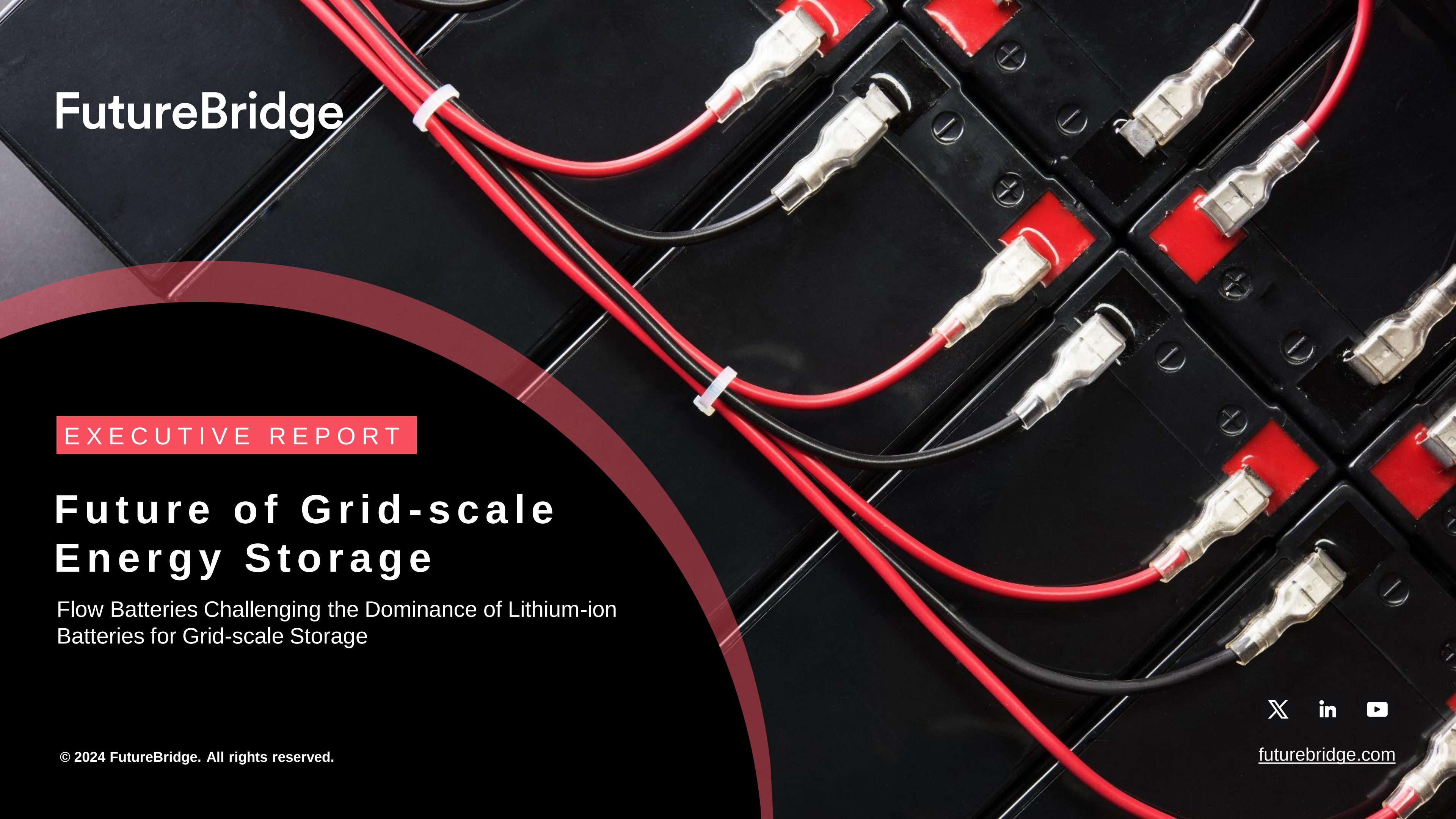


FutureBridge

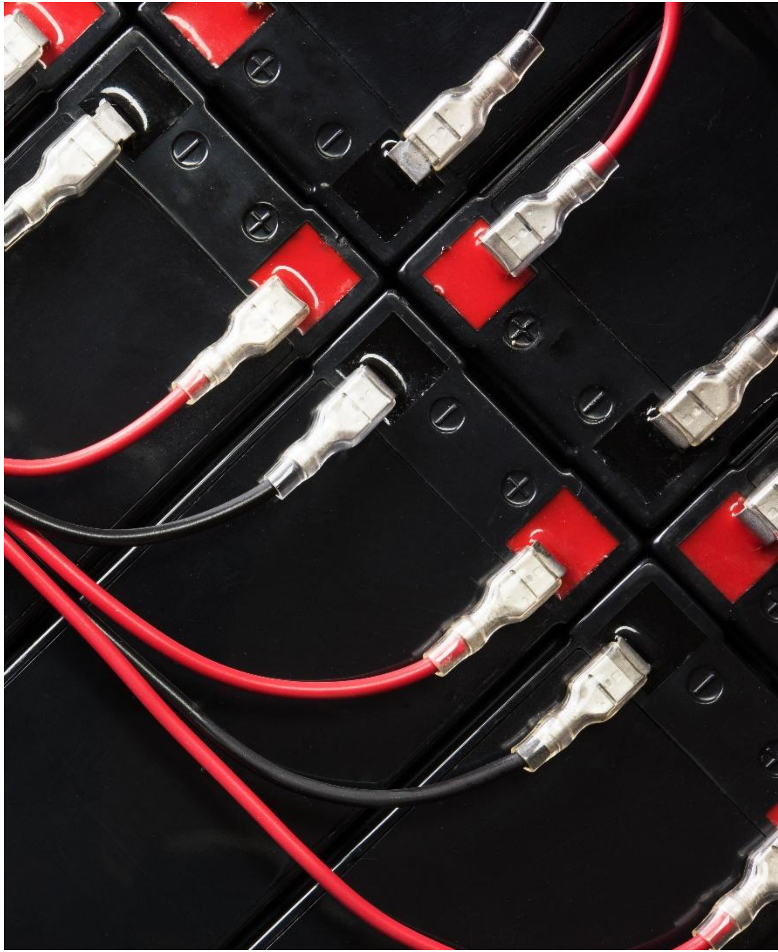
EXECUTIVE REPORT

Future of Grid-scale Energy Storage

Flow Batteries Challenging the Dominance of Lithium-ion Batteries for Grid-scale Storage

futurebridge.com

CONTENTS



EXECUTIVE SUMMARY

FLOW BATTERIES: FUTURE OF GRID-SCALE ENERGY STORAGE

"

For storage durations beyond 4 hours, Li-ion batteries become expensive, making long duration storage technologies like Flow Batteries a more suitable option

- With the massive build-out of renewable resources, the demand for reliable, affordable long-duration energy storage is critical to balance the demand-supply mismatch and ensure grid stability in the near future. Today's dominant energy storage technology, lithium-ion batteries, is not well-suited for these long-duration applications
- Flow batteries, particularly Vanadium Redox Flow Batteries offer several advantages over lithium-ion batteries, including lower scaling cost due to the decoupling of energy and power capacities, longer duration of storage, minimal degradation over time, and improved safety
- Vanadium Redox Flow Batteries face challenges related to supply chain disruptions and fluctuating prices of vanadium mineral. These supply disruptions and price volatility can hinder their competitiveness with lithium-ion batteries in terms of cost-effectiveness
- To enhance the competitiveness of flow batteries for long-duration energy storage, innovations in electrolyte chemistries and novel structural designs are needed. This includes increasing energy density, exploring alternative materials, and reducing system costs to make flow batteries a more attractive option for grid-scale energy storage

Grid Challenges in a High-Variable Renewable Energy Future

With the anticipated rise in variable renewable energy within the global energy mix, there is a growing need for storage solutions that extend beyond the short-duration capabilities of lithium-ion batteries. Lithium-ion becomes expensive for long duration energy storage

Key Challenges for the grid with high variable renewable energy penetration (solar and wind)

Demand-Supply mismatch

VRE are inherently intermittent and are affected by weather and seasonal fluctuations

Inadequate grid infrastructure

Grid expansion has not kept pace with the capacity surge, leading to grid congestion
Solution: Grid expansion

Reduced grid inertia

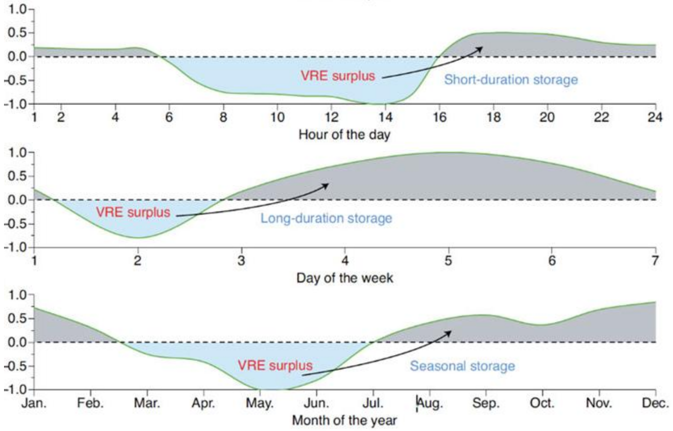
Moving away from spinning energy sources can affect grid frequency
Solution: Grid-forming inverters, Flywheels

Traditionally, the short-duration gap has been addressed by dispatchable peaker gas power plants or hydroelectric power and more recently by lithium-ion battery energy storage systems to some extent

Intraday Mismatch (<10 hours)

Multi-day mismatch (10 to 100 hours)

Seasonal mismatch (>100 hours)



Li-ion is a suitable technology only for less than 4 hours storage

Li-ion becomes prohibitively expensive

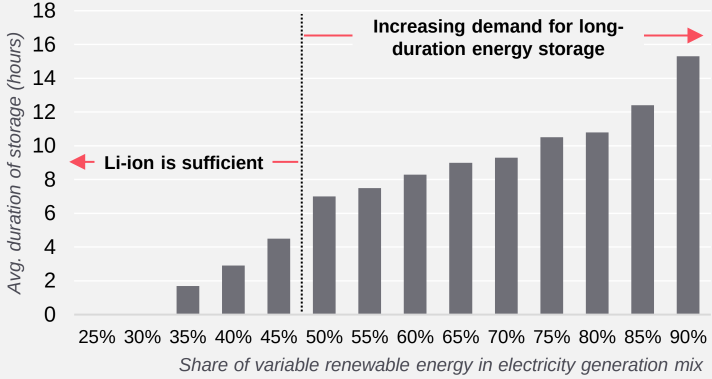
Li-ion storage is not possible

Why is Long Duration Energy Storage Required?

As variable renewable energy continues to grow in the global generation mix, the imbalance increases significantly, necessitating solutions beyond grid management, demand-side management, and short-duration energy storage (less than 4 hours)

The global variable renewable energy share is expected to increase rapidly, leading **to massive curtailments, grid blackouts, and frequent negative energy hours** if long-duration energy storage is not deployed.

Variable renewable energy share and storage duration requirements



Source: Nature, IDTechEx

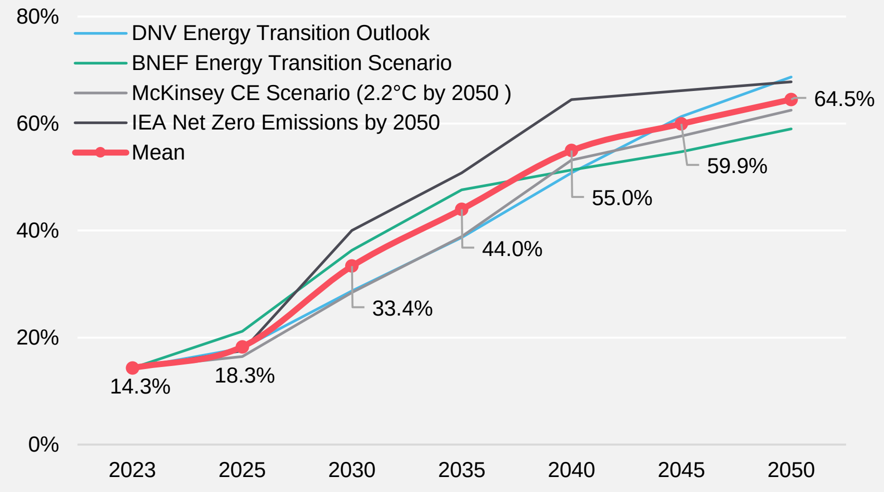
Market Outlook

The flow battery market is expected to grow after 2035 as variable renewable energy sources increase to over 40% of the global electricity mix. Regions with high solar and wind power penetration will likely see high demand for flow batteries

The projected rapid growth of variable renewable generation

Under various scenarios, the share of variable renewable generation is expected to increase rapidly from 14.3% in 2023 to between **39% to 50% by 2035** and **59% to 68% by 2050**

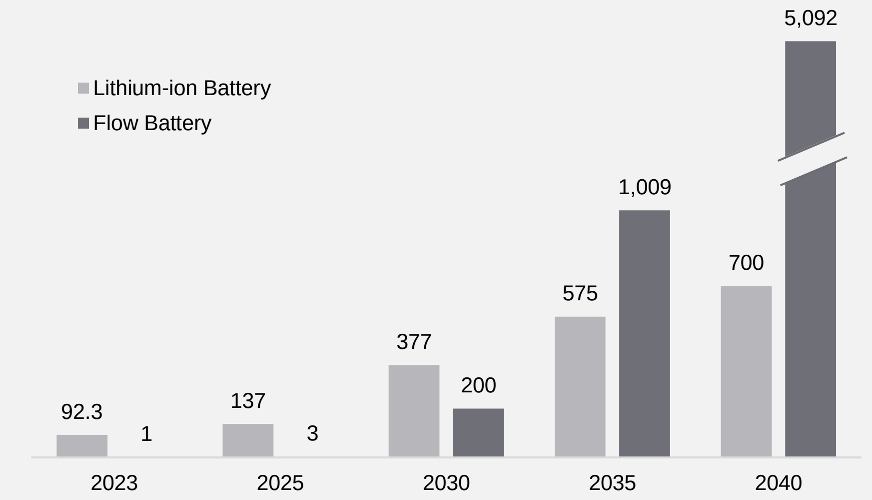
Projected share of variable renewable electricity in the global generation mix till 2050



Flow batteries to overtake Lithium-ion batteries from 2035

Flow batteries are poised to become a dominant force in the energy storage market by **2035**, particularly for long-duration energy storage (LDES) applications

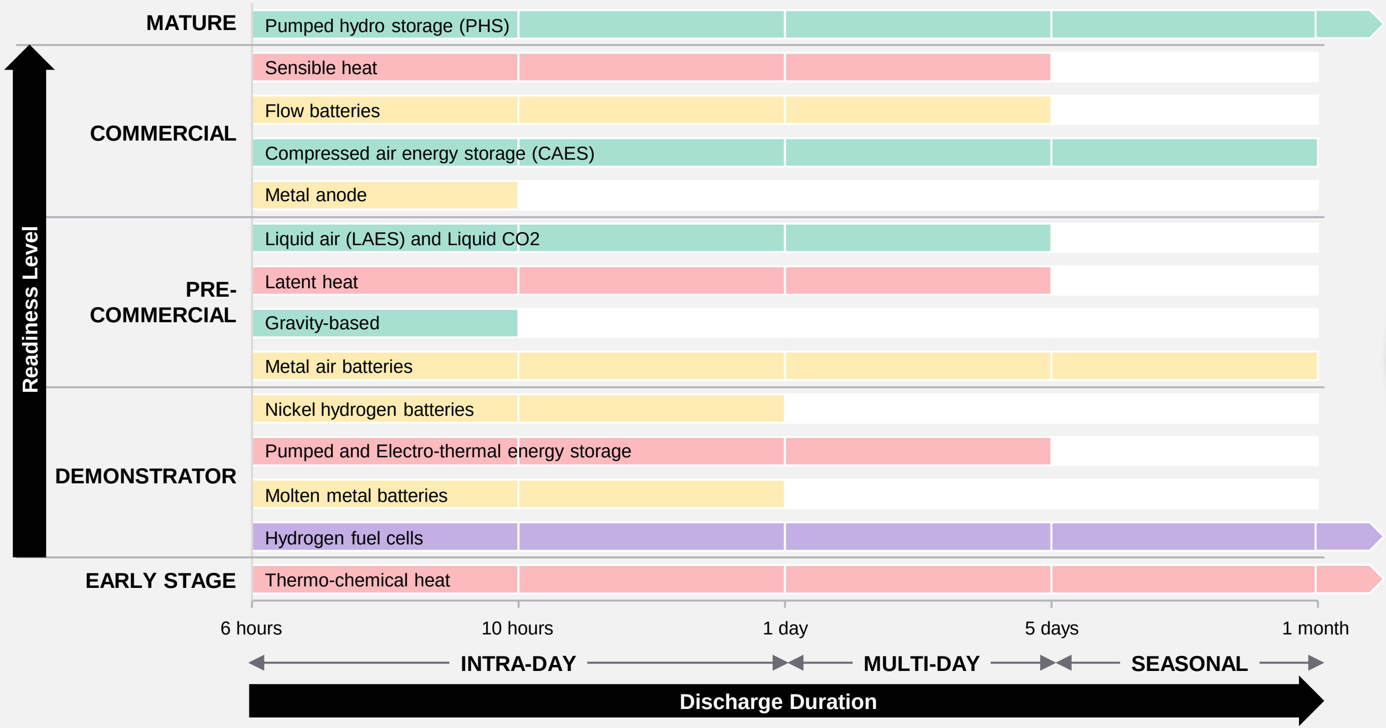
Annual grid-scale energy storage demand (GWh)



Source: DNV, BNEF, McKinsey, IEA, NREL, McKinsey

Long Duration Energy Storage

Flow batteries and thermal energy storage technologies are best suited for multiday and seasonal energy storage, balancing supply and demand in the power grid



According to the US Department of Energy, **long-duration energy storage (LDES)** is any storage technology that can store energy for 10 hours or more. However, LDES definitions can vary vastly, with the minimum threshold ranging between 4 to 10 hours >>

While **pumped hydro** and **compressed air energy storage** offer potential for large-scale energy storage their geographical limitations can be restrictive.

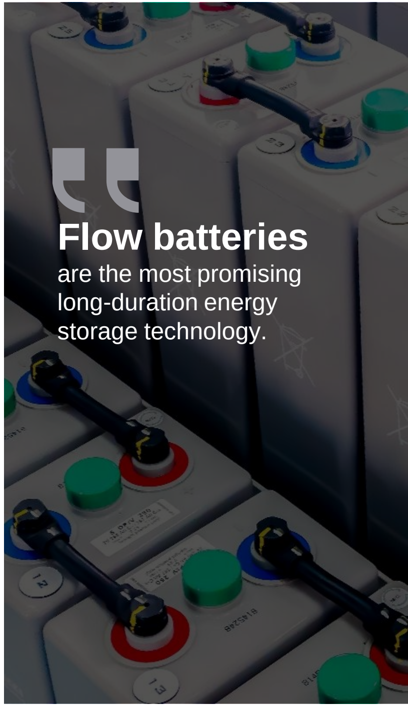
Sodium-ion batteries and **Nickel-hydrogen batteries**, though promising, face challenges in high discharge rates and costs for long-duration energy storage applications

Source: Future Cleantech Architects

Comparison of long-duration energy storage technologies

Flow batteries are the most promising options among alternative energy storage technologies explored for long-duration energy storage due to their low cost, high technical maturity, and relatively high round-trip efficiency

	Weightages	20%	20%	20%	20%	20%		
	Parameters	**Round-trip efficiency** (%)	**Self discharge rate** (%/month)	**Technology Readiness**	**System Capital Cost** (US$/ kW)	**Levelized Cost of Storage** (US$/MWh)	**Weightage Score** (Maximum: 5)	**Rank**
		>80 5 **40-80** 3 **<= 40** 1	**<1** 5 **1 to 15** 3 **>= 15** 1	**<= 8** 5 **=7** 3 **>= 6** 1	**<= 400** 5 **400 to 700** 3 **>= 700** 1	**>= 200** 5 **200 to 400** 3 **>= 400** 1		
1	**Thermal Storage**	25 - 34	30	9	400 - 700	50-200	**3**	**4**
2	**Gravity storage**	70 - 80	0	7	585	470	**3.3**	**3**
3	**Pumped and electro thermal**	55 - 60	1 -3	6	700 -1500	130	**2.8**	**6**
4	**Liquid air energy storage**	50 - 60	23	7	240 - 480	348	**3**	**4**
5	**Flow Batteries**	70 - 80	0.1	9	370	270	**4.2**	**1**
6	**Metal-air Batteries (Fe, Zn)**	50	30	5	500 - 1000	150	**2.2**	**7**
7	**Molten-metal batteries**	75 - 80	0.5	6	180 - 250	30 -100	**4.1**	**2**
8	**Hydrogen-Fuel cell**	31-40	0.1 (compressed) 30 (liquid tank)	5	1500 - 4500	400	**1.3**	**8**

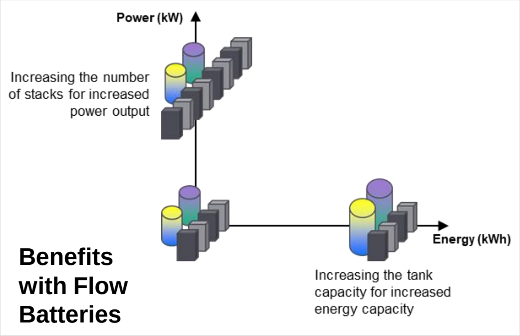


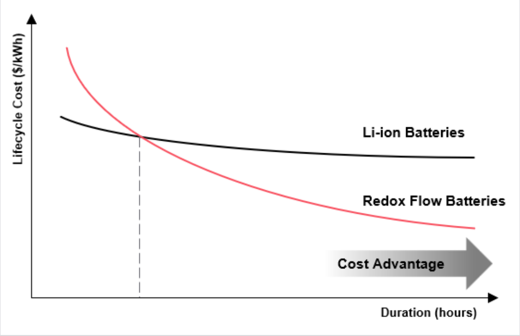
Source: FutureBridge Analysis

New Opportunities with Flow Batteries

Flow batteries offer the opportunity to reduce costs and enable flexible scaling for long-duration storage through their distinct architecture, which decouples energy storage capacity from the power delivery rate

Decoupling Energy and Power





COST ADVANTAGE OVER LI-ION

- Flow batteries have a distinct architecture that allows for the decoupling of energy and power
- The volume of the electrolyte tank determines the energy storage capacity while the power (rate of energy delivery) is determined by the number of electrochemical cells
- This decoupling of energy storage and power delivery leads to lower costs over longer durations and thus allows for more flexible scaling

Other Services that Flow Batteries are suitable

	Services	Lithium-ion Battery	Vanadium Redox Flow Battery	Zinc Bromine Flow Battery
Grid Services (Generation, Transmission, and Distribution)	Enhanced Frequency Response	✓	=	=
	Frequency Containment	✓	=	=
	Frequency Restoration/ Secondary Frequency Control	=	✓	=
	Energy Shifting/ Load Levelling	=	✓	=
Behind-the-meter (Buildings, Industry, and Residential)	Maximizing self-production and self-consumption of electricity	✓	✓	✓
	Particular requirements in power quality	✓	✗	✗
	End-user peak shaving	✓	=	✗
	Time-of-use energy cost management	✓	✓	✓

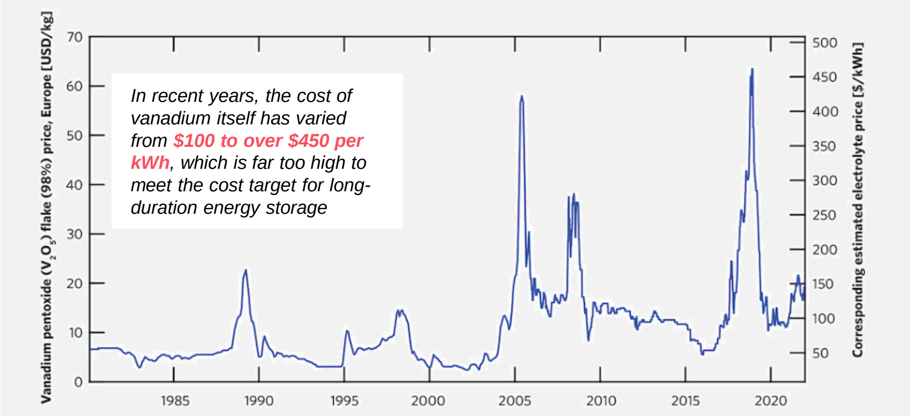
Source: Sumitomo Electric and FutureBridge Analysis

Understanding the Different Chemistries of Flow Batteries

Although vanadium is a perfect material for flow batteries its high cost and price volatility have led to the development of alternate flow battery chemistries

Challenges with Vanadium Flow Batteries: high and volatile prices

Vanadium is a perfect material for flow batteries. Its ability to exist in multiple oxidation states: V^{2+}, V^{3+} (negative electrolyte), and VO^{2+}, VO_2^{+} (positive electrolyte) avoids the issue of cross-contamination between electrolytes while its extremely high chemical stability avoids degradation for years. Other favorable properties include non-flammability and almost no self-discharge.



However, Vanadium production is heavily concentrated in Russia, China, and South Africa, creating supply chain risks due to geopolitical tensions. This concentration leads to high and volatile prices, hindering the widespread adoption of vanadium flow batteries.

Hence diversifying to alternate chemistries is necessary to de-risk mass flow battery deployment.

Source: MIT Energy Initiative

Alternate Flow Battery Chemistries

	Zinc-Bromine	Iron-Chromium	Hydrogen-Bromine	Aqueous Organic
Electrode Materials	Carbon (both)	Graphite (both)	Graphite (both)	Graphite (both)
Electrolyte	Zinc bromide	Iron chloride and chromium chloride	Bromine in water	Quinones, ferrocene derivatives
Energy Density (W-h/kg)	40-60	40-60	80-100	50-100
Lifecycle (cycles)	2000-10000	10000+	5000-20000	1000-5000
Key Players/ Startups	PRIMUS POWER, redflow	EnerVault, REDOX	elestor	QUINO ENERGY, cmblu

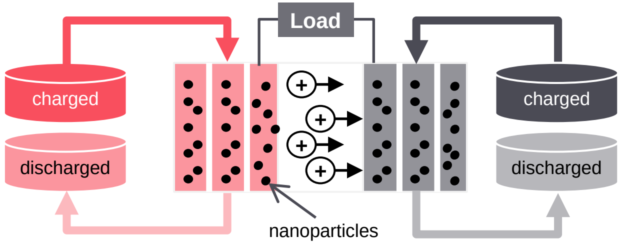
Innovations in Flow Batteries

Nanoelectrofuel flow batteries combine the energy density of solid-state batteries with the flexibility of liquid-based flow batteries, while membrane-less flow batteries lower costs by eliminating the need for membranes.

Ultra-high density flow batteries – Nanoelectrofuel flow battery

Nanoelectrofuel battery is a novel type of flow battery that uses an energy-dense nanofluid, a suspension of lithium, or any other transition metal oxide nanoparticles in the liquid electrolyte to significantly boost the energy density to up to 150 Wh/kg. The nanoparticles can compose up to 80% of the electrolyte weight while maintaining a low viscosity for easy pumping.

Influit Energy, a spinout of Argonne National Laboratory and Illinois Institute of Technology, is developing such a battery with a targeted energy density between 550 to 850 Wh/kg.



Energy Density	Current	2030 Target
	150 Wh/kg	550-850 Wh/kg
	Compared to 20 Wh/kg for present flow batteries	Compared to 160-200 Wh/kg for Li-ion

Cost	Current	2030 Target
	$130 / kWh	$50-$80 / kWh

Source: IEEE Spectrum, Royal Society of Chemistry

Membrane-less flow batteries

Flow batteries use membranes to separate the two electrolyte solutions and avoid mixing. However, these membranes are very expensive components, often fragile, and contribute significantly to the overall cost of the system.

Membrane-less flow batteries leverage a variety of techniques to avoid a physical membrane and reduce the cost of flow batteries, a few of which are:

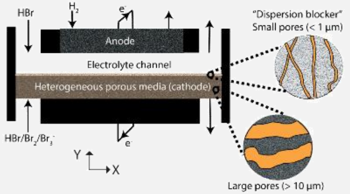
1. **Microfluidic flow**

   Unlike turbulent flow in bulk electrochemical cells, microchannel flows are extremely laminar (low Reynolds number) and vicious, which avoids electrolyte mixing even when in physical contact.

2. **Flow through Porous Electrodes**

   In this architecture, heterogenous porous electrodes enable ion diffusion without fluid mixing, eliminating the need for an ion exchange membrane.

Porous electrode HBr flow battery



3. **Immiscible liquid bridges**

   In this setup, the membrane is replaced with an electrolyte solution that is mutually immiscible with the two half-cell solutions, providing high Coulombic efficiency (99%) and capacity retention (~95%) over 24 hours

It is crucial for Membrane-less flow battery architectures to minimize reactant crossover while maintaining exceptional power density and capacity retention

Vanadium Redox Battery in Action: Case Examples

Sumitomo Electric, ESS Inc., Invinity Energy Systems, and Rongke Power are a few companies that are advancing the commercialization of flow batteries

Hokkaido Electric Power Network Project

Players: Hokkaido Electric Power Network, Inc., Sumitomo Electric

Location: Minami-Hayakita Substation, Japan

Power and Energy: 17MW x 3h (51MWh)

Application: Enhancing grid control for new 162MW wind turbines (e.g., Frequency regulation, Renewable generation smoothing)

Operational since April 2022

Operation term: 21 years

World's largest redox flow battery project in Dalian

Players: State Grid Corporation of China, Rongke Power Co., Ltd.

Location: Dalian, Liaoning Province, China

Power and Energy: 200MW x 4h (800MWh)

Application: Grid-scale energy storage for renewable integration, peak shaving, frequency regulation, and improving grid reliability

Operational since October 2022 (1st phase)

Operation term: 25 years

Yadlamalka Energy Storage Project

Players: Yadlamalka Energy, Invinity Energy Systems

Location: South Australia, Australia

Power and Energy: 2MW x 4h (8MWh)

Application: Renewable energy integration, grid stabilization, peak shaving

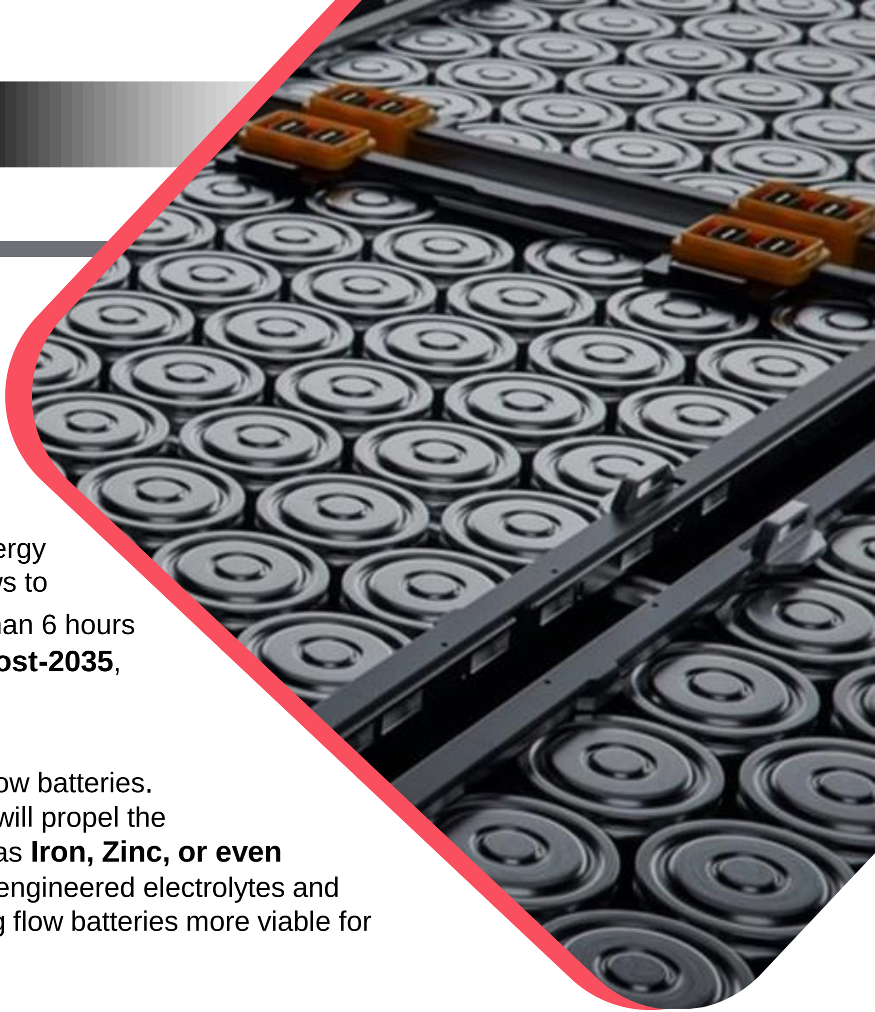
Operational since December 2023

Operation term: 25 years

Source: Sumitomo Electric, ARENA, China Energy Storage Alliance

FutureBridge Perspective

Will Flow Batteries challenge the dominance of Lithium-ion batteries for grid-scale storage?



We believe flow batteries will be the ideal energy storage technology for long-duration energy storage applications for the grid

With a global variable renewable generation (solar and wind) penetration of 14.3%, there is no immediate need for long duration energy storage. However, as the share of variable renewable generation grows to around 40-50% by **2035**, there will be an increasing need for more than 6 hours of storage. Therefore, **flow batteries will become more relevant post-2035**, with a steady increase in capacity leading up to that time

Vanadium redox flow batteries are the most favorable type of flow batteries. However, it faces challenges due to its high price and volatility, which will propel the development of alternate chemistries that use cheaper minerals such as **Iron, Zinc, or even Aqueous Organic Electrolytes**. Additionally, innovations like nano-engineered electrolytes and membrane-less cell designs can further reduce costs and bulk, making flow batteries more viable for use in mobility applications.

Thank you

NORTH AMERICA

55 Madison Ave, Suite 400
Morristown, NJ 07960
USA

EUROPE

Stadsplateau 7
3521 AZ Utrecht
The Netherlands

Holborn Gate, 330 High Holborn
London, WC1V 7QH
United Kingdom

ASIA PACIFIC

Millennium Business Park
Sector 3, Building # 4, Mahape
Navi Mumbai 400 710
India

www.futurebridge.com

FutureBridge