GRIDSTAR® FLOW

Introduction

LOCKHEED MARTIN

GRID DISRUPTION

Electric grids are undergoing unprecedented change as intermittent, non-dispatchable renewables continue to expand and displace traditional power generation sources. Growth of electric vehicles and distributed generation, such as rooftop solar, is adding to the variability of supply and demand. Energy storage is the key to reliably, economically, and sustainably balancing the grid, integrating renewables, and enabling transportation and industrial electrification.

BALANCING THE GRID: ENERGY STORAGE

To address these challenges, the grid requires energy storage in multiple durations. The wide use of storage technologies in recent years has provided short, high-power charging and discharging to regulate voltage and frequency and provide other ancillary services. The need for one to four hours of energy storage for peak shifting, smoothing, and short-duration arbitrage has also caused strong growth in battery deployments.

As supply and demand variability increases, so does the need for long-duration storage technologies that can store and discharge for more than four hours. Long-duration storage allows grid participants to manage variability for extended periods, capture value across a wide range of applications and time horizons, and evolve with market needs. Long-duration technologies provide unmatched optionality and flexibility, with key applications including:

- Bulk shifting renewable generation (large amounts of energy for many hours)
- Large-scale transmission & distribution deferral
- Replacing peaking units (traditionally gas turbines and internal combustion engines)
- Day-head energy, real-time energy and ancillaries
- Multi-day and portfolio optimization
- Strengthening resiliency, particularly in microgrids, islands, and military installations

To fulfill these applications, energy storage technology for the long-duration segment needs to be durable, flexible, safe, and able to successfully complete multiple daily charge/discharge cycles at grid scale with an acceptable total cost of ownership (TCO). Unfortunately, current storage technologies do not possess these attributes.

LITHIUM-ION

Lithium-ion (Li-ion) is today's most rapidly growing battery technology; however, it is challenged by significant capacity degradation in high-cycling environments. This degradation requires oversizing and augmentation, leading to increased TCO. Since Li-ion batteries have a fixed power-to-energy ratio, long-duration applications result in oversizing and derating of power capacity, further increasing costs. Due to these durability and power-to-energy limitations, the Li-ion value proposition breaks down for long-duration, high-cycling projects. We believe Li-ion batteries are best suited for applications of four hours or less.

PUMPED HYDRO

Pumped hydro has historically accounted for the largest share of grid-scale storage technology. However, owing to the technology's sheer scale and complexity, new pumped hydro projects face significant challenges and risks in siting, permitting, and construction. Because pumped hydro's scale typically requires facilities to be located far from dense load centers and the localized points of congestion – where storage can be most effective – its geographical constraints limit potential value.

FLOW BATTERIES

Unlike sealed batteries, redox flow batteries deconstruct battery architecture and increase 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 or convert energy stored in the electrolyte to electricity. The power rating of the battery is determined by the quantity of cell stacks, and the energy capacity is determined by the quantity of electrolyte.

RENDERING: 10 MW_{AC} , 100 MWh GridStar Flow installation consisting of five 2 MW_{AC} ESUs coupled together

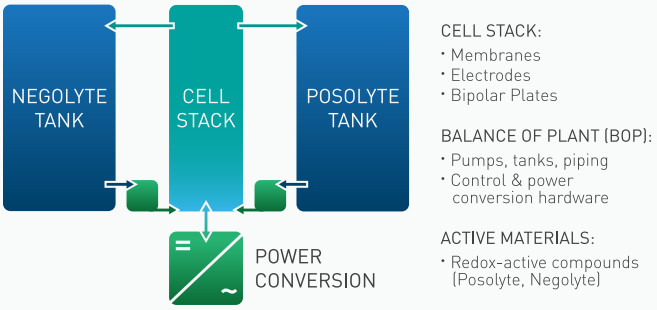
[1]TCO is the long-term cost of owning an asset based on the initial purchase price and the operation and maintenance costs accumulated over the asset's lifetime.

Redox flow batteries have the potential to address many of the limitations of existing battery architectures by offering several critical advantages:

- High-cycling capability, meeting a wide range of applications
- Low degradation under high cycling, meeting the durability needs of the long-duration segment
- Separation of power and energy enables tailoring the battery to each project's needs
- Low marginal cost of energy capacity, enabling cost-effective durations of 6-10+ hours
- 20-year life with low maintenance, reducing TCO

Current flow battery chemistries include vanadium, zinc iron, iron chloride, and zinc bromine. However, they are challenging to implement on a large scale due to difficulties with cost and availability of raw materials, siting, balance of system costs, and technical issues related to the various chemistries.

REDOX FLOW BATTERY ARCHITECTURE



THE LOCKHEED MARTIN SOLUTION

Lockheed Martin has developed and implemented energy solutions since 1933. Recently, we've focused on innovating energy storage to address the new, disruptive challenges faced by the grid. We have found that while current technologies won't meet the future needs of the long-duration segment, flow battery technology has the potential to do so.

GRIDSTAR FLOW

Lockheed Martin is commercializing a new flow battery technology – GridStar Flow. Unlike other flow batteries, GridStar Flow is a patented technology based on the principles of coordination chemistry, offering a new electrochemistry consisting of engineered electrolytes. The electrochemical properties of the electrolytes have been designed to optimize battery performance at a competitive TCO. The result is a flow battery that meets what the long-duration market requires.

RENDERING: GridStar Flow

GRIDSTAR FLOW PROPERTIES

- Durability: While it can operate at short charge-discharge durations, the system is optimized for applications requiring six or more hours of discharge duration and high annual cycle requirements. GridStar Flow achieves 100% depth-of-discharge without degradation for a design lifespan of 20 years.
- Flexibility: Power and energy are decoupled, providing customers the flexibility to customize the system to their specific needs. This flexibility optimizes first costs and allows GridStar Flow to evolve with market needs.
- Optionality: Engineered to respond rapidly, GridStar Flow is uniquely capable of providing a wide range of products for extended periods of time. The rapid response time combined with GridStar Flow's high cycling ability, resistance to degradation, and long duration, allows operators to switch between applications over any given time period – targeting known peaks or events as needed. For example, GridStar Flow can move seamlessly between renewables integration, sub-hourly energy arbitrage, operating reserves, and excess energy absorption in the course of a single operating day. This optionality provides operators maximum revenue opportunities.
- Locational Flexibility: GridStar Flow's footprint is competitive with other battery technologies, allowing it to be sited in a variety of environments.
- Safety: The use of aqueous electrolytes results in a nonflammable, noncorrosive, stable, and safe solution.
- Competitive Total Cost of Ownership: GridStar Flow systems are optimized to offer competitive TCO over the system lifetime. GridStar Flow's TCO includes all the costs for initial installation, as well as those associated with system replenishment, maintenance, and energy loss.

LOOKING FORWARD

Lockheed Martin is building the first commercial GridStar Flow system (500kW, 2.5-MWh), which will be installed in Andover, Mass. To learn more about GridStar Flow, visit **www.lockheedmartin.com/gridstarflow**.

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Your Mission is Ours.®

Let's Talk

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