

Exploring Alternatives to Lithium-Ion in Battery Packs

Kanak

Dept. of Mechanical and Automation Engineering

Indira Gandhi Delhi Technical University for Women

Address: James Church, New Church Rd, Opp. St, Kashmere Gate, New Delhi, Delhi 110006

Abstract

Lithium-ion (Li-ion) batteries have enabled the rapid rise of electric vehicles (EVs) due to their high energy density and mature manufacturing process. However, growing concerns over resource scarcity, rising costs, safety issues, and environmental impact are pushing researchers to develop new alternatives. In this report, I've studied ten different battery types—zinc-ion, magnesium-ion, sodium-ion, solid-state lithium-metal, lithium-sulfur, zinc manganese oxide, nickel-metal hydride, zinc-air, iron-air, and aluminum-air. I've highlighted how each of these works, their benefits, drawbacks, and how close they are to being used in real EVs.

- **Electrolyte:** Organic solvent with dissolved lithium salts.
- **Separator:** Porous polymer film preventing shorts while allowing ion flow.

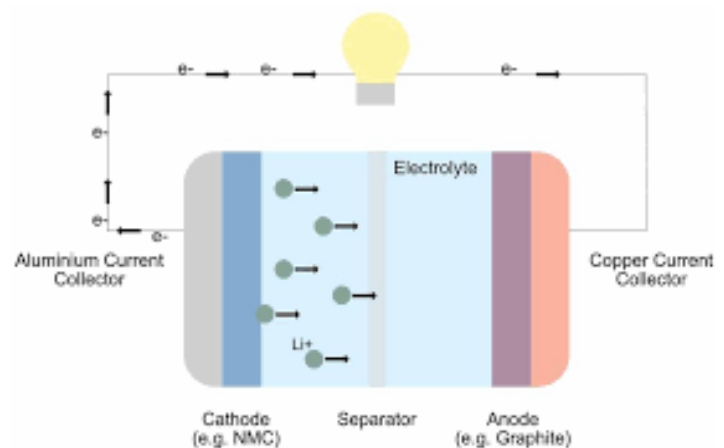


Fig. 1 – Structure Of Lithium Ion cell^[11]

INTRODUCTION

1. What Are Lithium-Ion Batteries

Lithium-ion batteries store and release electrical energy through the movement of lithium ions (Li⁺) between two electrodes separated by an electrolyte:

- **Cathode:** Lithium-metal oxide (e.g., NMC, NCA, LFP).
- **Anode:** Graphite or silicon-doped carbon.

Key Characteristics:

- Energy density: 150–250 Wh/kg
- Cycle life: 500–1,500 cycles
- Charge/discharge efficiency: >95%
- Operating voltage: 3.2–4.2 V per cell

Where They're Used in EVs:

- **Battery electric vehicles (BEVs):** These are the main power source in cars like the Tesla Model 3 or Nissan Leaf.

- **Plug-in hybrids (PHEVs):** Used alongside petrol engines, like in the Chevy Volt.
- **Battery management systems (BMS):** Monitor and protect the battery.
- **Performance EVs:** High-end EVs use stronger Li-ion types for faster acceleration.

2. Need for Alternative Chemistries

- **Resource Constraints:** Li, Co, Ni supplies are geopolitically concentrated.
- **Safety Risks:** Flammable electrolytes can cause thermal runaway.
- **Environmental Impact:** Mining and recycling have high carbon and water footprints.
- **Performance Limits:** Li-ion improvements face diminishing returns in energy and charging speed.

These factors drive development of new chemistries using abundant elements, enhancing safety, and offering novel performance benefits.

3. Alternative Battery Technologies

1) Zinc-Ion Batteries

Principle: Zn^{2+} ions shuttle between a zinc anode and manganese-oxide or Prussian blue cathode in an aqueous electrolyte.

Advantages: Abundant zinc; non-flammable; eco-friendly.

Limitations: Dendrite growth; ~ 1.5 V cell voltage; moderate energy density.

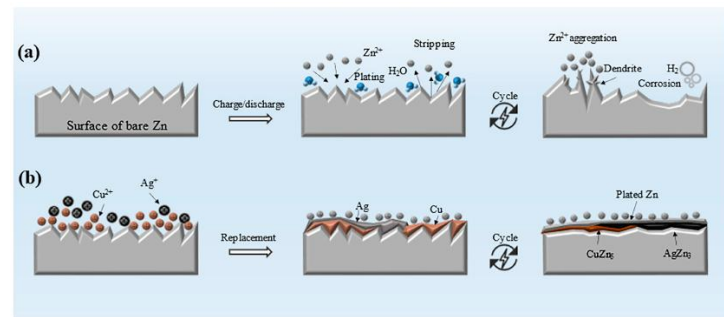


Fig. 2 – Structure Of Zinc Ion battery in aqueous solution^[12]

Performance Metrics:

- Energy density: 80–120 Wh/kg
- Cycle life: 500–1,000 cycles
- Safety: Excellent (aqueous)

Market Availability: Pilot grid/storage systems; EV modules from 2026.

2) Magnesium-Ion Batteries

Principle: Mg^{2+} ions shuttle between a magnesium metal anode and a Chevrel-phase Mo_6S_8 cathode.

Advantages: Divalent Mg^{2+} offers high capacity; abundant material; some electrolytes suppress dendrites.

Limitations: Slow Mg^{2+} diffusion; limited

cathode choices; lower voltage.

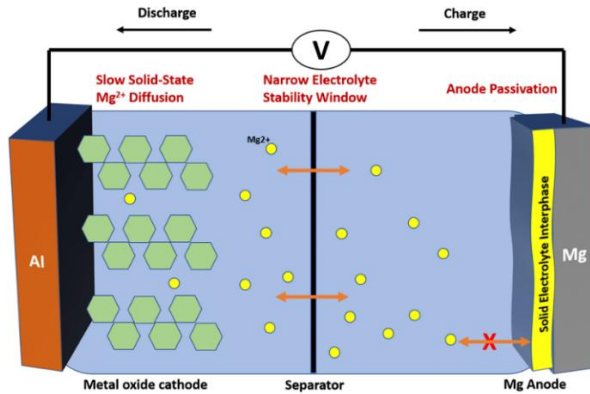


Fig. 3 – Structure Of Magnesium Ion cell^[13]

Performance Metrics:

- Energy density: 100–150 Wh/kg (projected)
- Cycle life: ~500 cycles
- Safety: Good

Market Availability: Laboratory research; demos by 2030.

3) Sodium-Ion Batteries

Principle: Na^+ ions intercalate into hard carbon anodes and layered oxide cathodes.

Advantages: Abundant sodium; leverages Li-ion production lines; safe, cold-tolerant.

Limitations: Larger ion radius equals lower density.

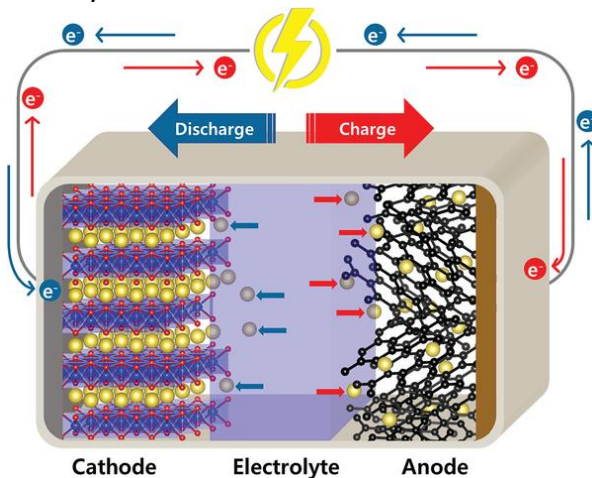


Fig. 4 – Structure Of Sodium Ion cell^[14]

Performance Metrics:

- Energy density: 120–160 Wh/kg
- Cycle life: 1,000–2,000 cycles
- Safety: Very good

Market Availability: E-scooter cells from 2024; EV modules from 2026.

4) Solid-State Lithium-Metal Batteries

Principle: Li-metal anode with solid ceramic/polymer electrolyte replaces flammable liquid.

Advantages: Potential 300–500 Wh/kg; non-flammable; fast charge.

Limitations: Electrolyte brittleness; dendrite risk; high cost.

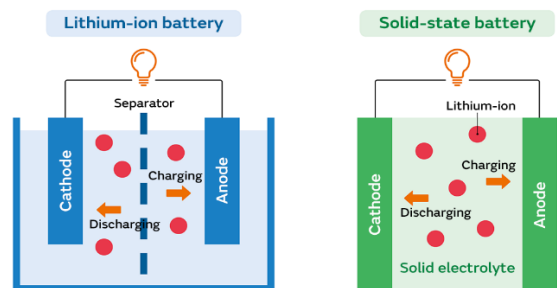


Fig. 5 – Structure Of Lithium Ion battery and Solid State battery^[15]

Performance Metrics:

- Energy density: 300–500 Wh/kg
- Cycle life: 500–1,000 cycles
- Safety: Excellent

Market Availability: Pilot demos 2025–26; small EV fleets by 2028.

5) Lithium–Sulfur Batteries

Principle: Sulfur cathode forms Li_2S with Li anode via polysulfide intermediates.

Advantages: High theoretical energy (~2,600 Wh/kg); cheap sulfur.

Limitations: Polysulfide shuttle; volume

changes; Li-metal safety.

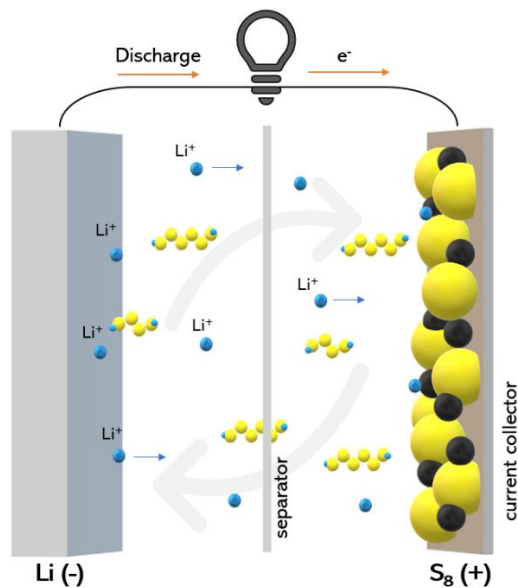


Fig. 6 – Structure Of Lithium Sulphur Battery [16]

Performance Metrics:

- Energy density: 300–500 Wh/kg (prototype)
- Cycle life: 200–500 cycles
- Safety: Moderate

Market Availability: Pilot-scale demos; production by 2030.

6) Zinc Manganese Oxide Batteries

Principle: Zn^{2+} ions shuttle between Zn anode and MnO_2 cathode in water.

Advantages: Abundant; aqueous safety.

Limitations: Mn dissolution; dendrites.

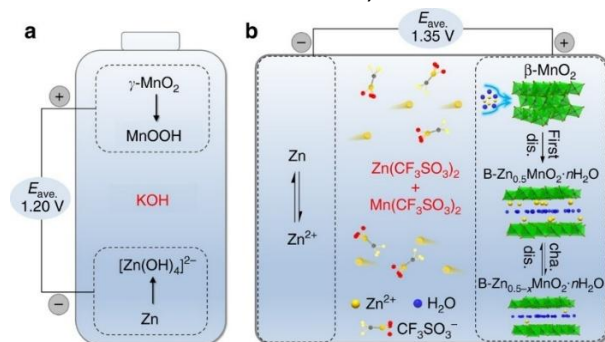


Fig. 7 – Structure Of Zinc Manganese Oxide cell [17]

Performance Metrics:

- Energy density: 100–150 Wh/kg
- Cycle life: ~500 cycles
- Safety: Good

Market Availability: Pilots by 2027.

7) Nickel–Metal Hydride (NiMH) Batteries

Principle: $\text{NiOOH}/\text{Ni}(\text{OH})_2$ cathode and metal-hydride anode in alkaline electrolyte.

Advantages: Mature; safe; robust.

Limitations: Moderate energy; self-discharge.

Performance Metrics:

- Energy density: 60–120 Wh/kg
- Cycle life: 500–1,000 cycles
- Safety: Excellent

Market Availability: Widespread since the 1990s

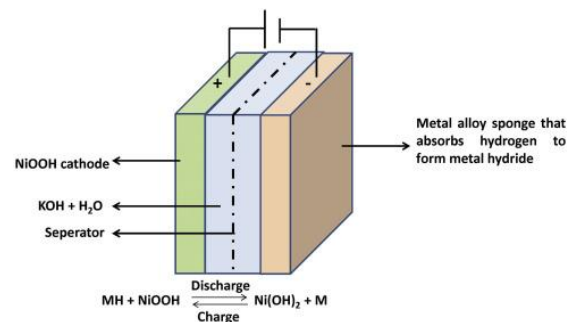


Fig. 8 – Structure Of Nickel metal Hydride cell [18]

8) Zinc–Air Batteries

Principle: Zn anode oxidizes with O_2 at air cathode in alkaline electrolyte.

Advantages: High primary energy; cheap.

Limitations: Catalyst/humidity; limited recharge cycles.

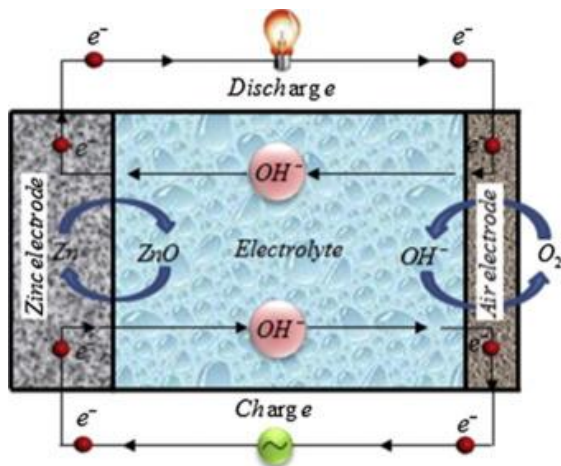


Fig. 9 – Structure Of Zinc Air cell^[19]

Performance Metrics:

- Energy density: 300–400 Wh/kg (primary)
 - Cycle life: <100 cycles
 - Safety: Excellent
- Market Availability:** Hearing aids; grid pilots.

9) Iron–Air Batteries

Principle: Fe anode oxidizes to Fe_2O_3/Fe_3O_4 , reducing O_2 at cathode.

Advantages: Ultra-low cost; multi-day discharge.

Limitations: Low efficiency; slow kinetics.

Performance Metrics:

- Energy density: ~50 Wh/kg
 - Cycle life: >1,000 cycles
 - Safety: Excellent
- Market Availability:** Form Energy grid systems.

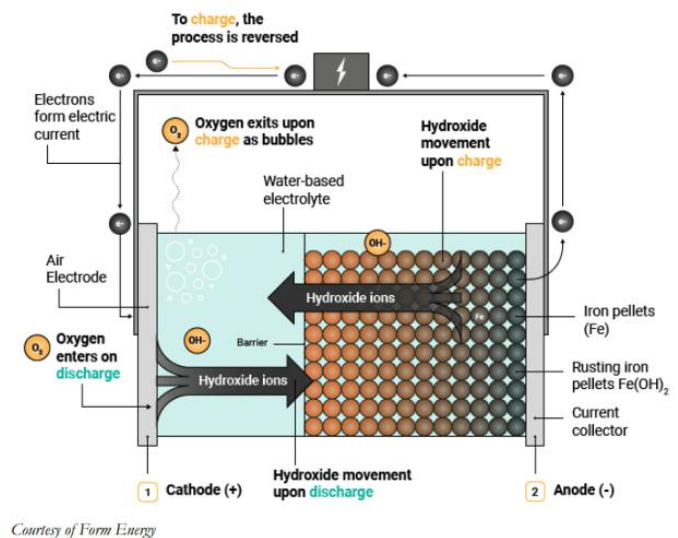


Fig.10 – Iron Air Battery technology^[20]

10) Aluminum–Air Batteries

Principle: Al anode oxidizes with O_2 ; anode replacement enables extended use.

Advantages: High theoretical energy; abundant.

Limitations: Non-rechargeable; corrosion; replacement required.

Performance Metrics:

- Energy density: 300–500 Wh/kg
 - Cycle life: Replaceable anodes
 - Safety: Good
- Market Availability:** Prototypes; commercial readiness by 2035.

4. Conclusions

A diversified EV battery strategy leveraging multiple chemistries balances performance, safety, and supply resilience. Near-term (2025–2026) sodium-ion and zinc-ion offer ready alternatives; mid-term (2028–2030) solid-state and lithium–sulfur deliver high energy; long-term (>2030) emerging aqueous systems and modular designs will further transform EV mobility.

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