Li-ion battery
&
Redox Flow battery

CH5106 L-19-AD

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A battery is a device that stores chemical energy and converts it into electrical energy through electrochemical reactions. It typically consists of two electrodes

Anode: (negative electrode during discharge)

Cathode: (positive electrode during discharge)

Electrolyte: a medium that allows ions to move between the electrodes.

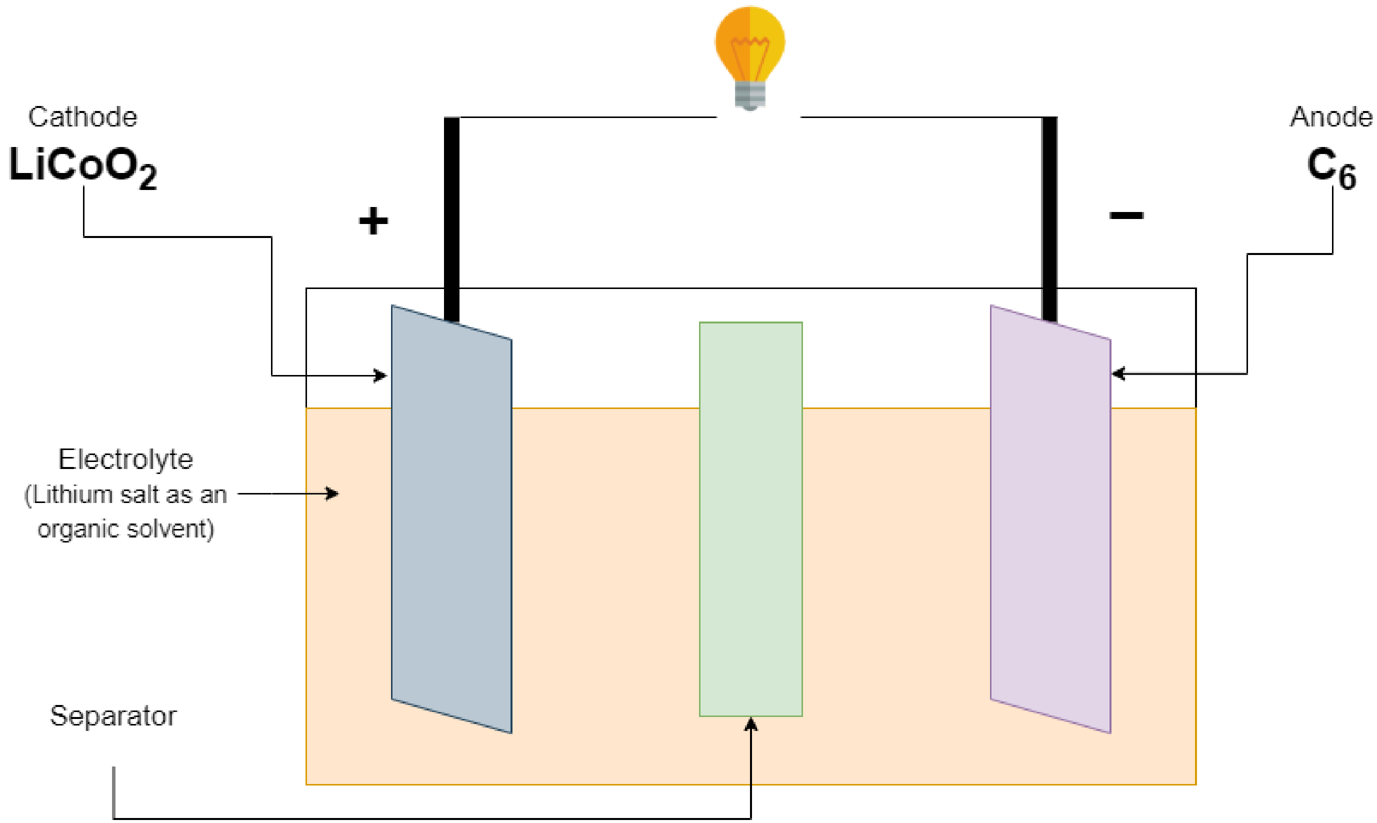
Separator: prevents direct contact between electrodes while allowing ionic flow.

When connected to an external circuit, electrons flow from the anode to the cathode, providing usable electric power.

Batteries can be:

- **Primary (non-rechargeable)** — e.g., alkaline batteries
- **Secondary (rechargeable)** — e.g., lithium-ion, lead-acid batteries

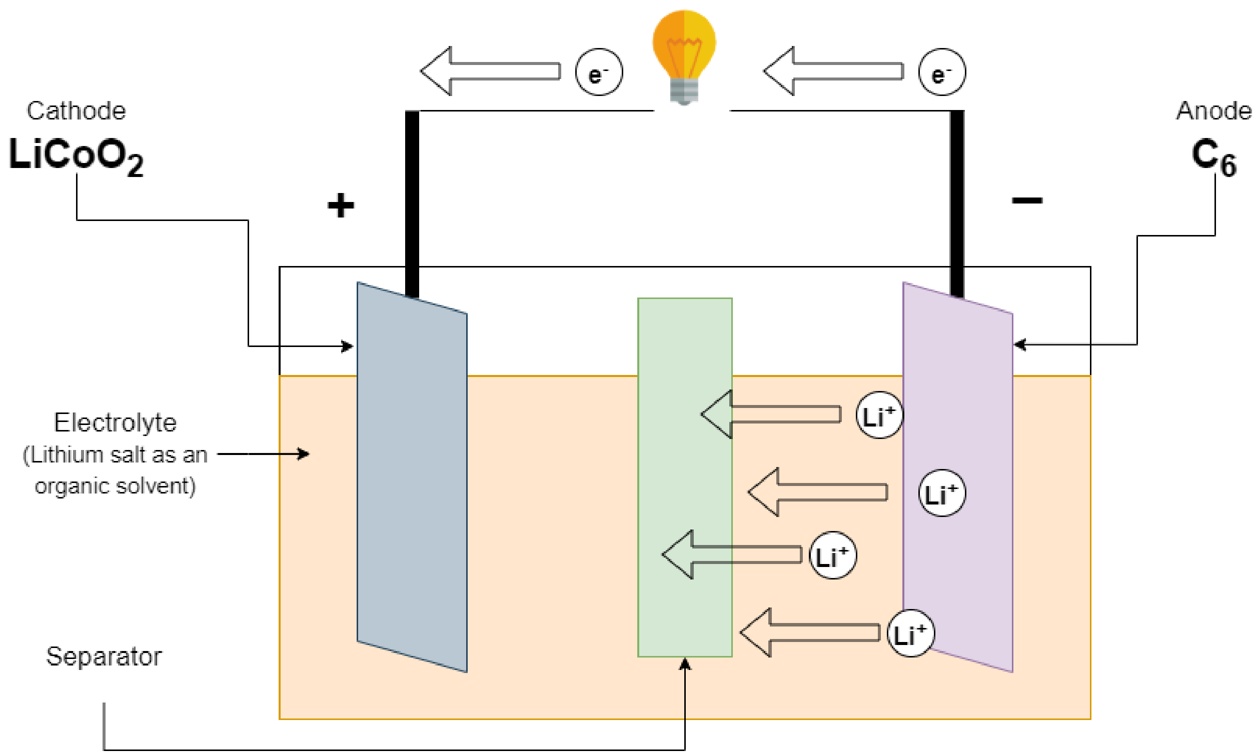
Li-ion batteries: A Lithium-ion battery was developed by Akira Yoshino in 1985. The positive electrode (cathode) is made of lithium cobalt oxide and the negative electrode (anode) is made of graphite. Lithium salt as an organic solvent is used as an electrolyte. A separator is used to separate electrodes



The nominal voltage of the lithium-ion battery is 3.60V. When the battery is in full charge the voltage is about 4.2 V and when the battery is fully discharged the voltage is about 3.0V.

https://www.engineersgarage.com/how-rechargeable-batteries-charging-and-discharging-cycles-work/

Discharging of Li-ion batteries



Reaction at the Negative electrode

$LiC_6 \rightarrow C_6 + Li^+ + e^-$

Reaction at the Positive electrode

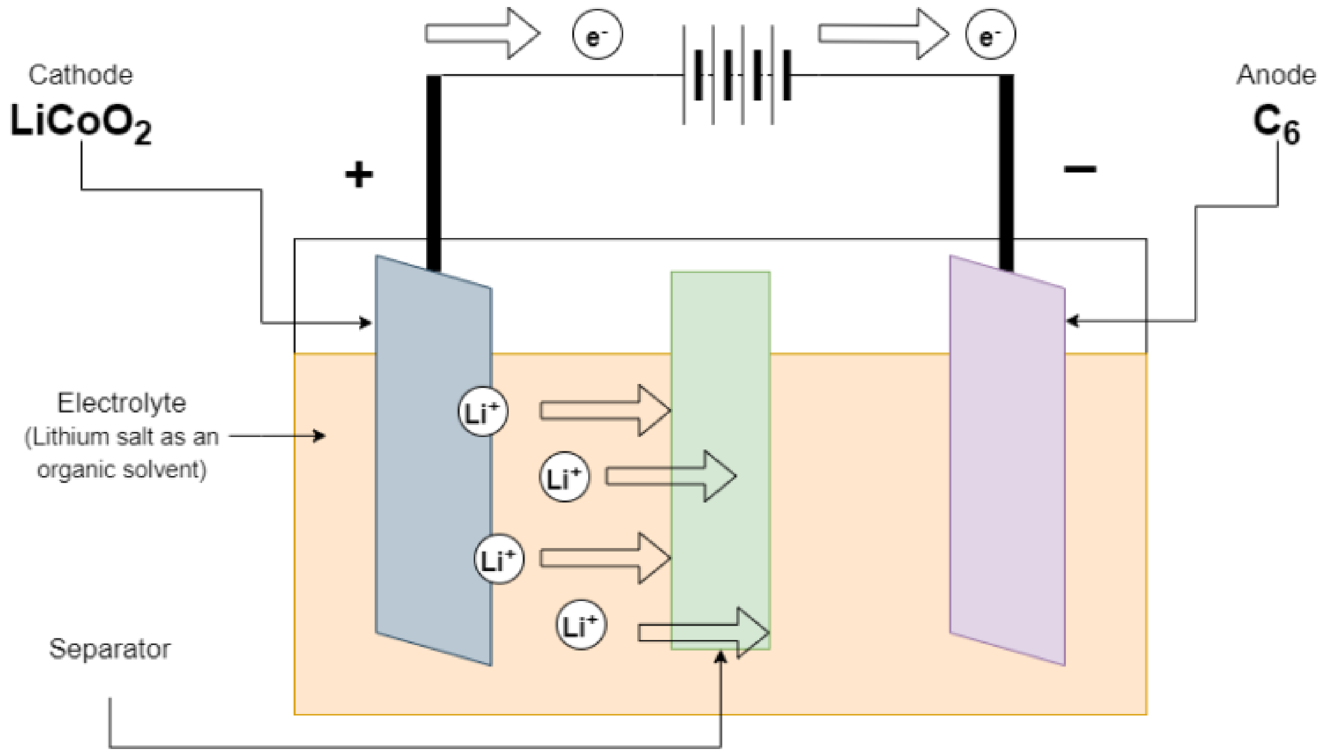
$CoO_2 + Li^+ + e^- \rightarrow LiCoO_2$

Overall Reaction

$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2$

https://www.engineersgarage.com/how-rechargeable-batteries-charging-and-discharging-cycles-work/
https://www.sigmobile.org/pubs/getmobile/articles/Vol19Issue3_1.pdf

Charging of Li-ion batteries



Reaction at the Positive electrode

$LiCoO_2 \rightarrow CoO_2 + Li^+ + e^-$

Reaction at the Negative electrode

$C_6 + Li^+ + e^- \rightarrow LiC_6$

Overall reaction:

$C_6 + LiCoO_2 \rightarrow LiC_6 + CoO_2$

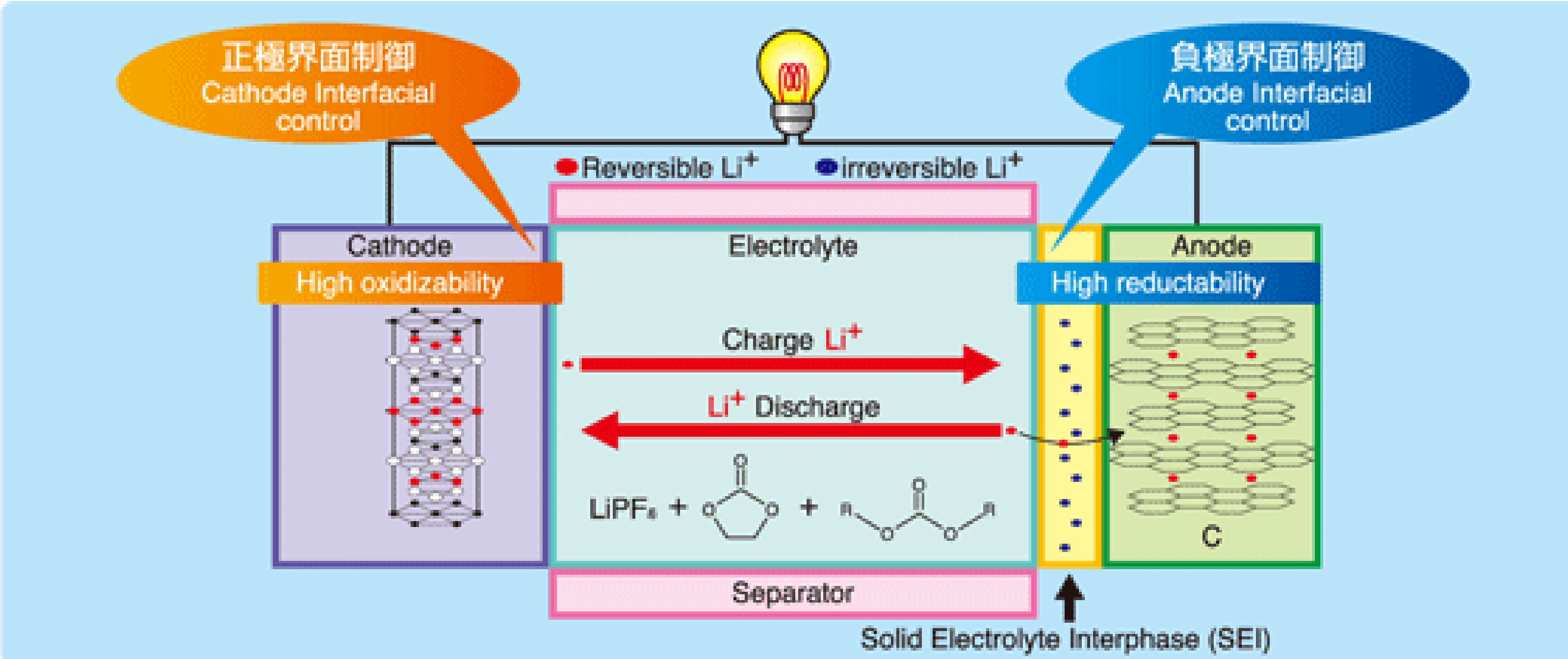
https://www.sigmobile.org/pubs/getmobile/articles/Vol19Issue3_1.pdf

https://www.engineersgarage.com/how-rechargeable-batteries-charging-and-discharging-cycles-work/

Sol-Rite™

MU Ionic Solutions Corporation

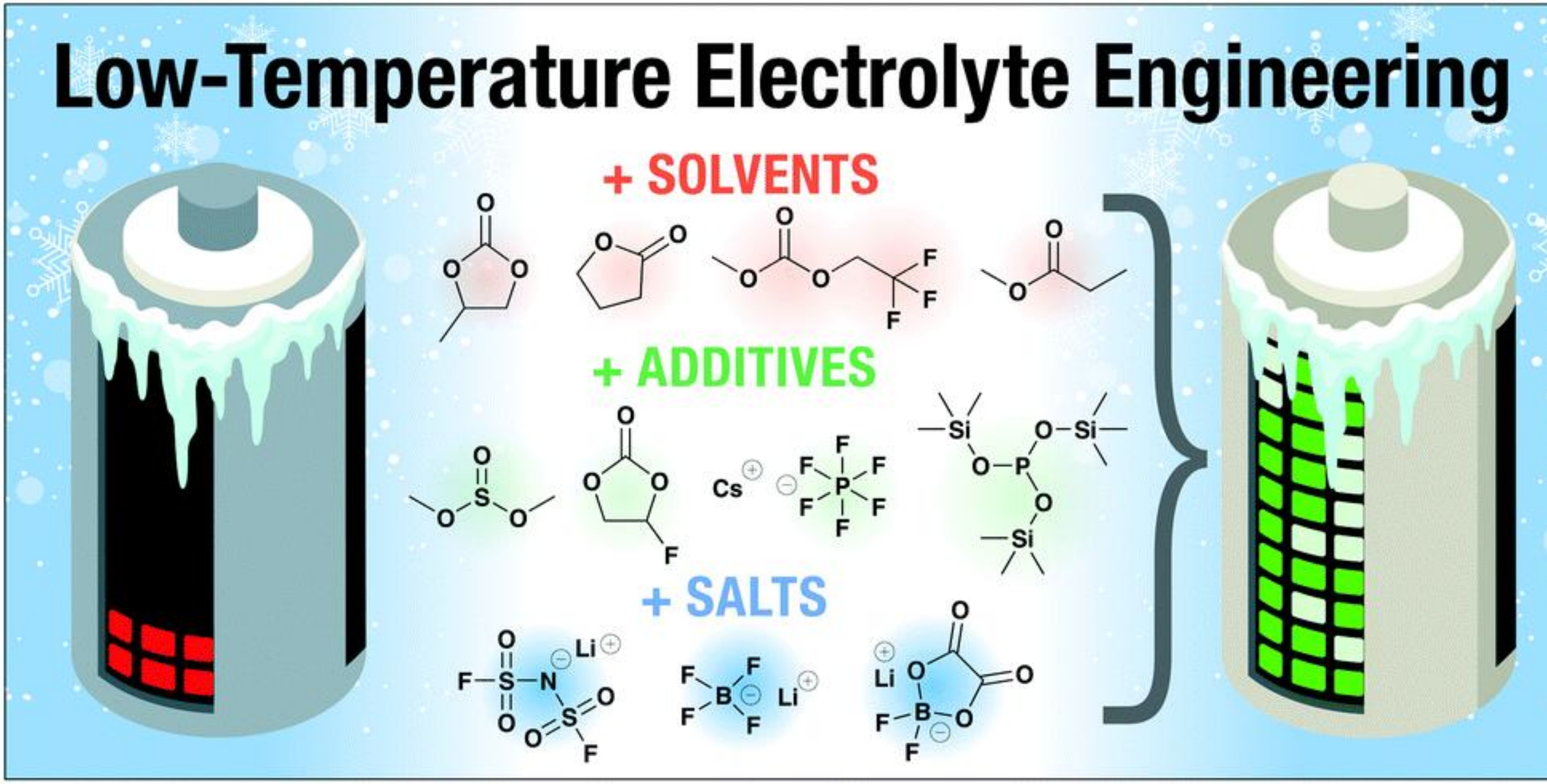
https://www.sigmobile.org/pubs/getmobile/articles/Vol19Issue3_1.pdf



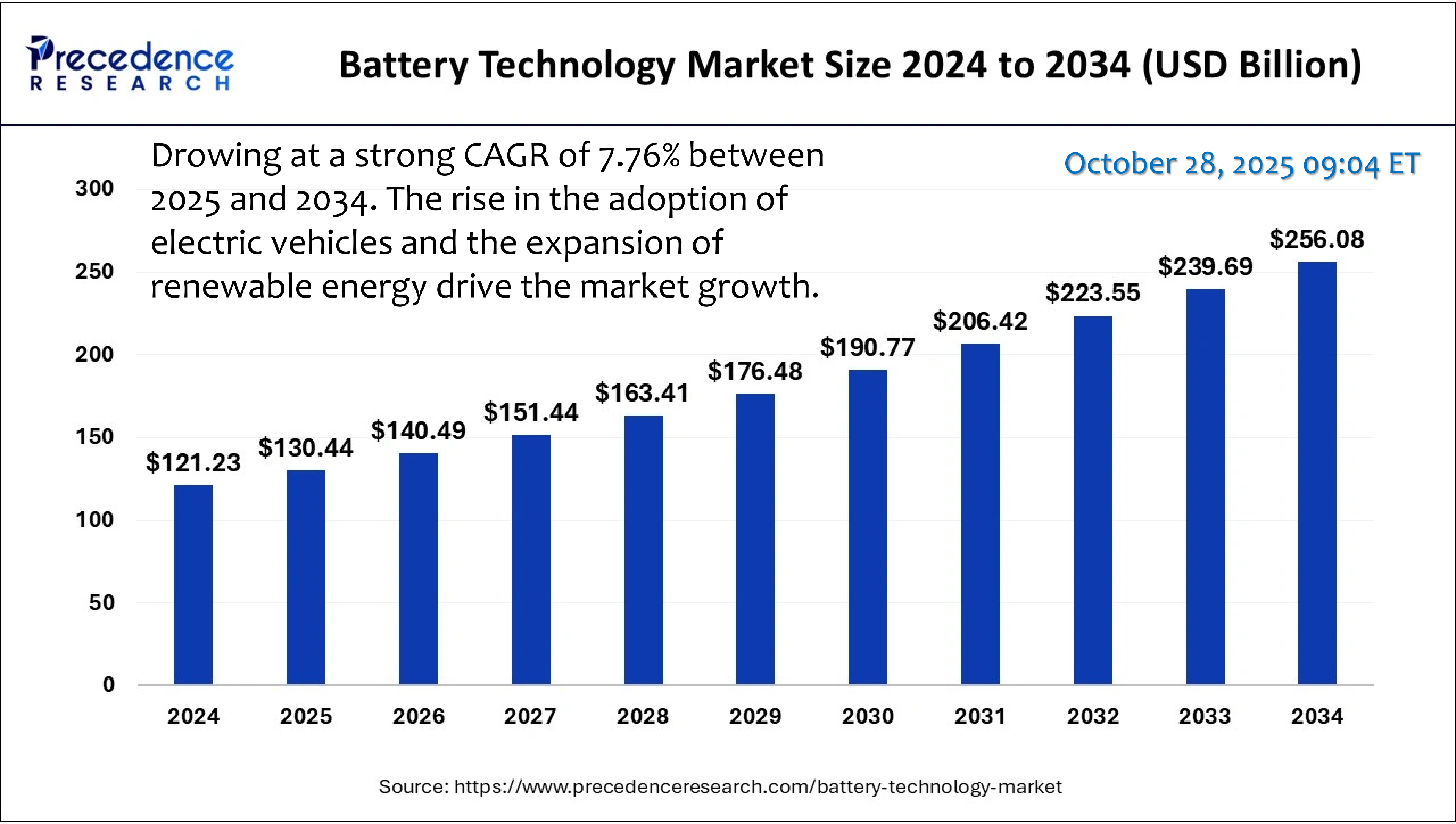
Sol-Rite™ formulated electrolytes in organic solvents, are used for lithium-ion batteries. The formulations are designed to meet the customer needs and to optimize the battery performance.

The formulation mainly consists of organic solvents such as ethylene carbonate and lithium salt electrolytes such as $LiPF_6$. Patented technologies and know-hows are incorporated into the formulations to control the solid electrolyte interface on cathode and anode.

https://www.m-chemical.co.jp/en/products/departments/group/muis/product/1211431_9448.html



Energy Environ. Sci., 2022, **15**, 550-578

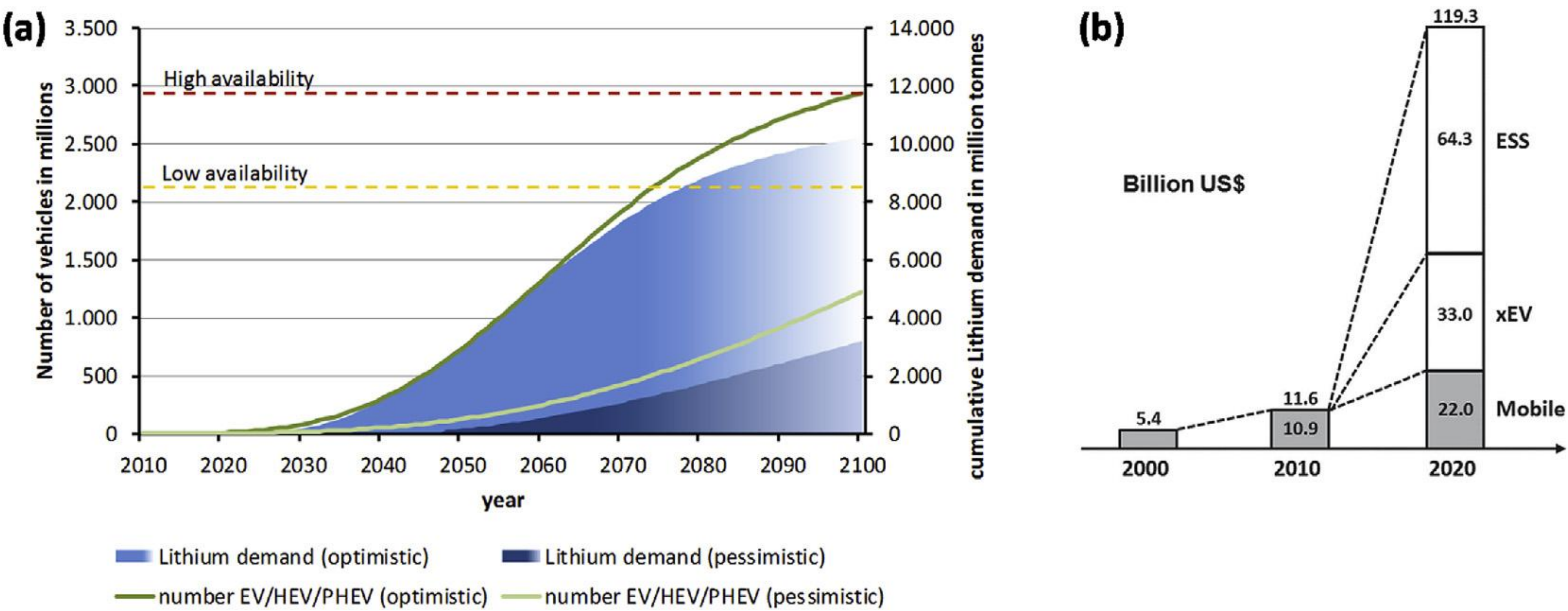


https://www.globenewswire.com/news-release/2025/10/28/3175538/0/en/Battery-Technology-Market-Size-Worth-USD-256-08-Billion-by-2034.html

The Li-ion Batteries (LIBs) are the most advanced technologies for electrochemical storage and conversion and undergoing a market expansion with respect to the increase of the electrical vehicles sales and a range of mobile applications. Although extensive studies have been undertaken in order to increase the energy density and power in LIBs, however, the achieved energy storage capability so far is still not adequate to meet the continuous demand from the growing markets, and keep up with challenges for building “sustainable” batteries in terms of performance/energy density as well as cost-efficiency and safety. LIBs suffer from the rare abundance of Li metal, and the apparent decrease of the price of LIBs in general, owing to mass production, does not justify the decrease of the overall resources involved in LIB components and processes. For more than a quarter century of commercialization, LIBs have been embraced as high energy density and long-cycle-life technology, and consequently dominated portable electronics and rechargeable battery systems for the emerging electric/hybrid vehicles.

Even though this technology is considered as a possible choice for future electric vehicles and grid-scale energy storage systems; one must admit, insufficiency on a global scale of lithium resources and safety factors will strongly limit its further use in large-scale applications

Journal of Alloys and Compounds 817 (2020) 153261



Long-term assessment of lithium availability and demand, and number of electric vehicles (EV, HEV and PHEV) over time. Lithium run out could be expected for low availability and optimistic electric vehicles production; (b) Market expectation of rechargeable batteries. xEV: all electric vehicles such as full (EV), hybrid (HEV) and plug-in hybrid (PHEV) types. ESS: other Energy storage systems as a part of smart grids and renewable energies.

World Mine Production and Reserves: Reserves for Argentina, Australia, Canada, Chile, China, the United States, Zimbabwe, and other countries were revised based on new information from Government and industry sources.

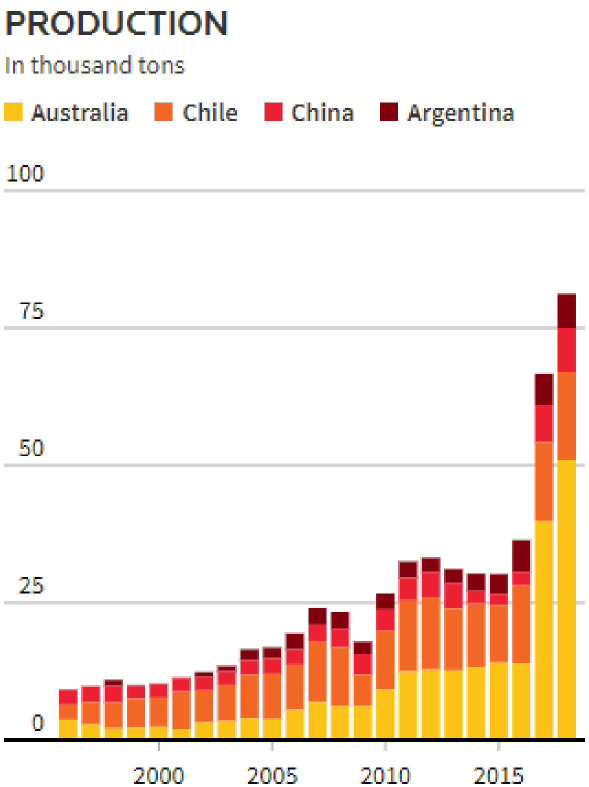
	Mine production		Reserves[5]
	2019	2020[e]	
United States	W	W	750,000
Argentina	6,300	6,200	1,900,000
Australia	45,000	40,000	[6]4,700,000
Brazil	2,400	1,900	95,000
Canada	200	—	530,000
Chile	19,300	18,000	9,200,000
China	10,800	14,000	1,500,000
Portugal	900	900	60,000
Zimbabwe	1,200	1,200	220,000
Other countries[7]	—	—	2,100,000
World total (rounded)	[8]86,000	[8]82,000	21,000,000

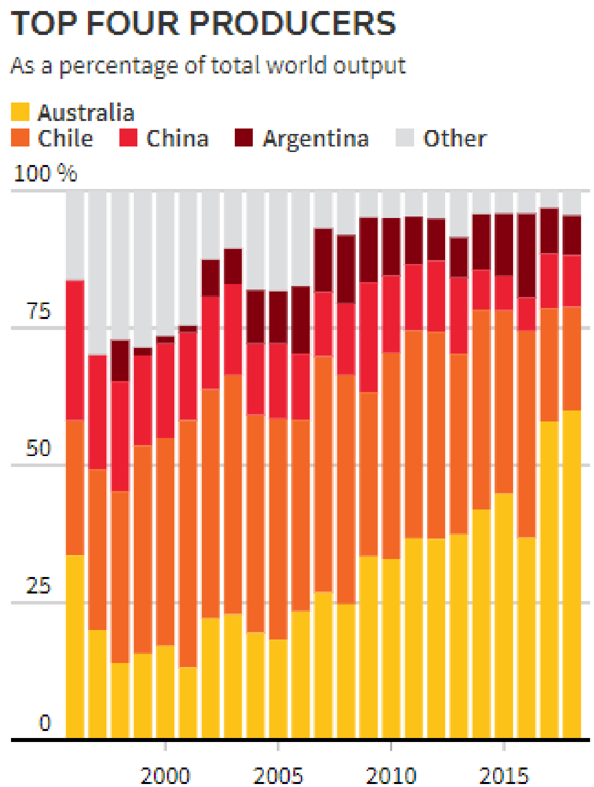
U.S. Geological Survey, Mineral Commodity Summaries, January 2021

Tianqi Lithium, a Chinese company, recently paid more than $4 billion to become the second-largest shareholder in Sociedad Químicay Minera (SQM), a Chilean mining company. The deal gives the company effective control over nearly half the current global production of lithium, a critical component in battery technology. The Chilean government is worried that giving Tianqi so much control over lithium could distort the market. [https://qz.com/1292202/china-now-effectively-controls-half-the-worlds-lithium-production/]

Global lithium production

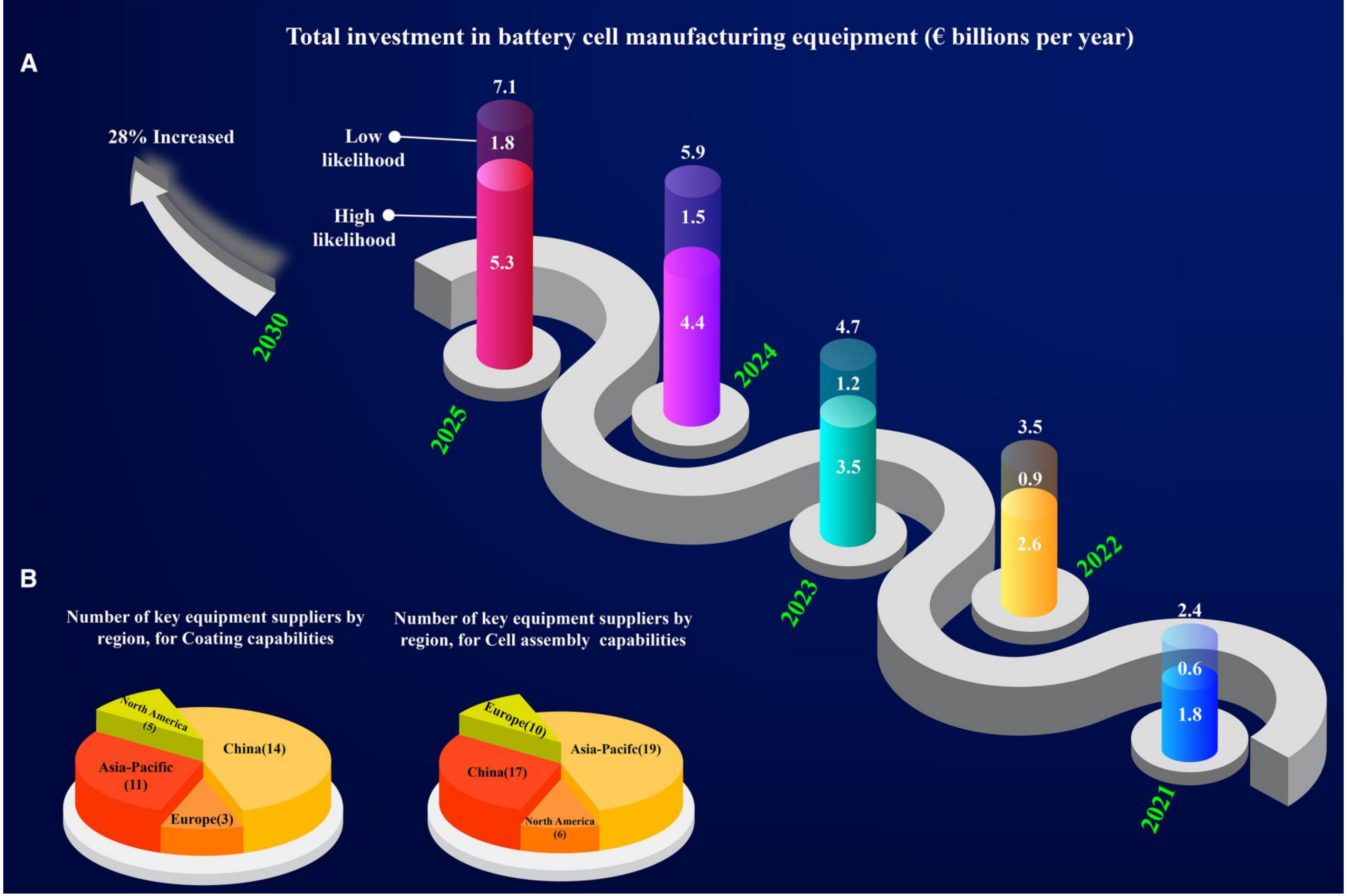
Chile, once the world's top lithium producer, has seen its market share shrink as miners in the South American nation face increasing regulatory hurdles and scrutiny from environmental and indigenous activists.





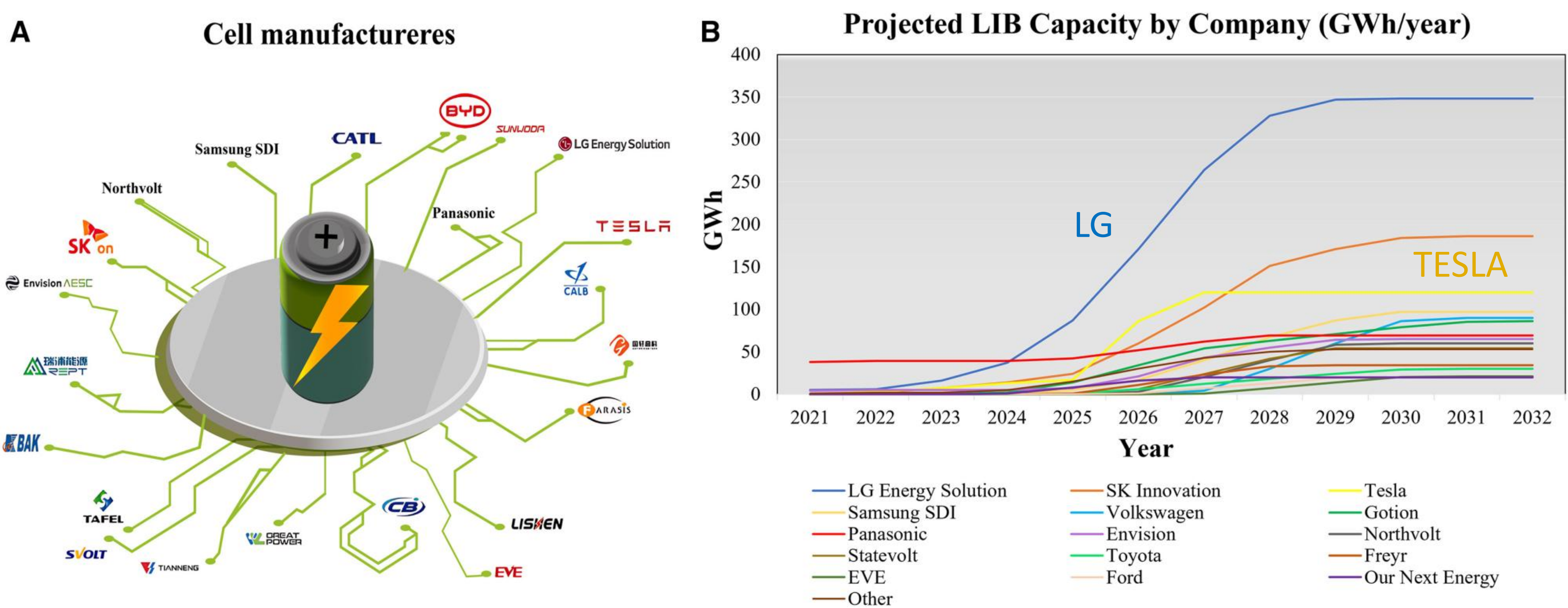
https://www.reuters.com/article/us-chile-lithium-analysis-idUSKCN1T00DM

The new company, Khanij Bidesh India Ltd — incorporated in August, 2019 by three state-owned companies, NALCO, Hindustan Copper and Mineral Exploration Ltd, with a specific mandate to acquire strategic mineral assets such as lithium and cobalt abroad — is also learnt to be exploring options in Chile and Bolivia, two other top lithium-producing countries. by Anil Sasi; The Indian Express, New Delhi | Updated: January 5, 2021



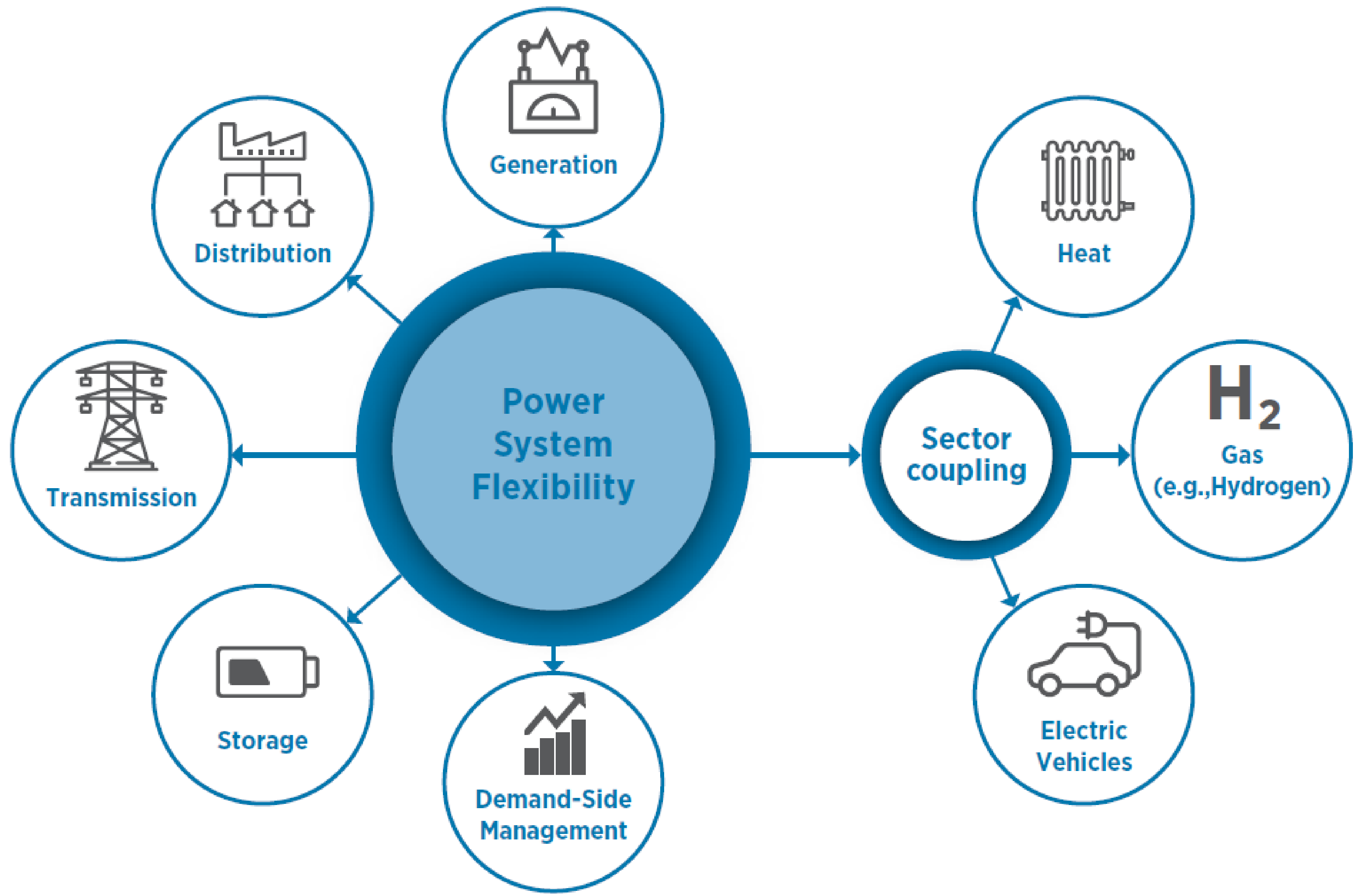
Investment in equipment and key suppliers: (A) Total investment in cell manufacturing equipment is increasing to €5–7 billion by 2025. (B) Key equipment suppliers for coating and cell assembly by region

iScience, 2025, 28, 112691, https://doi.org/10.1016/j.isci.2025.112691



iScience, 2025, 28, 112691, https://doi.org/10.1016/j.isci.2025.112691

Figure 18: Power system flexibility enablers in the energy sector



Redox Flow battery

National Power Grid:

A National Power Grid is a large interconnected network of power generation, transmission, and distribution systems that delivers electricity from power plants to consumers across the entire country. It allows a reliable and efficient supply of electricity by linking multiple power stations and load centres.

Key Components

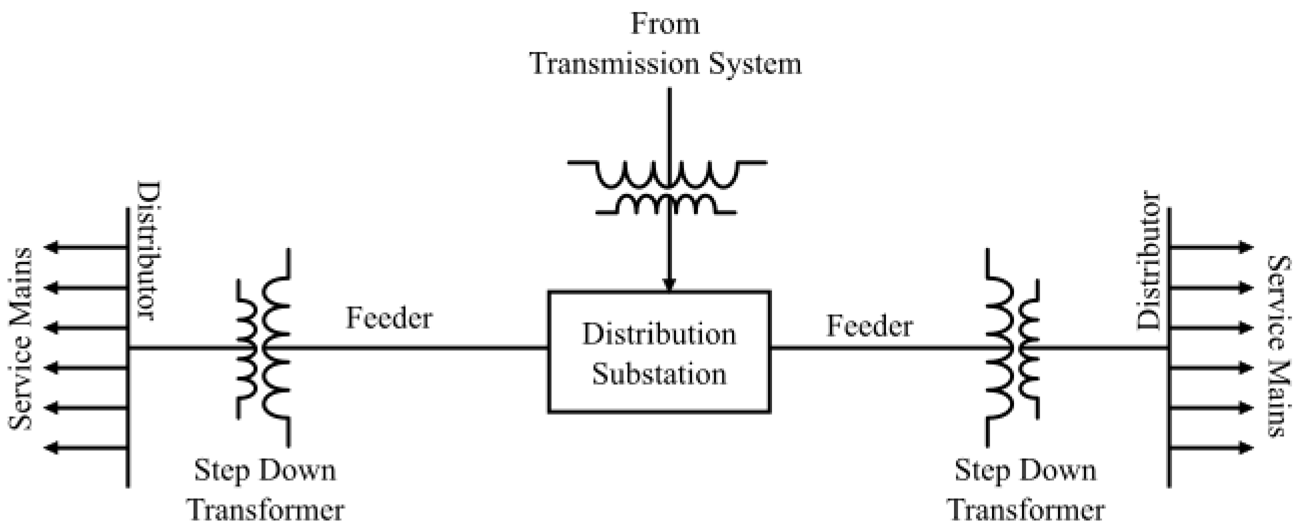
1. Power Generation: Thermal, hydro, nuclear, solar, wind, etc.
2. Transmission Network: High-voltage lines (e.g., 132 kV, 220 kV, 400 kV, 765 kV) that carry electricity over long distances.
3. Distribution Network: Lower-voltage lines that deliver electricity to homes, industries, and businesses.
4. Substations: Step-up/step-down transformers to adjust voltage levels.

Why a National Grid Is Important

- Ensures stable and continuous power supply
- Balances electricity demand and generation
- Allows power sharing between regions
- Reduces power cost and wastage
- Helps integrate renewable energy (solar, wind)

What is a Distribution System?

The part of the power system that distributes electric power for local use is called as *distribution system*. Generally, a distribution system is the electrical system between the substation fed by transmission system and the consumer's meters. A typical distribution system is shown in the figure.



https://www.tutorialspoint.com/electric-power-distribution-system-basics

Requirements of a Distribution System

Some of the requirements of a good distribution system are –

Proper Voltage: The voltage variations at consumer's terminals should be as low as possible. The statutory limit of voltage variations is ± 6 % (India) of the rated voltage at consumer's terminals.

Availability of Power on Demand: The electric power must be available to the consumers in any amount that they may require from time to time.

Reliability: The modern industry is almost dependent on electric power for its operation. This calls for reliable service as much possible.

India suffered the world's biggest-ever power outage in July 2012 as transmission networks serving areas inhabited by 680 million collapsed, putting the nation's ramshackle infrastructure on stark display. This caused losses to businesses estimated in the hundreds of millions of dollars.

A report from Wall Street Journal, **India's Power Network Breaks Down**
Second Blackout This Week Affects Area Where 680 Million Live.

Grid frequency is a critical aspect of power system operations, with global standards requiring that grid frequency be kept close to 50 hertz (Hz). India’s grid code calls for the grid frequency to be in the range of 49.5 - 50.2 Hz. Any sudden change in demand pattern impacts the grid frequency.

Reasons for power grid failure

In the summer of 2012, leading up to the failure, extreme heat had caused power use to reach record levels in New Delhi leading to coal shortages in the country (as fossil fuels stocks are rationed by government and are imported offshore.)

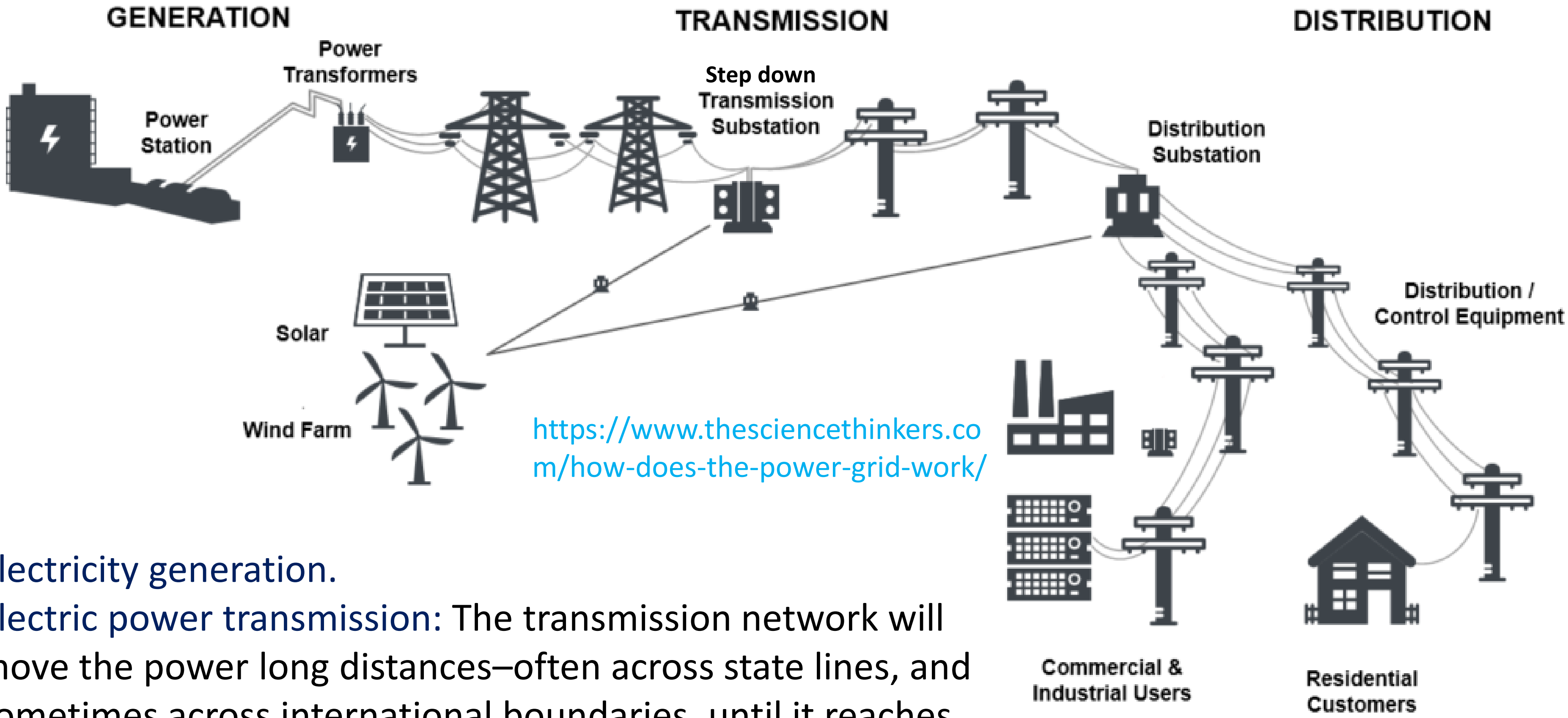
Due to the late arrival of monsoons, agricultural areas in Punjab and Haryana drew increased power from the grid (Farmers using energy intensive water pumps for irrigation)

The late monsoon also meant that hydropower plants were generating less than their usual production and hence the load on thermal power plants increases to support the demand of load.

Illegal utilization of electricity is also a major reason for power grid failure.

9 of the Worst Power Outages in United States History

- Northeast Blackout (1965) ...
- New York City (1977) ...
- West Coast Blackout (1982) ...
- Western North America Blackout (1996) ...
- North Central U.S. (1998) ...
- Northeast Blackout of (2003) ...
- Southwest Blackout of (2011) ...
- Derecho Blackout (2012)



https://www.thesciencethinkers.com/how-does-the-power-grid-work/

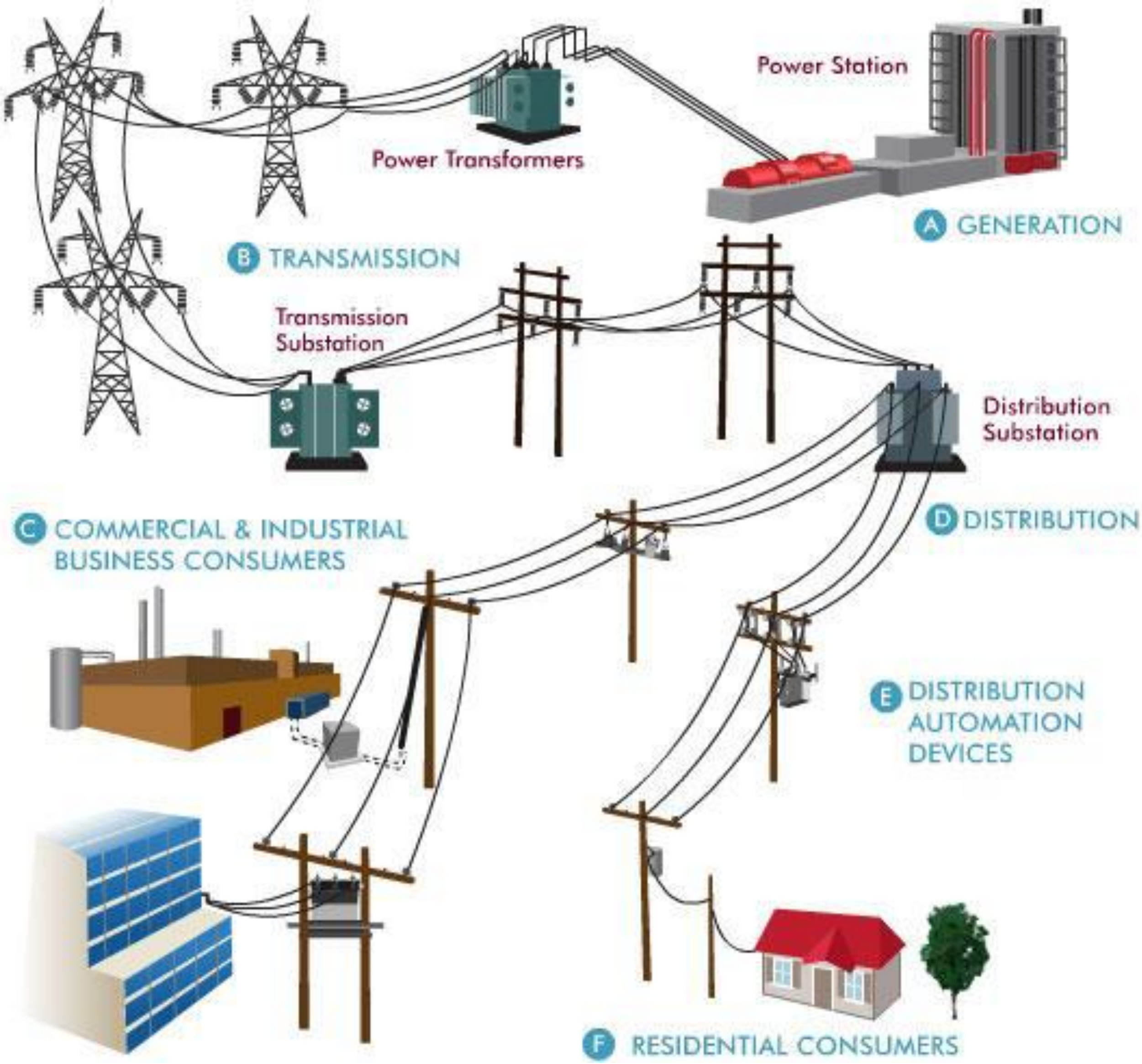
Electricity generation.

Electric power transmission: The transmission network will move the power long distances–often across state lines, and sometimes across international boundaries, until it reaches its wholesale customer.

Electricity distribution:

The final goal of the power grid is simply that the supply meets the demand. Power production and consumption happen on a real-time basis.

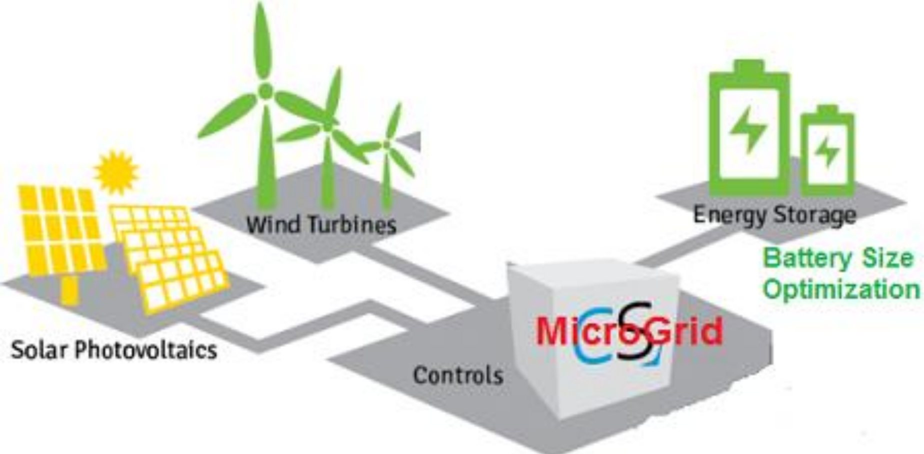
Grid operators balance the demand by dispatching generation capacity in real time. The cheapest sources of power are used to fulfil the base load that’s more consistent, and higher cost sources are used for peaking when demand exceeds the base.

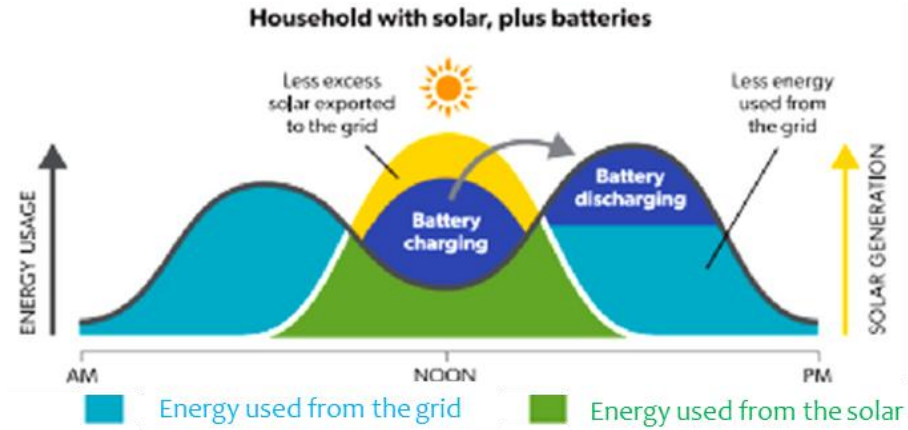


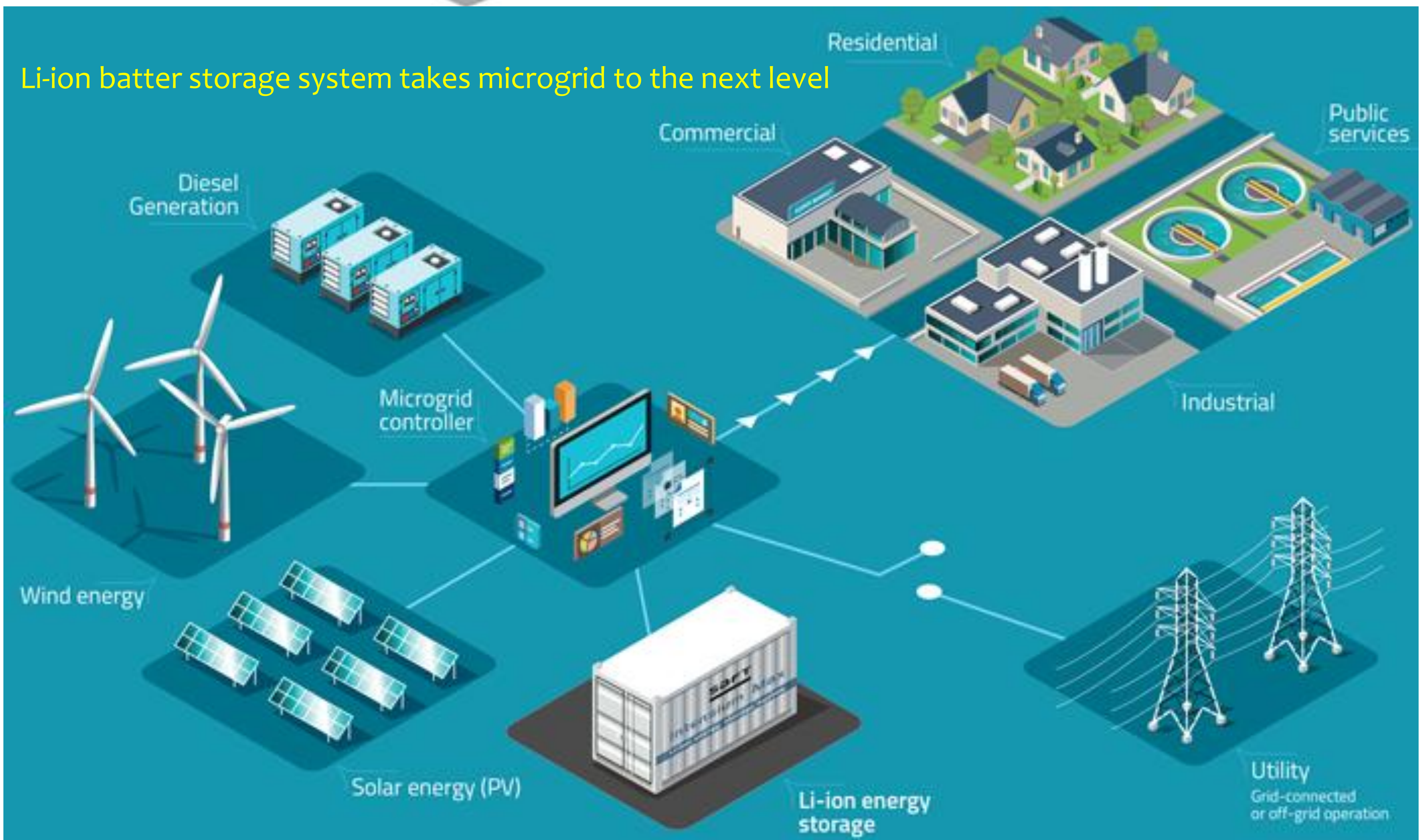
The stability of the grids depends on a delicate equilibrium of demand-supply chain. The amount of load is directly proportional to the amount of power generated.

When the equilibrium between power generated and consumed gets disturbed and the load becomes more, it leads to tripping of the line.

The role of Load Dispatch Centre's is to maintain the frequency between minimum 48.5 to maximum of 50.2 Hz. The National Load Dispatch Centre is also responsible for maintaining the Overdraw done by states.


Wind Turbines
Energy Storage
Battery Size
Optimization
Solar Photovoltaics
Controls
MicroGrid


Household with solar, plus batteries
Less excess
solar exported
to the grid
Less energy
used from
the grid
Battery
discharging
Battery
charging
ENERGY USAGE
SOLAR GENERATION
AM
NOON
PM
Energy used from the grid
Energy used from the solar


Li-ion batter storage system takes microgrid to the next level
Residential
Commercial
Public
services
Diesel
Generation
Industrial
Microgrid
controller
Wind energy
Solar energy (PV)
Li-ion energy
storage
Utility
Grid-connected
or off-grid operation

A redox flow battery is a rechargeable battery that stores energy in liquid electrolytes pumped through a system of electrochemical cells.
The energy capacity is determined by the volume of the electrolytes in external tanks, while the power is determined by the size of the cell stack, allowing for independent scaling of energy and power.
These batteries are well-suited for large-scale energy storage, such as grid stabilisation and storing renewable energy, because they can be made with durable, water-based electrolytes and have a long lifespan.

Components:

Electrolytes: Two liquid electrolytes, one positive and one negative, are stored in separate tanks.

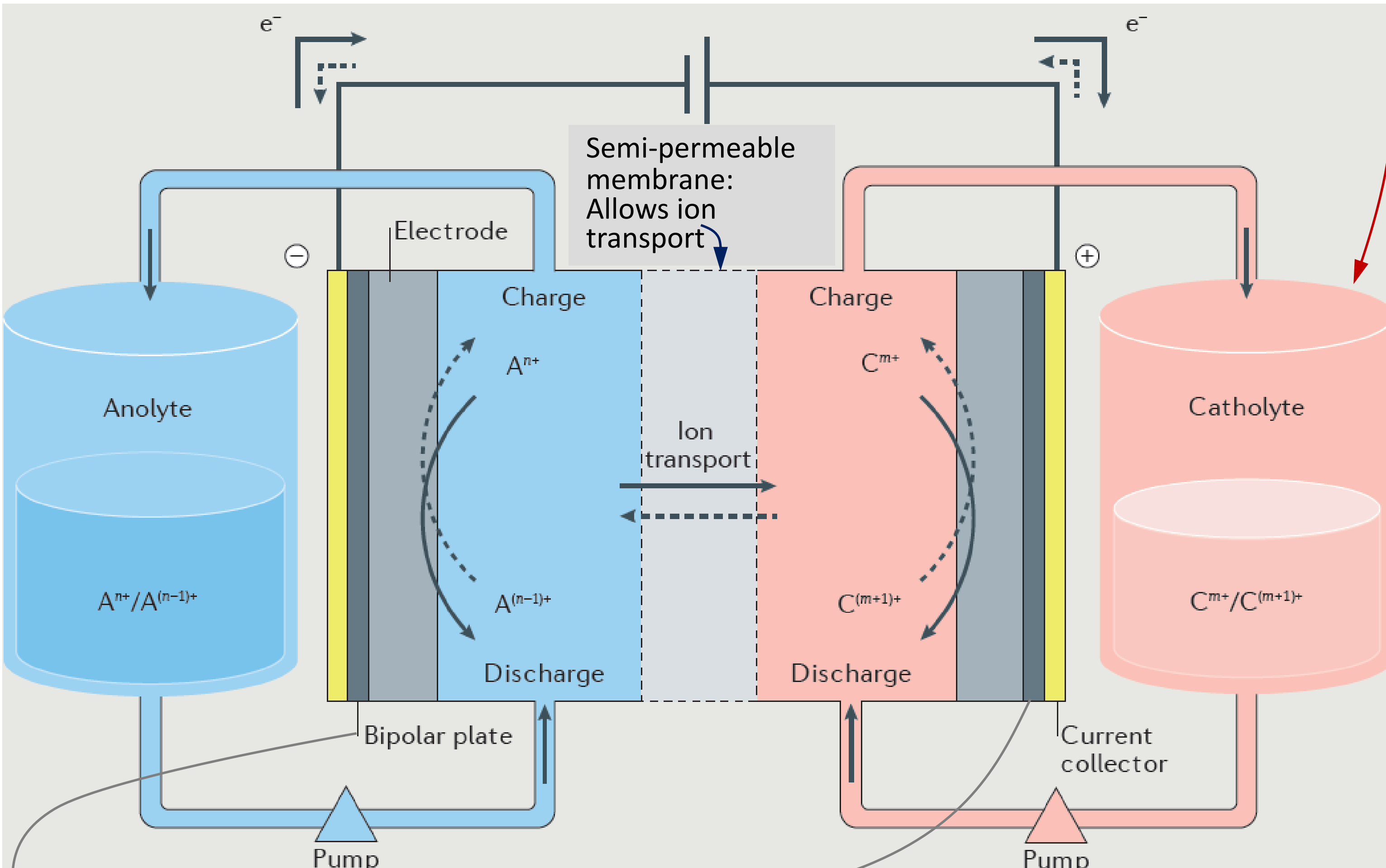
Electrochemical cell: The liquids are pumped from their tanks through a central electrochemical cell that is divided by a membrane.

Redox reactions: At the electrodes within the cell, the electrolytes undergo oxidation and reduction, converting chemical energy to electrical energy (discharge) or vice versa (charge).

Scaling: To increase energy storage capacity, more electrolyte is added to the tanks. To increase power output, more cell stacks are added to the system

The negative electrolyte tank contains anodic redox-active materials dissolved in an electrolyte solution, referred to as the anolyte

positive tank contains dissolved cathodic redox-active materials, referred to as the catholyte



Bipolar plates (that prevent direct contact between the electrolyte and current collectors)

Nature Rev. Mater, 2016, Article number 16080
doi:10.1038/natrevmats.2016.80

A flow battery, or redox flow battery is a type of electrochemical cell where chemical energy is provided by two redox-active chemical components dissolved in liquids that are pumped through the system on separate sides of an ion-exchange membrane. Ion exchange (accompanied by flow of electric current) occurs through the membrane while both liquids circulate in their own respective space.

A flow battery may be used like a fuel cell (where the spent fuel is extracted and new fuel is added to the system) or like a rechargeable battery (where an electric power source drives regeneration of the fuel). While it has technical advantages over conventional rechargeables, such as potentially separable liquid tanks and near unlimited longevity, current implementations are comparatively less powerful and require more sophisticated electronics.

The electrochemical stability voltage window of aqueous batteries is as narrow as ~1.23 V, which seriously restricts the optimal choice of cathode and anode materials due to the existence of hydrogen and/or oxygen evolution reactions. This excludes most electrochemical couples that occur above the output voltage of 1.5 V, which limits the enhancement in energy density of full devices.

Energy Environ. Sci. 2020, 5, 9743–9746
Nat. Energy 2019, 4, 495–503. doi: 10.1038/s41560-019-0388-0
Adv. Energy Mater. 2014, 8:1702384. doi: 10.1002/aenm.201702384

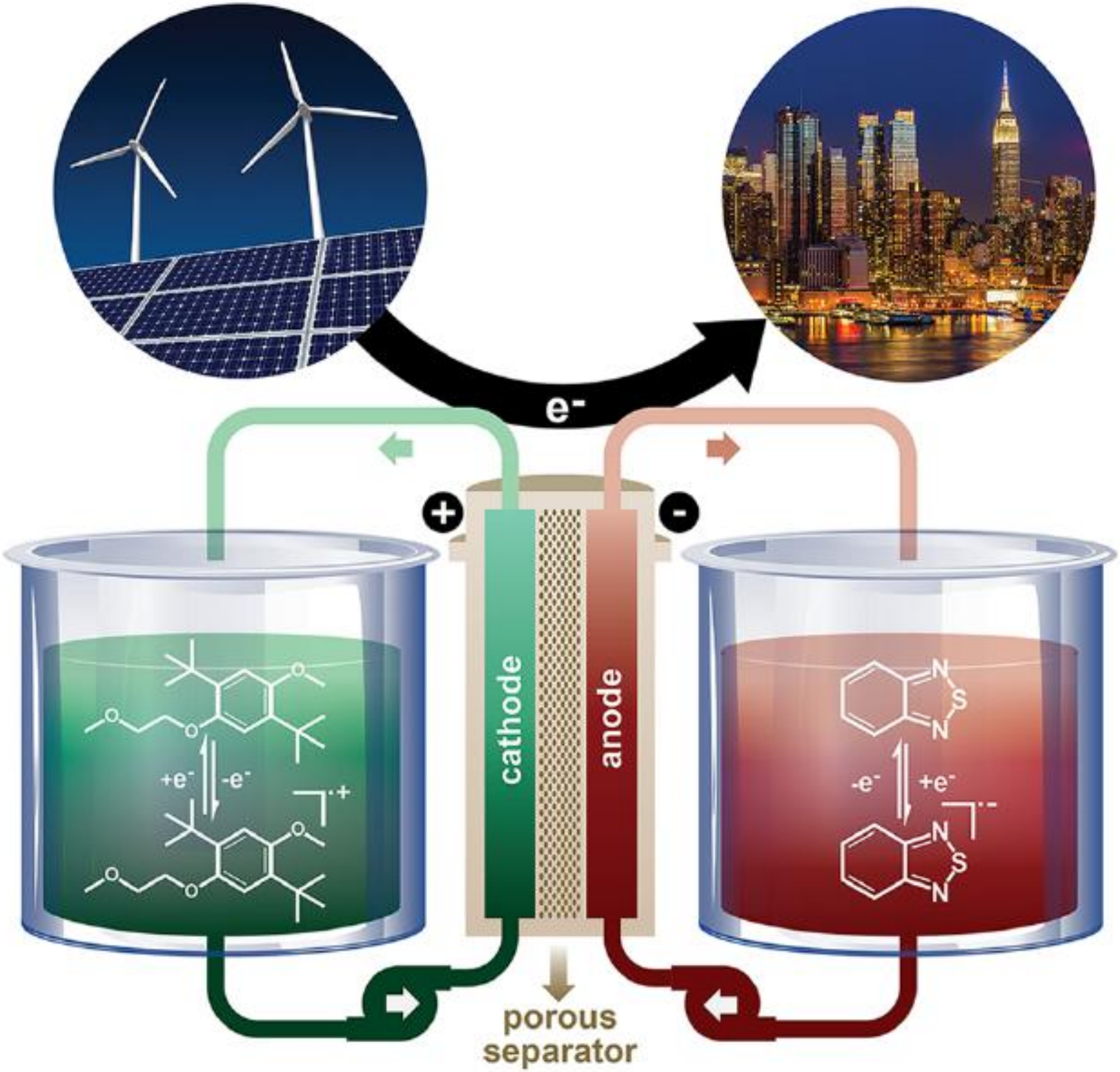


Illustration of the BzNSN/DBMMB flow battery and the cell reactions

ACS Energy Lett. 2017, 2, 1368–1369
ACS Energy Lett. 2017, 2, 1368–1369
Angew.Chem. Int. Ed. 2017, 56,686 –711

- ✓ The total energy output depends on the volume of these tanks, which implies that high-solubility catholytes and anolytes are preferred to achieve the high volumetric energy densities.
- ✓ These electrolytes are continuously supplied in the stack, and the redox reactions occur on the surface of the electrode materials that provide redox-active sites.
- ✓ The oxidized and reduced redox couples on the electrode are accumulated in the external tanks, and charge-balancing ions penetrate through the membrane. This result in minimal structural changes in the electrode and high stability.
- ✓ The size of the active area inside the stack determines the total power output, thus the power density is an important factor related to the capital cost.
- ✓ The performance of RFBs is measured in terms of the Coulombic efficiency (CE), voltage efficiency (VE) and energy efficiency (EE).

  CE is the ratio of charge and discharge capacities.

  VE is the ratio of charge and discharge voltages.

  Energy efficiency is the product of the CE & VE.

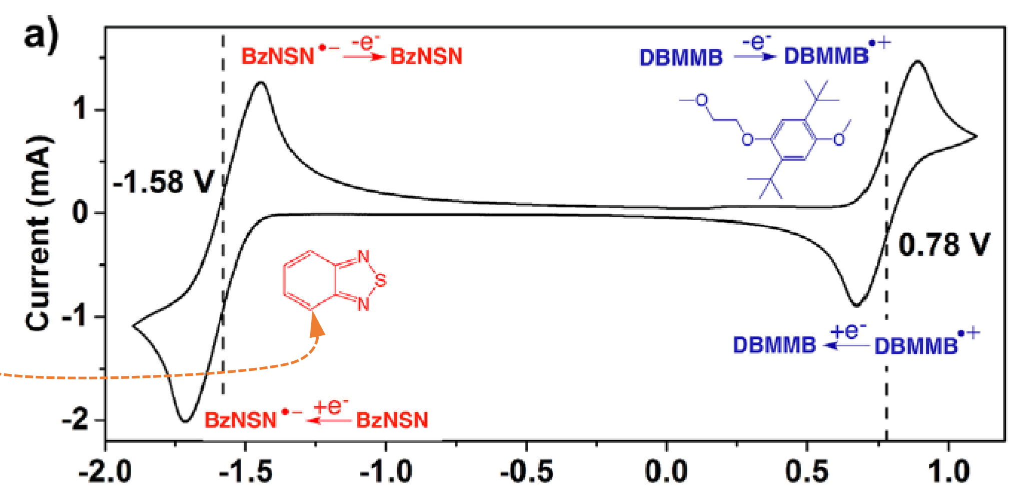
REDOX FLOW BATTERY:

Scalable energy storage is vital for future smart grids, enabling efficient use of intermittent renewables and enhancing grid performance. Redox flow batteries are strong candidates for grid-scale storage, using circulating electrolytes containing redox-active materials. These electrolytes, called catholyte and anolyte, flow through separate positive and negative electrode compartments to convert energy. Because the electrodes and external electrolyte tanks are spatially separated, flow batteries decouple power and energy: power depends on electrode area, while energy capacity depends on electrolyte volume.

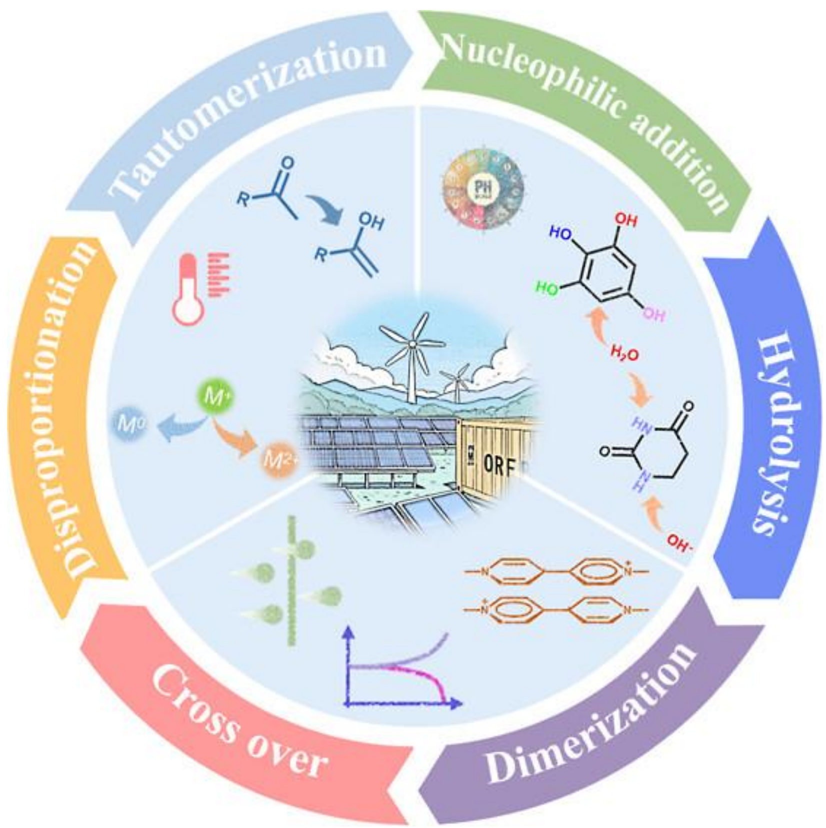
Flow batteries with aqueous electrolytes are becoming commercially available, but their energy densities are limited by the intrinsically low operating voltages (<1.8 V). An attractive alternative to address this limitation is to develop nonaqueous flow batteries, taking advantage of the wider electrochemical windows (>2 V), which offers a new pathway to achieve high energy density and access attractive new redox materials.

ACS Energy Lett. 2017, 2, 1156−1161

2,1,3-Benzothiadiazole



Aqueous organic flow batteries (AOFBs) are emerging as promising large-scale energy storage systems owing to their safety, low cost, and environmental compatibility. However, their long-term performance is hindered by the chemical instability of redox-active molecules (RAMs), which degrade over repeated cycling, causing capacity fading and efficiency loss. Various degradation pathways of RAMs—such as nucleophilic addition, hydrolysis, tautomerization, disproportionation, dimerization, and molecular crossover. [ACS Appl. Energy Mater. 2025, 8, 19, 14001–14013]



The electrochemical window (ECW) of a chemical compound is the electrode electric potential range between which the compound is neither oxidized nor reduced. The EW is one of the most important characteristics to be identified for solvents and electrolytes used in electrochemical applications.

Energy Environ. Sci., 2015, 8, 3515

Solvent	E_{red} (V vs. SHE)	E_{ox} (V vs. SHE)	ECW (V)
Nitromethane (NM)	-1.0	2.9	3.9
g-Valerolactone (GVL)	-2.8	5.4	8.2
Methoxyacetonitrile (MAN)	-2.5	3.2	5.7
g-Butyrolactone (GBL)	-2.8	5.4	8.2
Acetonitrile (AN)	-2.6	3.5	6.1
Trimethyl phosphate (TMP)	-2.7	3.7	6.4
Propylene carbonate (PC)	-2.8	3.8	6.6
1,2-Butylene carbonate (BC)	-2.8	4.4	7.2
3-Methoxypropionitrile (MPN)	-2.5	3.3	5.8

Classic vanadium redox flow batteries

discharge: $\rightarrow$
charge: $\leftarrow$

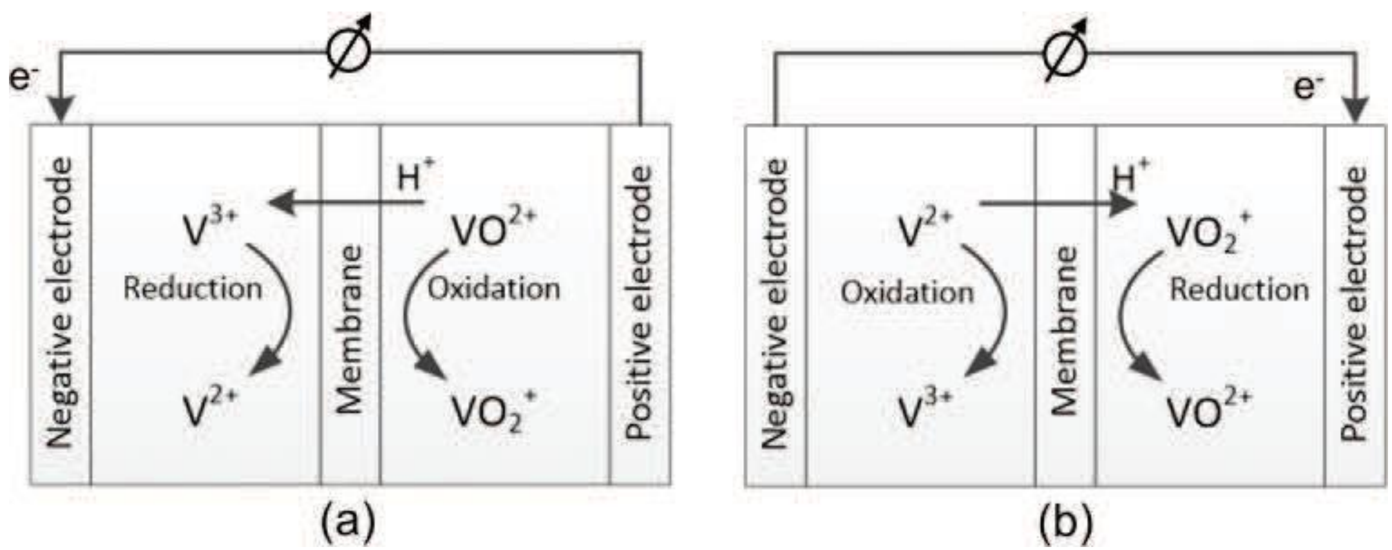
$$\text{Cathode-side:}\quad VO_2^+ + 2\,H^+ + e^- \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} VO^{2+} + H_2O$$

$$\text{Anode-side:}\quad V^{2+} - e^- \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} V^{3+}$$

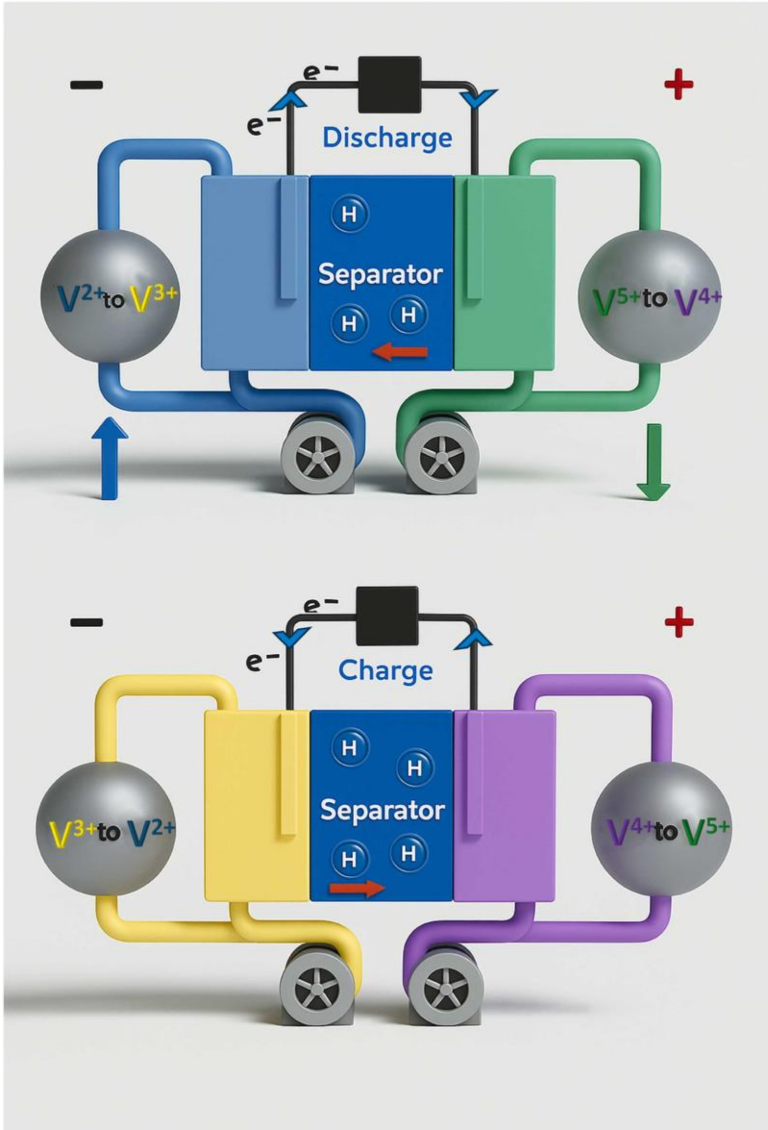
$$\text{Cell reaction:}\quad VO_2^+ + V^{2+} + 2\,H^+ \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} VO^{2+} + V^{3+} + H_2O$$

The standard cell voltage for the all-vanadium redox flow batteries is 1.26 V. At a given temperature, pH value and given concentrations of vanadium species, the cell voltage can be calculated based on the Nernst equation

$$E = 1.26\text{ V} - RT/F \ln\left(\left[VO^{2+}\right]\cdot\left[V^{3+}\right]\right)/\left(\left[{VO_2}^{+}\right]\cdot\left[H^{+}\right]^2\cdot\left[V^{2+}\right]\right) \qquad (4)$$



A schematic of a vanadium redox flow battery: (a) charge reaction and (b) discharge reaction



Overall reaction

$$V^{3+} + e^- \leftrightharpoons V^{2+} \qquad E^0 = -0.255 \quad V$$

$$VO_2^+ + 2H^+ + e^- \leftrightharpoons VO^{2+} + H_2O \quad E^0 = 1.004 \quad V$$

Charging Process

$$Negative\ electrode: V^{3+} + e^- \leftrightharpoons V^{2+}$$

$$Positive\ electrode: VO^{2+} + H_2O \leftrightharpoons VO_2^+ + 2H^+ + e^-$$

$$Overall\ Reaction: VO^{2+} + V^{3+} + H_2O \leftrightharpoons VO_2^+ + V^{2+} + 2H^+ \quad E^0_{Cell} = -1.259 \quad V$$

Discharge Process

$$Negative\ electrode: V^{2+} \leftrightharpoons V^{3+} + e^-$$

$$Positive\ electrode: VO_2^+ + 2H^+ + e^- \leftrightharpoons VO^{2+} + H_2O$$

$$Overall\ Reaction: VO_2^+ + V^{2+} + 2H^+ \leftrightharpoons VO^{2+} + V^{3+} + H_2O \quad E^0_{Battery} = 1.259 \quad V$$

Journal of Alloys and Compounds,
Volume 1038, 20 August 2025, 182869

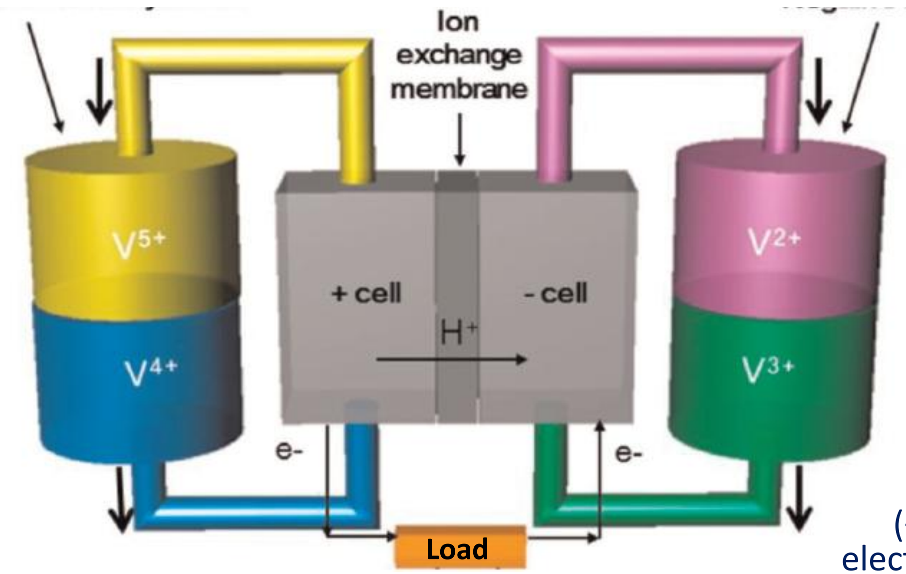
From an environmental standpoint, both vanadium redox flow batteries (VRFBs) and lithium-ion batteries (LIBs) present distinct pros and cons. LIBs rely on scarce and environmentally harmful materials such as lithium and cobalt, whereas VRFBs use vanadium, an abundant and recyclable resource. Although the vanadium electrolyte poses corrosive hazards, VRFBs are fully recyclable, exhibit lower carbon footprints, and offer longer lifespans. Overall, VRFBs represent a more sustainable and eco-friendly alternative for large-scale energy storage.

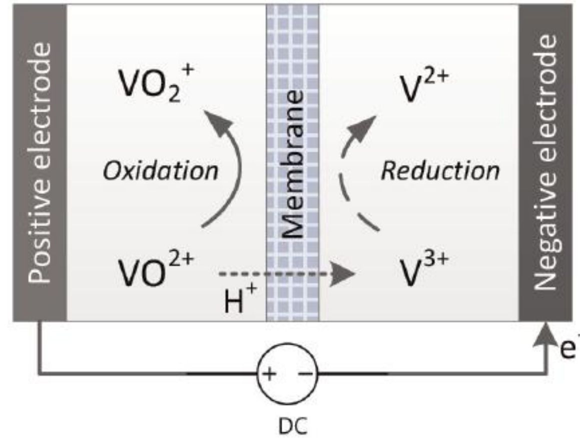
Journal of Alloys and Compounds, Volume 1038, 20 August 2025, 182869

Charging

Positive Electrolyte tank

Negative Electrolyte tank





(-) electrode de: $V^{2+} \leftrightarrow V^{3+} + e^- \quad E^0 = -0.255\ V$ (1)

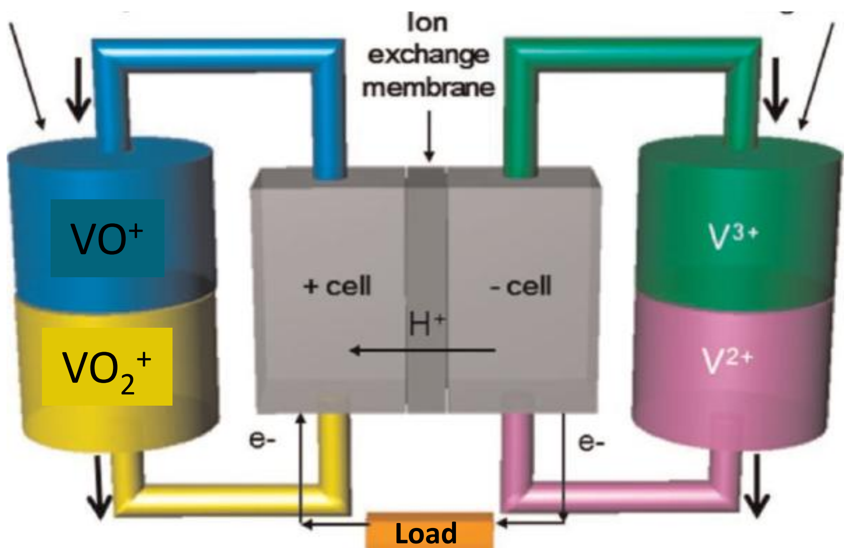
(+) electrode $VO_2^+ + e^- + 2H^+ \leftrightarrow VO^{2+} + H_2O \quad E^0 = +1.004\ V$ (2)

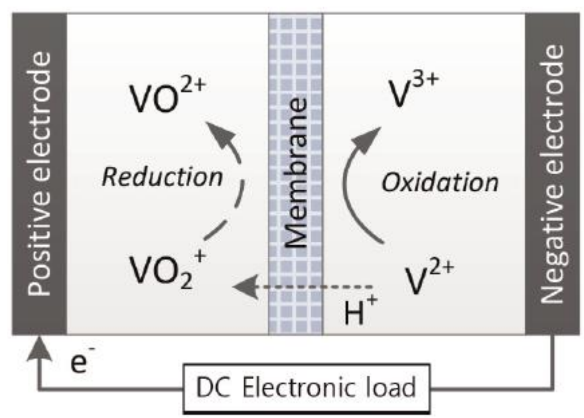
Overall reaction: $VO_2^+ + V^{2+} + 2H^+ \leftrightarrow VO^{2+} + V^{3+} + H_2O \quad E^0 = +1.259\ V$ (3)

Discharging

Positive Electrolyte tank

Negative Electrolyte tank





- **Vanadium redox flow batteries (VRFBs) are commercial** and being deployed at grid scale (MW–hundreds of MW). Large projects and new product lines launched in 2024–2025 show active commercial roll-out.

China has completed the main construction works on the world's largest vanadium redox flow battery (VRFB) energy storage project. The project, backed by China Huaneng Group, features a 200 MW/1 GWh VRFB system paired with a 1 GW solar farm. July, 2025 Report: https://www.ess-news.com/2025/07/04/china-completes-worlds-largest-vanadium-flow-battery-plant/

- **Manufacturers scaling production**: established firms (Invinity, Sumitomo, Stryten, Largo-linked ventures and others) are expanding manufacturing and taking orders for commercial systems.

The UK-based vanadium flow battery (VFB) maker says it has secured orders for its new product, including 84 MWh worth for projects backed by the US Department of Energy (DoE), Dec 2024 Report: https://www.ess-news.com/2024/12/05/invinity-secures-orders-for-new-endurium-vanadium-flow-battery

- **Non-vanadium chemistries (iron, zinc-bromine, organic) are at various pilot / early commercial stages.** Iron flow (e.g., ESS Inc.) is gaining pilots for long-duration storage; some zinc/organic players have had setbacks (e.g., Redflow). ESS Tech, Inc.+1

Market momentum but still niche vs Li-ion. Li-ion dominates Global Battery Energy Storage System deployments; flow batteries are carving a growing niche for long-duration (4–10+ hour) and safety-sensitive applications.

Why flow batteries are commercializing now

- **Long-duration use case** (4–10+ h) where Li-ion becomes uneconomic.
- **Intrinsic safety & long cycle life** (electrolyte tanks, low thermal runaway risk) attractive for certain sites.
- **Local policies and procurement** (some utilities & governments procuring LDES pilots) accelerating deployments.

Remaining barriers / risks

- **Capital cost vs Li-ion (today):** flow systems can be competitive for long durations but still face higher upfront cost per kW for shorter duration use. (market analyses and project economics are the deciding factor).
- **Vanadium supply & price volatility** — affects VRFB economics and motivates local supply chain projects.
- **Manufacturing scale & quality** — some smaller vendors have failed (e.g., Redflow), so bankability and track record matter for buyers.
- **Competition from rapidly falling Li-ion prices** and evolving grid procurement rules.

Short project economics — ballpark numbers & when flow makes sense

Important: these are **ballpark, system-level** indications drawn from 2024–2025 reports and market analyses. Exact economics depend heavily on project size, duration, local capex, BOS, financing, and vanadium prices.

- **Li-ion (utility-scale 4-hour systems)**: pack & system prices have been falling; pack prices **~$100–140/kWh (pack)** in 2024–2025 and system-level (installed 4-hr) often in the **$200–350/kWh** range depending on region and BOS. Lazard and NREL analyses provide the most current 4-hr baselines. https://img.saurenergy.com/2025/03/volta-foundation-study_compressed_compressed.pdf
- **Vanadium flow batteries (VRFB)**: a wide range reported — earlier market sources commonly cited **$300–$600+/kWh** installed for multi-hour (6–10 h) systems depending on vanadium electrolyte cost and system scale; some techno-economic studies show possibilities to approach **~€260–$300/kWh** at 10-hour durations with optimistic supply chain improvements. FlowBatteryForum and academic/industry papers summarize these ranges. https://flowbatteryforum.com/wp-content/uploads/2025/06/4.-Conrad-Nichols.pdf

Vendor / group	Chemistry	Typical commercial scale (examples)	Notable commercial references (2024–2025)	Status / risk
Invinity Energy Systems	Vanadium redox flow (VRFB)	Containerised MW→multi-MW systems (modular)	Manufacturing & licensing announcements, capacity expansion plans (2024–2025). (Invinity)	Commercial product; scaling manufacturing (Europe + licensing in China). Bankability improving but growth depends on scaling orders. (Invinity)
Sumitomo Electric	VRFB	Utility / municipal systems (kW → MW × 8 h)	Completed 1 MW × 8 h installations; announced new product/orders and began taking orders in 2025. (Sumitomo Electric)	Large, well-banked OEM with multiple field installations; low technology risk. Good choice for conservative utility procurements. (Sumitomo Electric)
Rongke / Dalian Rongke Power	VRFB	Very large utility projects (MW → GWh)	Commissioned GWh-scale / 200 MW / 1 GWh projects in China (2025 reporting). (vanitec.org)	Demonstrated GWh projects — China leads in scale. Good proof of scale but buyers outside China may care about vendor/local support. (vanitec.org)
ESS, Inc.	Iron flow (all-iron)	MW-scale long-duration systems (multi-hour to >20 h architecture)	Active pilots and commercial bids for LDES; public company announcements and ongoing commercial activity (2024–2025). (ESS Tech, Inc.)	Prominent non-vanadium LDES vendor. Tech attractive for long durations; commercial maturity improving but still earlier stage vs big VRFB OEMs. (ESS Tech, Inc.)
Stryten Energy / Largo (JV / Storion etc.)	VRFB (electrolyte + value chain)	Electrolyte manufacturing, supply chain for VRFBs	JV / partnership announcements to localize electrolyte supply and scale domestic manufacturing (Dec 2024 onward). (Business Wire)	Addresses a major VRFB risk (vanadium electrolyte supply/price). Positive for bankability in North America if JV executes. (Business Wire)
			[illegible]	Higher vendor risk — check

When flow typically becomes competitive vs Li-ion:

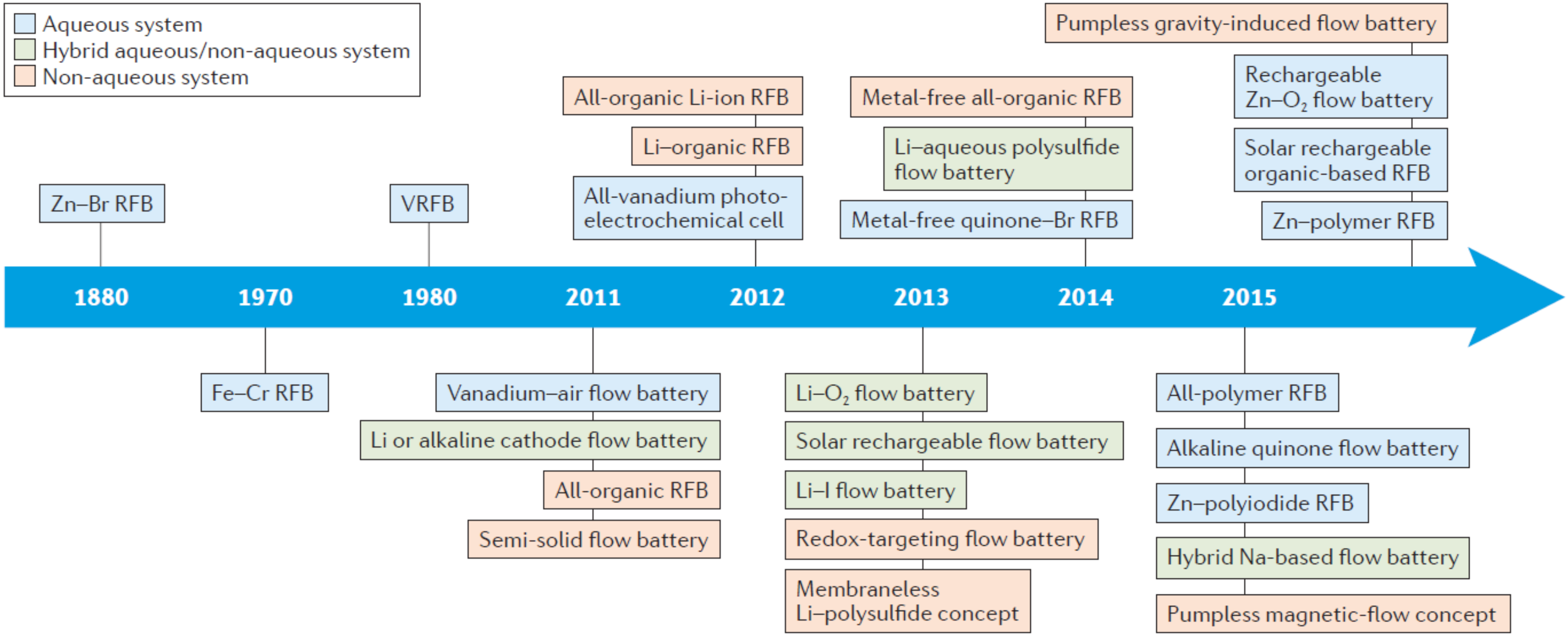
For durations ≤4 hours: Li-ion is usually cheaper on CAPEX and levelized cost.
https://www.lazard.com/media/eijnqja3/lazards-lcoeplus-june-2025.pdf

For durations ≥8–10 hours (LDES use cases): flow batteries (VRFB, iron flow) can be more economical because Li-ion costs scale roughly linearly with hours while flow batteries scale energy capacity cheaply (tank size), improving $/kWh for long durations. Multiple reports show the crossover around **~6–10 hours**, depending on local capex and vanadium price volatility. [https://flowbatteryforum.com/wp-content/uploads/2025/06/4.-Conrad-Nichols.pdf]

The New Energy and Industrial Technology Development Organization (“NEDO”) and Sumitomo Electric Industries, Ltd. have installed a redox flow battery (RFB) system for a demonstration project to improve the power quality of the transmission and distribution network in California. NEDO has decided to extend the project to conduct an additional demonstration of a microgrid, in which a part of the distribution line, including residential customers. The project is scheduled to run until December 2021. It aims to demonstrate not only the technical features that strengthen resilience, but also the commercial value of the RFB system as a power source for a microgrid in emergency situations as well as for market participation in normal times. Grid resilience is increasingly important as California grapples with more frequent Public Safety Power Shutoffs (a tool implemented statewide to reduce wildfire risk) and also reliability concerns during peak summer periods.

Redox flow battery (RFB) system installed in California

https://www.nedo.go.jp/english/news/AA5en_100433.html



Timeline of key developments in the area of flow-battery systems. Recent advances presented in each box are categorized as either aqueous, hybrid aqueous/non-aqueous or non-aqueous systems. VRFB, vanadium redox-flow battery