flexibility**
  Whether the application is renewables integration, transmission and distribution deferral, or energy storage for microgrids, future operational needs for an energy storage project are hard to predict. The inherent flexibility of the system meets end-of-life capacity in large part regardless of the duty cycle. This provides customers with valuable optionality.

  – Lack of degradation for full 100 percent depth-of-discharge cycles allows for future operational flexibility, in contrast to some battery chemistries which have limitations in their ability to respond to unplanned types of operation.

  – Operators can increase just energy capacity in the future – due to separation of energy and power. They can add more electrolyte to increase system energy, allowing systems to accommodate future changes of uses cases.

- **Optimized for Total Cost of Ownership**
  Energy storage system selection should be based on the total cost of ownership (TCO) of an energy storage system, not just the first costs. GridStar® Flow systems are optimized to offer low total cost of ownership over the system lifetime. This includes all the costs for initial installation (electrolyte, stacks, power conversion/inverters, software and controls, balance of plant, engineering, procurement and construction) as well as costs associated with system replenishment, operation and maintenance, and energy loss. As depicted in the graphic below, the TCO of a flow battery system can be considerably lower than that of a lithium-ion battery system for many applications.

Figure 3: Total Cost of Ownership Comparison of Lithium-Ion and Flow Batteries.



- **Safe**
  A focus on safety permeates product design choices. For example, in contrast with the highly acidic or caustic chemistries typically employed in flow batteries, the CCFB framework of proprietary coordination complexes results in a low-cost, mildly alkaline aqueous electrolyte solution that is both stable and safe.

Figure 4: Rendering of 10 MW x 10 hr GridStar® Flow System at a wind farm

CONCLUSION: ENGINEERING FOR THE FUTURE OF ENERGY STORAGE

As the evolving grid increasingly requires energy storage with longer duration and higher flexibility, there is recognition of the demand for technologies that can better meet these requirements. Even though lithium-ion has been the most widely used battery technology for stationary applications and will continue to address a variety of needs on the grid – it has significant durability, flexibility, and cost limitations. Coordination chemistry flow batteries have the potential to address many of these limitations by offering a number of critical advantages. With GridStar® Flow energy storage systems, Lockheed Martin Energy delivers a fully-integrated energy storage system designed to optimize battery performance with greater durability, flexibility and value.

Long-Term, Technology-Focused, Global Partner

STABLE, LONG-TERM PARTNER
Lockheed Martin Energy has an over 100-year history and a strong track record of honoring customer commitments.

FOCUS ON CONTINUOUS PRODUCT IMPROVEMENT
Lockheed Martin Energy employs a robust and continuous development process that includes incorporating industry and customer feedback and previous lessons learned into product design and development.

GLOBAL SCALE AND DEPLOYMENT
Lockheed Martin Energy operates in more than 40 countries and has a dedicated global team. SEEload® is deployed at some of the largest electric utilities in the United States, supporting over five million customers with over 500,000 active enrollments across several different DR programs on a single cloud-hosted production instance.

CYBERSECURITY EXPERTISE
With a focus on enhanced cybersecurity, security issues are core for all Lockheed Martin Energy products. As the world's largest defense contractor offering cyber security for customers including the army, Lockheed Martin Energy's history is rooted in designing cyber secure systems.

LOCKHEED MARTIN ENERGY'S APPROACH TO ENERGY STORAGE

From satellites to microgrids, Lockheed Martin has been deploying and developing batteries for various products for over 60 years. Incorporating learnings from these energy storage experiences, Lockheed Martin Energy focuses on designing energy storage systems that are reliable and robust, offer a competitive total cost of system ownership, and can be easily updated or augmented in the future.

Lockheed Martin Energy provides turnkey energy storage solutions for utility, commercial, industrial and military applications. Turnkey installations include upfront project evaluation, analytics, design, configuration and layout, as well as delivery of complete energy storage systems – from batteries, thermal management, power conversion to system controls to maintenance options and a warranty backed by Lockheed Martin Energy.

The company offers a portfolio of products to address different project requirements. Lockheed Martin Energy's GridStar® energy storage solution has two core offerings: GridStar® Lithium for short and medium-duration energy storage and GridStar® Flow for long-duration energy storage.

About Lockheed Martin Energy

Lockheed Martin Energy is a line of business that delivers comprehensive solutions across the energy industry to include energy storage, demand management solutions, microgrids, military energy solutions, nuclear systems and bioenergy generation. For additional information, visit our website: **www.lockheedmartin.com/energy.**

To learn more about the distributed grid and what it can do for your organization, contact:

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Footnotes

[1] T&D World Magazine, "Global T&D Infrastructure Investment to Reach $351bn Per Year by 2026," 31 August 2016, https://www.tdworld.com/overhead-transmission/global-td-infrastructure-investment-reach-351bn-year-2026

[2] UPS Battery Center, "A Brief HIstory of Flow Battery," 20 June 2017, http://www.upsbatterycenter.com/blog/flow-batteries-history/


Energy is everywhere.
It just takes engineering to unlock it.
The grid is changing and we can help your business change with it. From renewable energy integration to storage and resiliency – we're applying innovative technology from the world's leading research and development company to help customers power their future. Because the energy challenge is an engineering challenge. And that's what we do best.
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