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D5.4 Undergraduate/Master Curricula Implemented

Title of Course

Materials in Electrical Engineering

Title of the presentation

NEW Battery Technologies for Electric Vehicles

др Арсић Небојша

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Partnership for Promotion and Popularization of Electrical Mobility through Transformation and Modernization of WB HEIs Study Programs/PELMOB

Call: ERASMUS-EDU-2022-CBHE-STRAND-2

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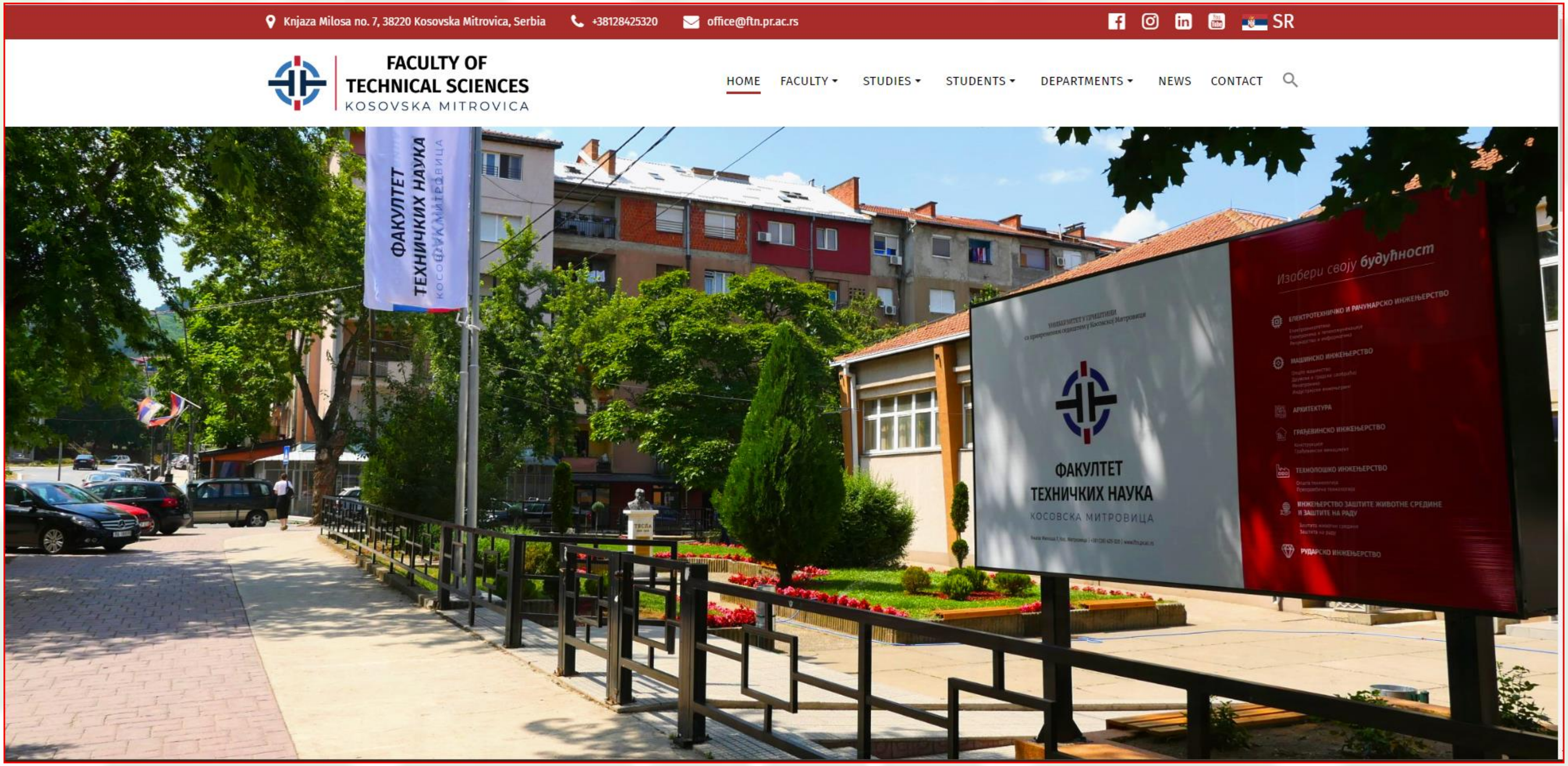

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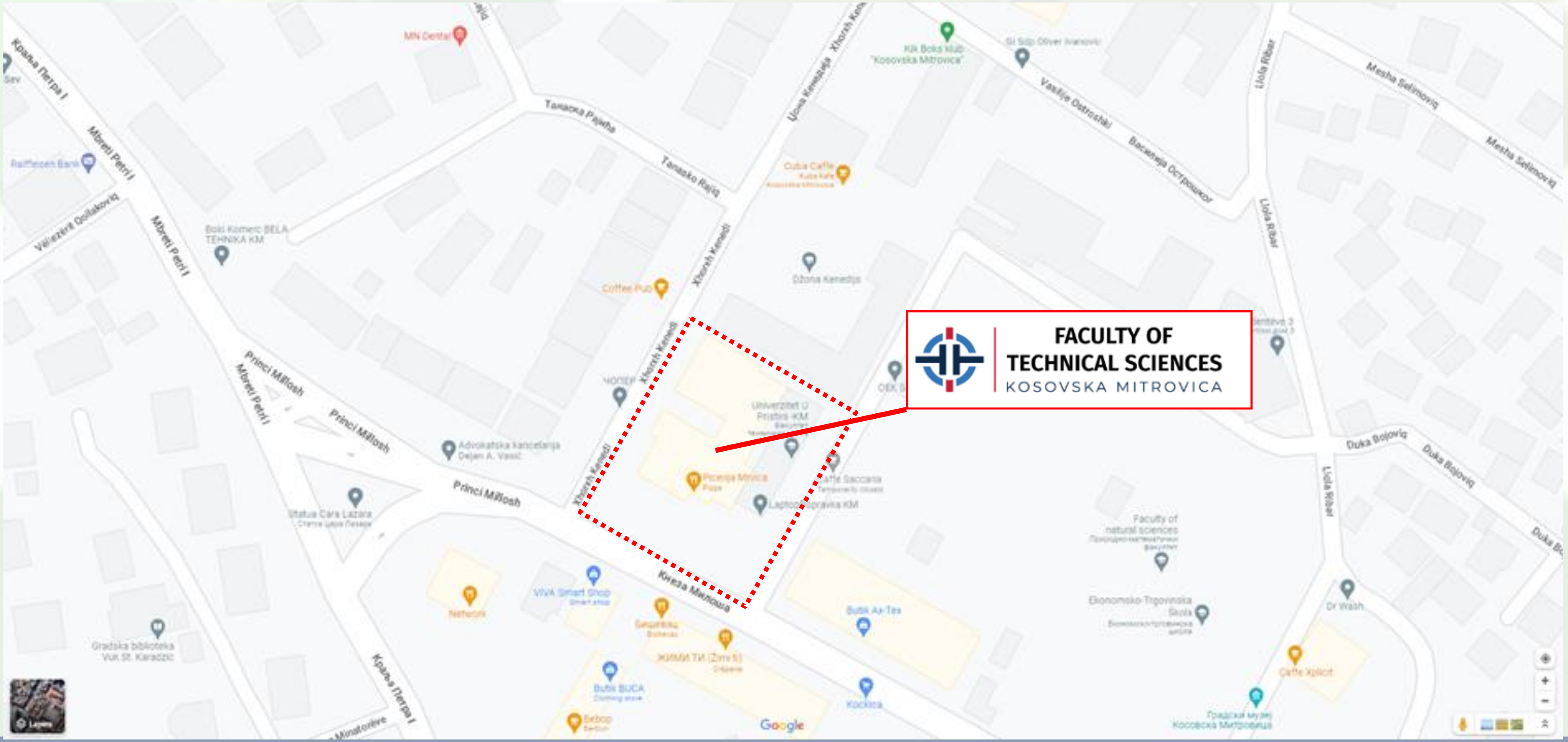


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Introduction

1. Solid-State Batteries
2. Lithium-Sulfur (Li-S) Batteries
3. Sodium-Ion (Na-Ion) Batteries
4. Potassium-Ion (K-Ion) Batteries
5. Silicon Anode Batteries (Li-Ion)
6. Cobalt-Free Batteries (Li-Ion)
7. Graphene Batteries
8. Self-Healing Batteries
9. Dual-Carbon Batteries

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1. Solid-State Batteries

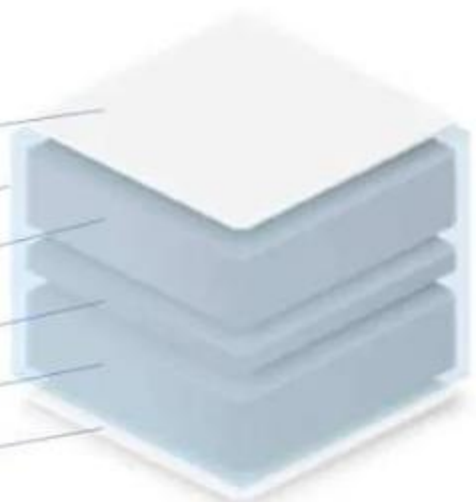
How Solid-State Batteries Work

Unlike conventional lithium-ion batteries, which use a liquid or gel electrolyte, **solid-state batteries use a solid electrolyte** (ceramic, polymer, or glass). This fundamental change brings several advantages:

- **Anode:** Typically, lithium metal (instead of graphite), enabling higher energy density.
- **Electrolyte:** Solid (e.g., sulfide, oxide, or polymer-based).
- **Cathode:** Can be traditional (NMC, LFP) or advanced (sulfur, air).

1. Solid-State Batteries

Lithium-ion with traditional liquid electrolyte



* Anode host with Liquid Electrolyte
** Cathode with Liquid Electrolyte

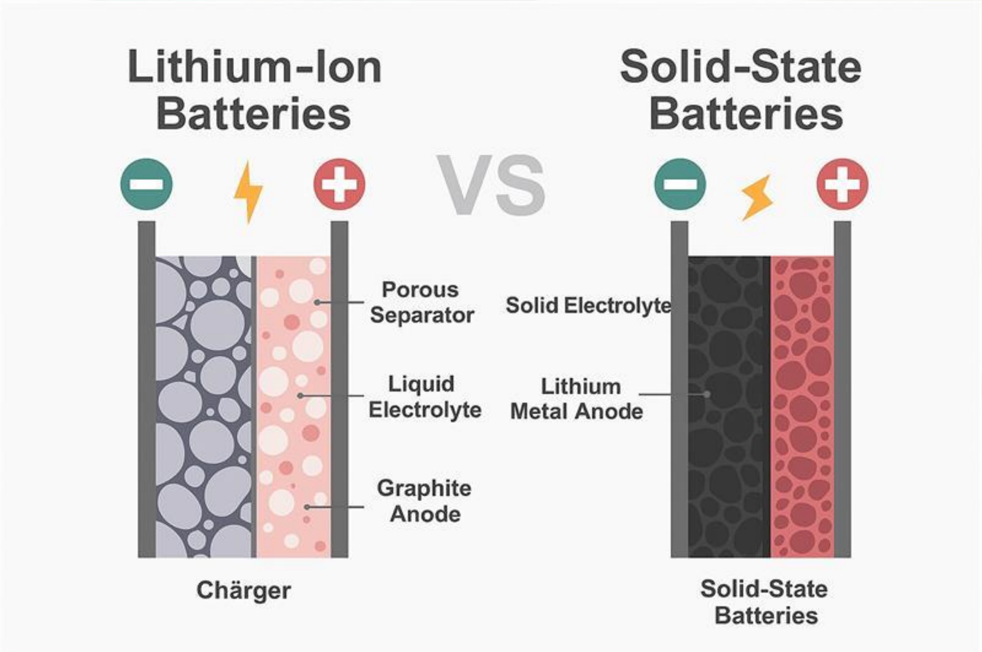
Current Li-ion cells have a composite cathode and a host anode separated by a porous polymer layer. Liquid electrolyte is injected and slowly percolates throughout the cell.

Lithium-metal with Nuvvon solid electrolyte

† SPE: active layer of Solid Polymer Electrolyte as Separator
†† Cathode EPE: pre-mixed Electrode Polymer Electrolyte as the solid Catholyte

Nuvvon's solid polymer electrolytes provide both the active separator and the catholyte. No liquids or gels or nanoparticles. Ionically conductive across a wide temperature range (currently -10 to 80°C)

1. Solid-State Batteries



1. Solid-State Batteries

Lithium-ion Battery	Solid State Battery
1. Electrolyte Material:	
Li-ion batteries use liquid or gel electrolytes that facilitate the movement of lithium ions between the electrodes during charging and discharging.	Solid-state batteries utilize solid electrolytes, which are typically ceramic or polymer-based materials that enable ion transport between the electrodes.
2. Safety	
Li-ion batteries have a small risk of thermal runaway and potential for electrolyte leakage, which can lead to fire or explosion in extreme cases.	Solid-state batteries are generally considered safer because they eliminate the flammable liquid electrolytes, reducing the risk of leaks, spills, and thermal runaway.
3. Energy Density	
Li-ion batteries have a mature technology base and currently offer relatively high energy density, allowing them to store a significant amount of energy in a given volume.	Solid-state batteries have the potential to achieve even higher energy density than Li-ion batteries, which could lead to longer-lasting batteries with extended runtimes.
4. Charging Speed	
Li-ion batteries typically have slower charging rates due to limitations in ion mobility within the liquid electrolyte.	Solid-state batteries have the potential for faster charging due to improved ion conductivity in the solid electrolytes, allowing for quicker charge transfer.
5. Cycle Life	
Li-ion batteries have a finite cycle life and gradually lose their capacity over time as they undergo charge and discharge cycles.	Solid-state batteries have the potential for a longer cycle life, enabling them to withstand more charge and discharge cycles without significant capacity degradation.
6. Commercial Avialbility	
Li-ion batteries are well-established, widely used, and commercially available in various sizes and configurations for numerous applications.	Solid-state batteries are still in the research and development phase, with limited commercial availability. Large-scale production and market adoption are yet to be realized.

Materials in Electrical Engineering

New Battery Technologies for Electric Vehicles

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1. Solid-State Batteries

COMPARISON

Liquid or gel (flammable)	Solid (non-flammable)
150-250 (Current)	300-500+ (Potential)
Up to 400+ miles (Current)	600+ miles (Potential)
20-60 minutes (Current)	10-15 minutes (Potential)
Lower (Risk of thermal runaway)	Higher (Reduced risk of thermal runaway)
1,000-3,000 (Typical)	8,000-10,000+ (Potential)
Decreasing, LFP more cost-effective (Current)	Higher (Current), Potential for parity in mid-2030s
Mature, widely available	Development & early production stages
Established, robust	Developing, challenges in scaling & material sourcing

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1. Solid-State Batteries

Key Advantages Over Lithium-Ion Batteries

Feature	Lithium-Ion (Current)	Solid-State (Future)
Energy Density	~250-300 Wh/kg	400-500+ Wh/kg (2x improvement)
Charging Speed	20-80% in ~30 min	0-80% in ~10 min
Safety	Flammable liquid electrolyte	Non-flammable solid electrolyte
Lifespan	~1,000-2,000 cycles	5,000+ cycles (expected)
Temperature Range	Degrades in extreme cold/heat	Better performance in extreme temps

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1. Solid-State Batteries

Why Solid-State Batteries Are a Game-Changer for Evs

1. **Longer Range** – With 2-3x higher energy density, EVs could achieve **600-1,000+ miles per charge** (vs. ~300-400 today).
2. **Faster Charging** – Could recharge in **minutes**, comparable to gas refueling.
3. **Safer** – No liquid electrolyte means **no fires/explosions** (a major issue with current batteries).
4. **Smaller & Lighter** – Higher energy density allows for **smaller battery packs**, freeing up space in vehicles.
5. **Longer Lifespan** – Expected to last **2-3x longer** than lithium-ion, reducing replacement costs.

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1. Solid-State Batteries

Who's Leading Solid-State Battery Development?

Company	Progress	Estimated Mass Production
Toyota	Prototype with 900+ km range, aiming for 2027-2030	2027-2030
QuantumScape (VW-backed)	800+ cycles tested, targeting 2025-2026	2025-2026 (limited scale)
Solid Power (BMW, Ford)	Pilot production in 2024, EVs by 2026	2026-2028
Nissan	Plans pilot plant by 2025, EVs by 2028	2028
Samsung SDI	Prototypes with 500 Wh/kg, targeting 2027	2027+

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1. Solid-State Batteries

Challenges Holding Back Solid-State Batteries

1. Manufacturing Complexity & Cost

- Solid electrolytes (e.g., ceramics) are expensive to produce.
- Current prototypes cost **5-10x more** than lithium-ion.
- Scaling up production is difficult (Toyota, QuantumScape working on solutions).

2. Durability Issues

- Lithium metal anodes can form **dendrites** (needle-like growths), causing short circuits.
- Solid electrolytes can crack under repeated charging cycles.

3. Material Limitations

- Finding a **chemically stable, highly conductive solid electrolyte** is challenging.
- Some materials (e.g., sulfide-based) degrade in moisture, complicating production.

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1. Solid-State Batteries

When Will We See Solid-State EVs?

- **2025-2027:** Limited production (luxury/high-performance EVs).
- **2028-2030:** Mass-market adoption expected.
- **Beyond 2030:** Potential dominance if costs drop.

First EVs Likely to Use Solid-State Batteries:

- **Toyota** (2027-2030)
- **BMW** (with Solid Power, ~2026-2028)
- **Lucid Motors** (exploring SSBs for ultra-long-range models)

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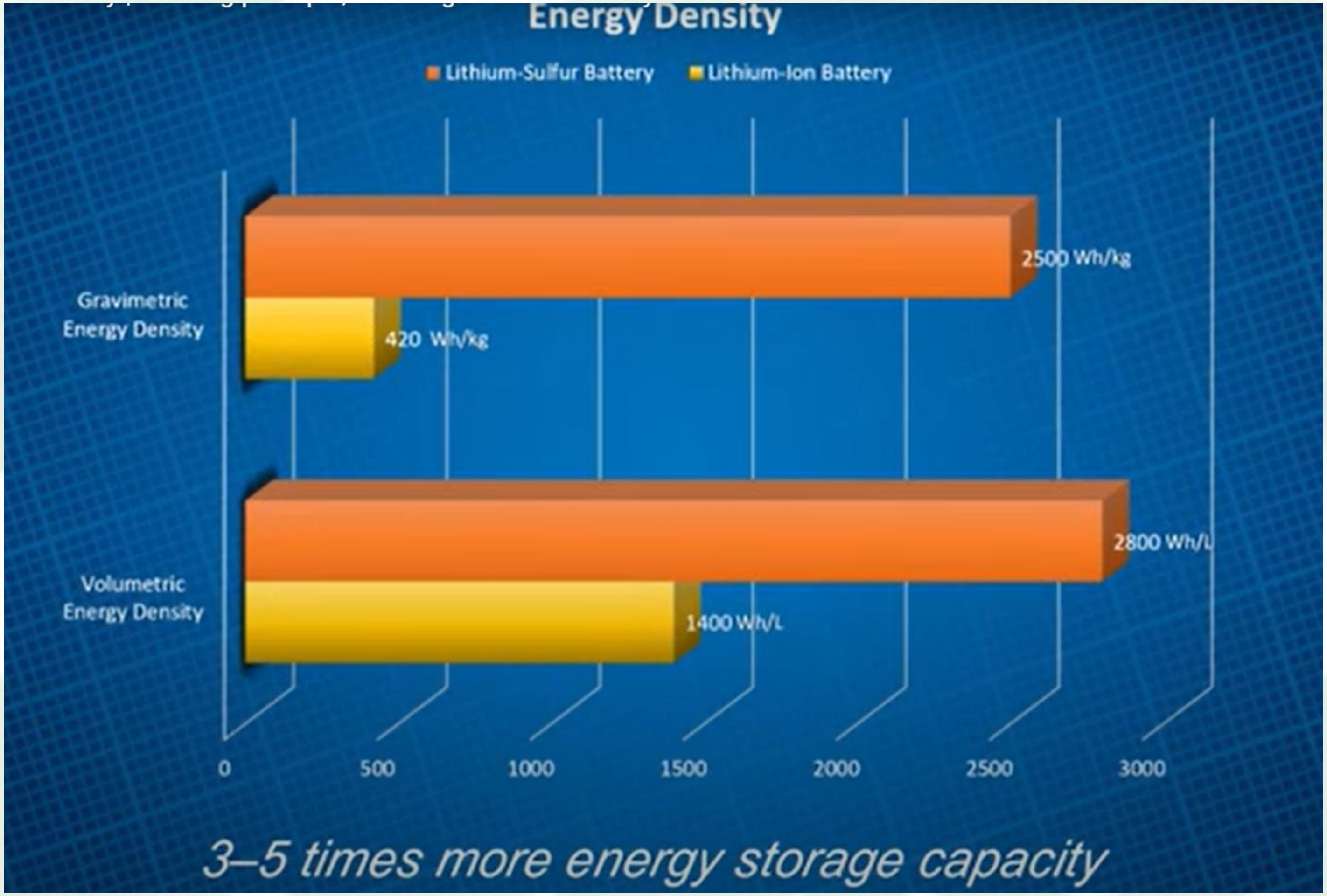
The Future of Solid-State Batteries

Solid-state batteries could revolutionize EVs by **doubling range, slashing charging times, and improving safety**. However, **high costs and manufacturing challenges** must be overcome before they become mainstream.

Outlook:

- **Short-term (2025-2027):** Limited high-end EVs.
- **Long-term (2030+):** Potential to replace lithium-ion entirely.

2. Lithium-Sulfur (Li-S) Batteries



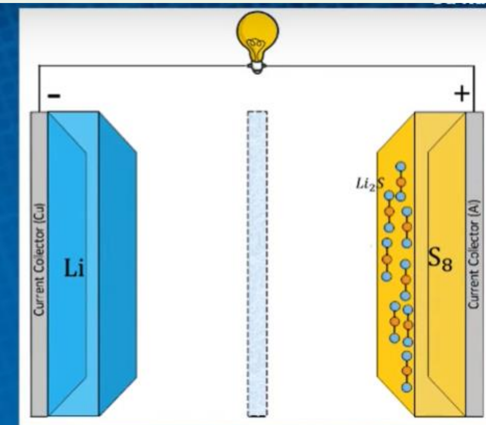
Materials in Electrical Engineering

New Battery Technologies for Electric Vehicles

2. Lithium-Sulfur (Li-S) Batteries

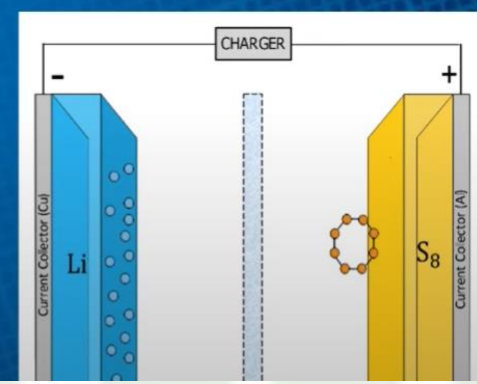
At negative electrode:

$$\mathrm{Li} \underset{\text{Charging}}{\overset{\text{Discharging}}{\rightleftarrows}} \mathrm{Li}^{+} + e^{-}$$

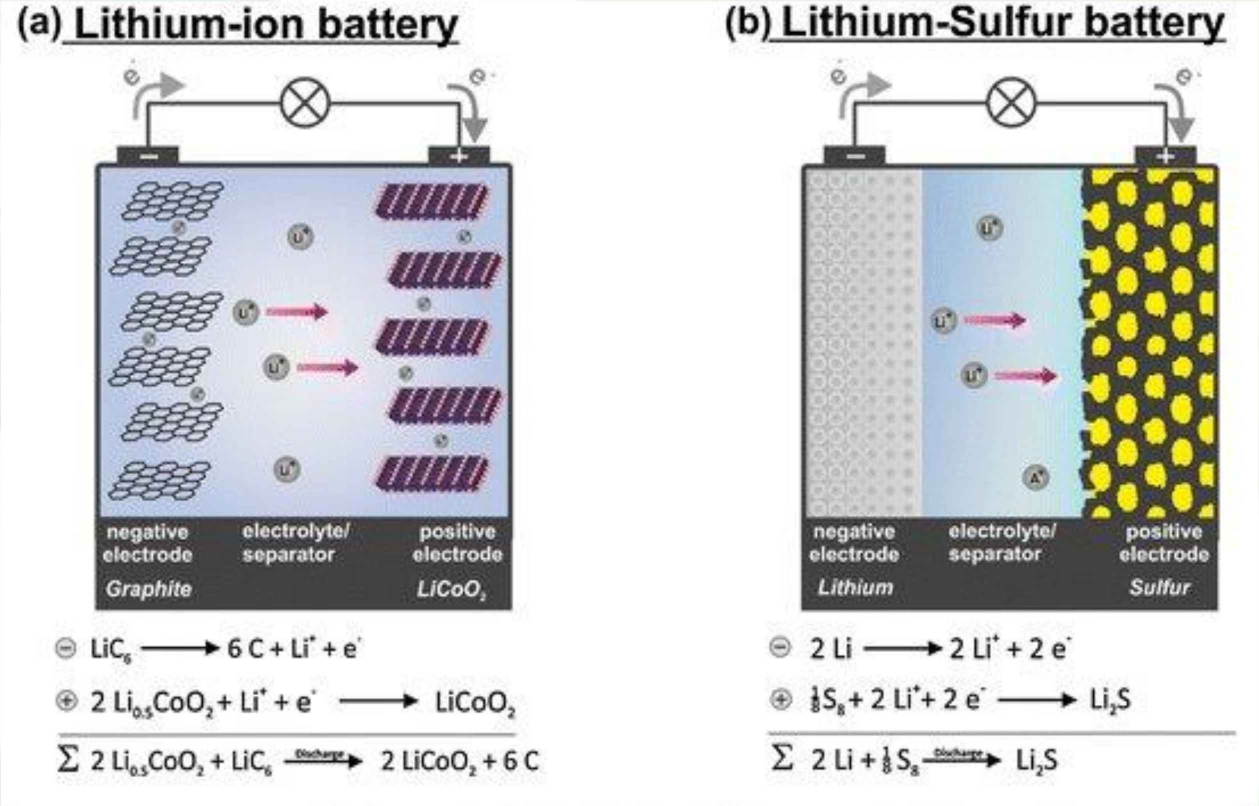


At positive electrode:

$$S_8 + 16\mathrm{Li}^{+} + 16e^{-} \underset{\text{Charging}}{\overset{\text{Discharging}}{\rightleftarrows}} 8\mathrm{Li}_2\mathrm{S}$$

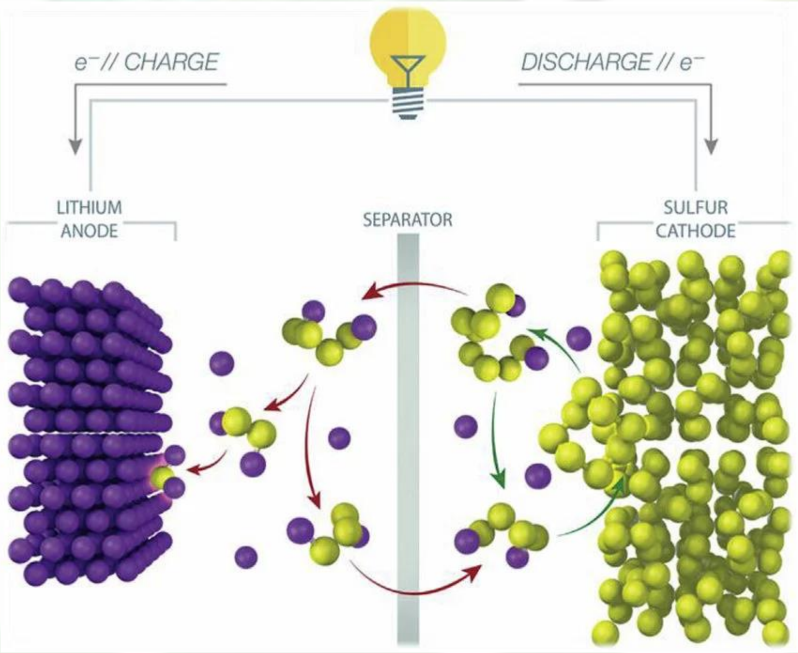


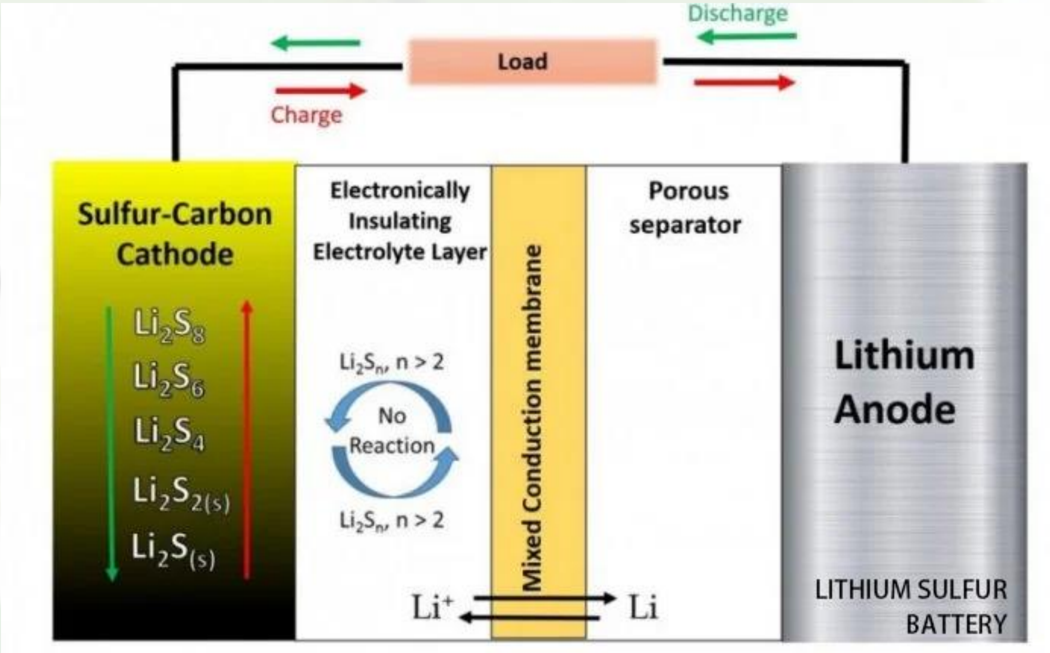
2. Lithium-Sulfur (Li-S) Batteries



Schematic comparison of (a) the lithium-ion battery concept with graphite and LiCoO2 as electrode materials and (b) the analogue lithium–sulfur cell. The positive electrode usually consists of sulfur distributed within a porous carbon framework that provides electronic wiring. For the positive electrode, other metals such as Na, K, or Mg might be used instead of lithium

2. Lithium-Sulfur (Li-S) Batteries

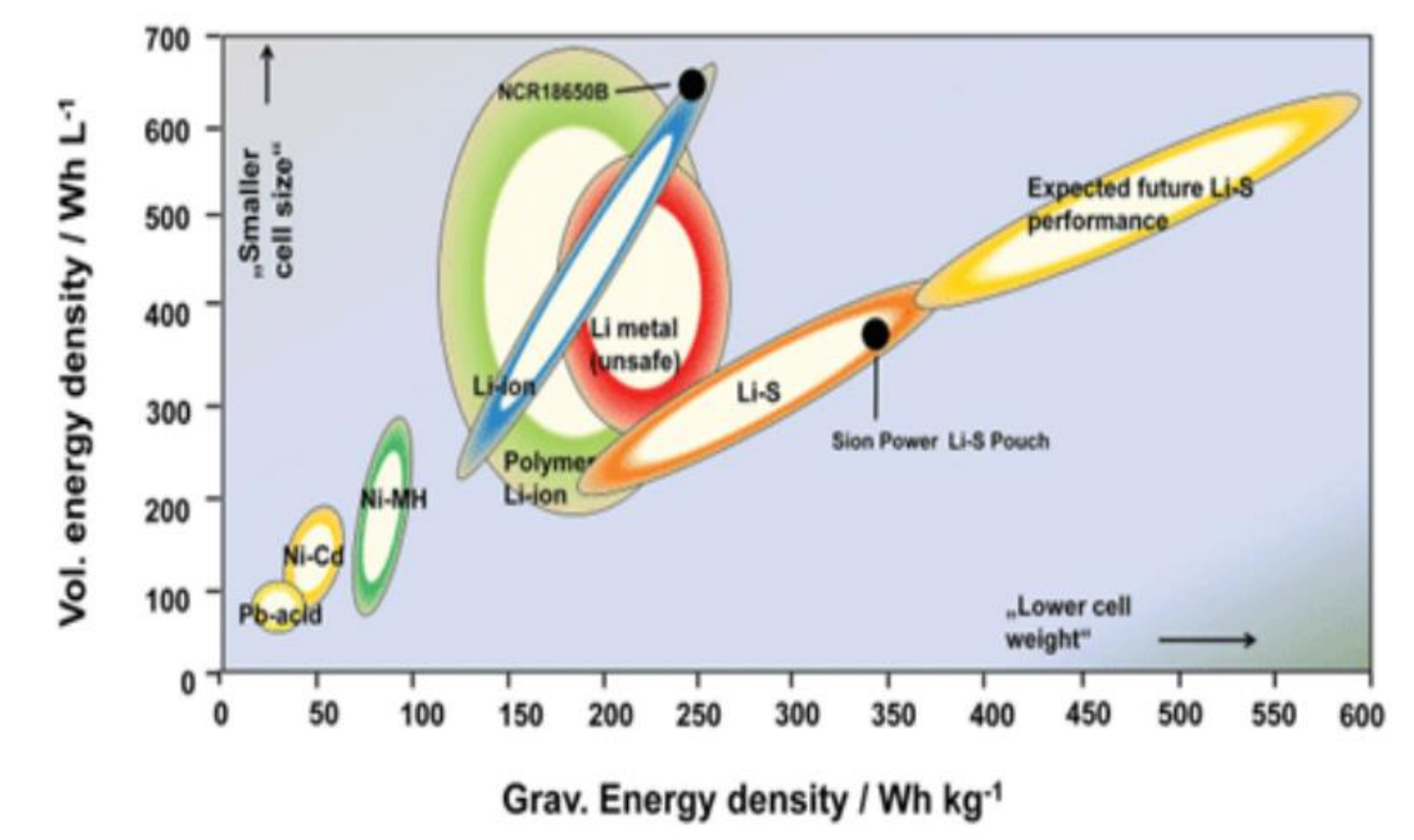




Lithium sulfur battery is a rechargeable battery that uses lithium as the anode and sulfur as the cathode. Compared to other batteries, lithium sulfur batteries are known for their high energy density and low cost potential. During the discharge process, lithium ions in the anode react with sulfur in the cathode to generate lithium sulfide and release electrons. When charging, this process will be reversed, allowing the battery to be repeatedly charged and used.

2. Lithium-Sulfur (Li-S) Batteries

Energy densities of different batteries chemistry Source ((Hagen et al., 2015)



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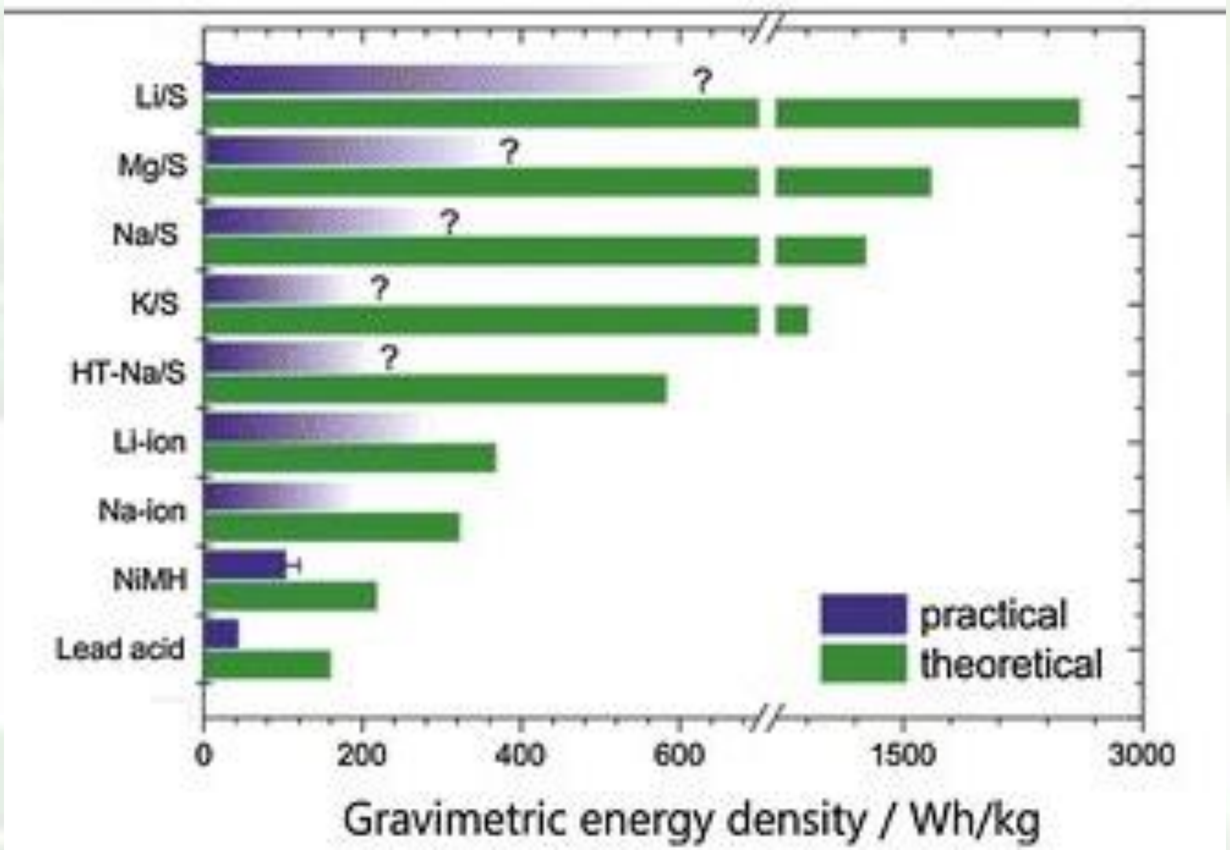
2. Lithium-Sulfur (Li-S) Batteries



The graph shows a comparison of theoretical and practical energy densities for a variety of battery types (cell level). To date, only the lead acid, the nickel metal hydride, the Li-ion, and the high temperature Na/S battery are commercialized. Practical energy densities of the metal–sulfur cells are estimates.

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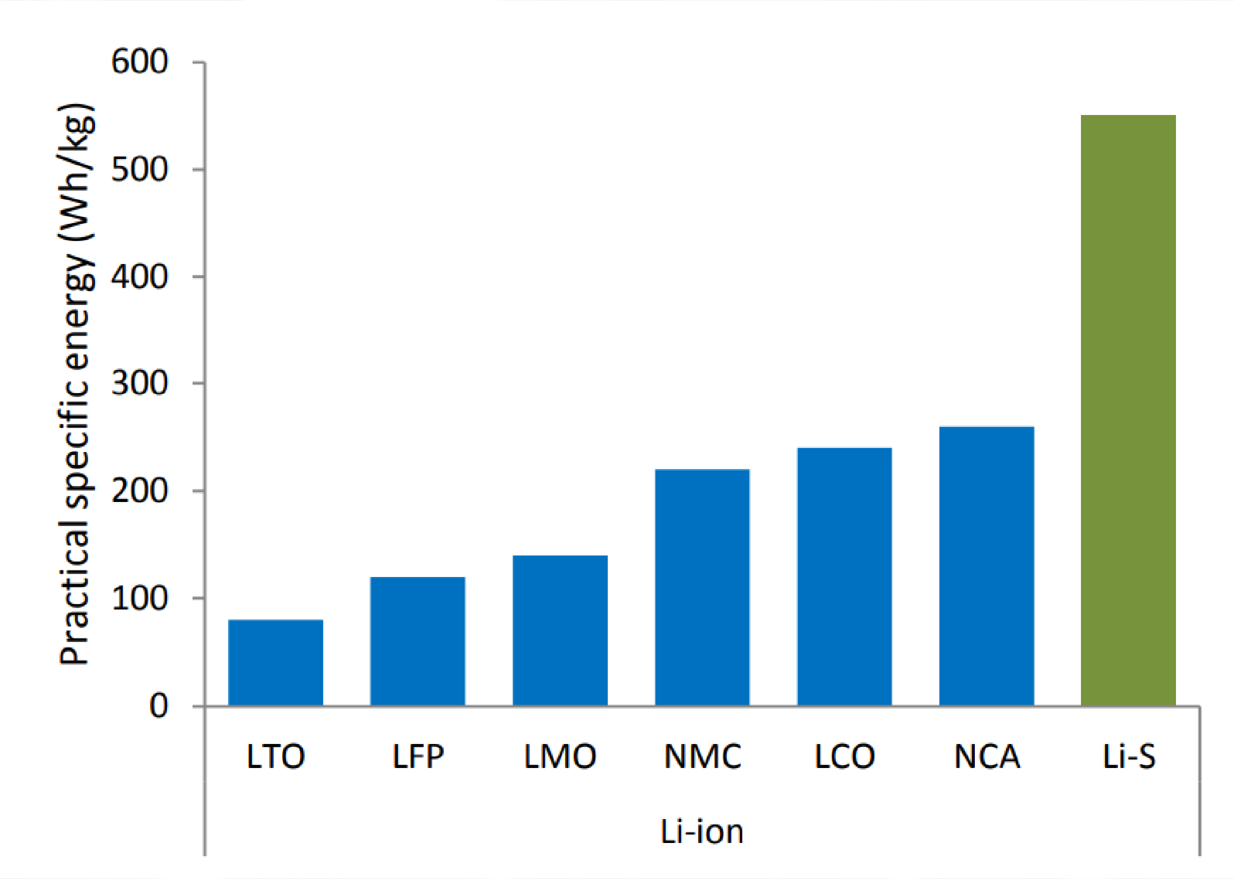
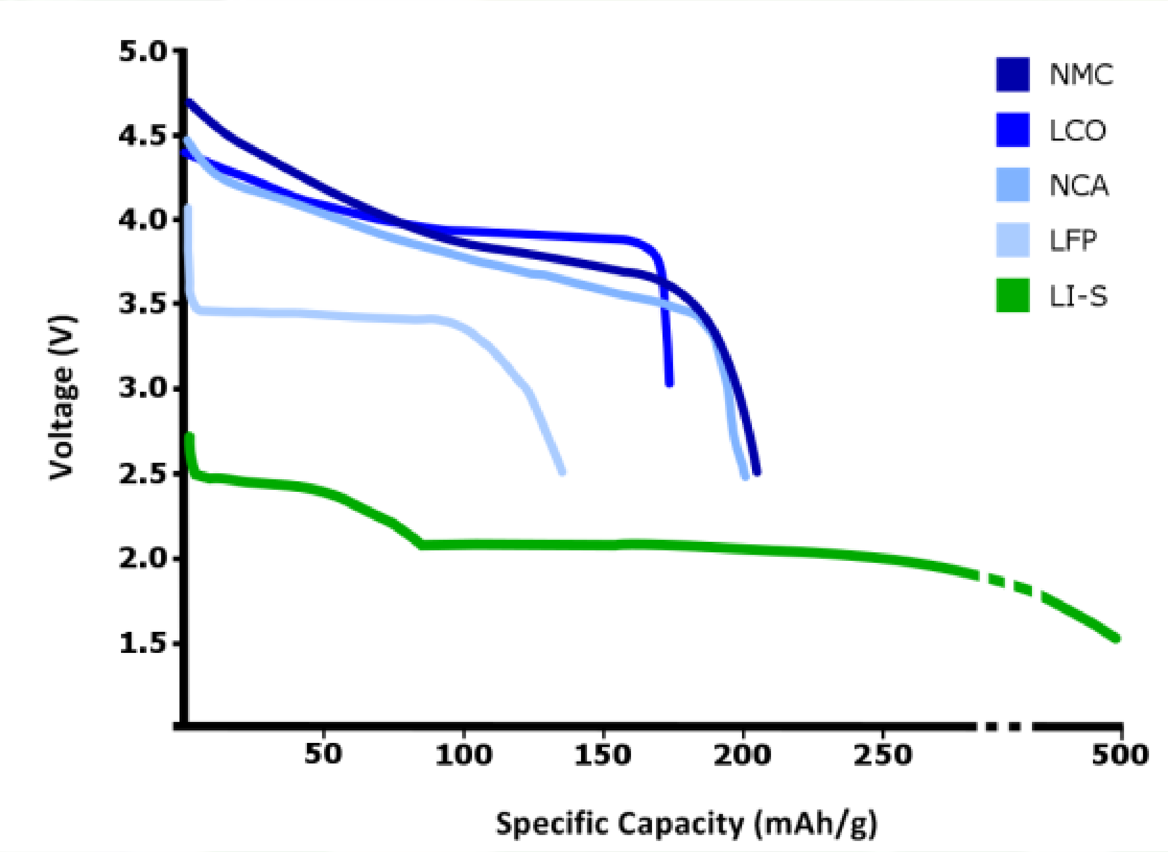
2. Lithium-Sulfur (Li-S) Batteries

Comparison of the Practical Specific Energy (Wh/kg) of Li-ion and Li-S



2. Lithium-Sulfur (Li-S) Batteries

Discharge curves of Li-S and different Li-ion chemistries



2. Lithium-Sulfur (Li-S) Batteries

Comparison of the characteristics of Li-ion and Li-S cells and batteries

	Li-ion				Li-S
	NMC	NCA	LCO	LFP	
Cell voltage (V)	3,70	3,60	3,65	3,20	2,15
Theoretical specific energy (Wh/kg)	400-600	400-600	400-600	300-400	2600
Practical specific energy (Wh/kg)	220	260	240	120	200 – 550
Practical/Theoretical correlation	≈ 1/2,5	≈ 1/2,5	≈ 1/2,5	≈ ½	≈ 1/10
Power density (W/L)	320	270	450	200	100-200
Cycle life (cycles)	1000 – 2000	500	≈ 700	1000 – 2000	≈ 50
Self-Discharge Rate (month)	1%	1%	1%	1%	8-15%
Thermal runaway (ºC)	210	150	150	270	120
Work window (SOC)	15 – 95 %	15 – 95 %	15 – 95 %	15 – 95 %	0 – 100 %
Memory effect	No				Yes
Properties	High voltage, good specific capacity, high safety risk, good lifetime	High energy, high density, expensive	High safety risk, good lifetime	Long lifetime, high stability, basic low cost	High energy density, cheap, low environment al impact, low safety risk
Applications – Automotive	EV, HEV, PHEV	EV, HEV, PHEV	EV, HEV	EV, HEV, PHEV	EV

2. Lithium-Sulfur (Li-S) Batteries

Summary table of the performance of the different Lithium chemicals

	Li-ion				Li-S
	NMC	NCA	LCO	LFP	
Energy density	+	+	+	+ –	+ + +
Power density	+ +	+ +	+ +	+	+ –
Lifecycle	+ +	+ –	+	+ +	– –
Self-discharge	+ +	+ +	+ +	+ +	– –
Safety	+	–	–	+ –	+
Price	–	+ –	+ –	+	+++
Model	+ +	+ +	+	+ –	–
Environmental	–	–	– –	+ –	+ +

Li-S batteries are better qualified than Li-ion ones in safety (better), price (lower) and environmental impact (lower)

This positive aspects are not enough for Li-S to substitute Li-ion batteries in EV applications.

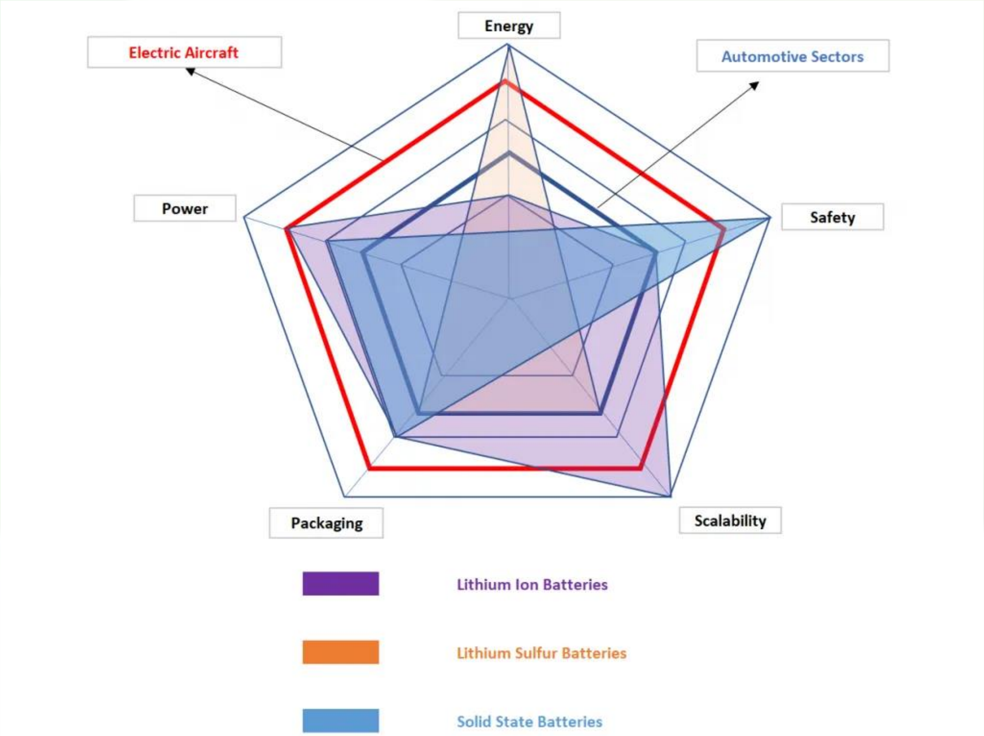
In order to have real opportunities to substitute Li-ion, Li-S batteries should get closer to Li-ion on at least three parameters: durability, self-discharge and modelling.

2. Lithium-Sulfur (Li-S) Batteries

List of element prices of the analysed batteries (USGS, 2017)

Unit value ($/t)						
Year	**Lithium**	**Aluminium**	**Cobalt**	**Nickel**	**Manganese**	**Sulphur**
2000	4.470	1.640	29.700	8.640	582	24,70
2001	1.490	1.520	23.300	5.950	529	10,00
2002	1.590	1.430	17.100	6.770	471	11,80
2003	1.550	1.500	20.600	9.630	599	28,70
2004	1.720	1.850	43.400	13.800	1.090	32,60
2005	1.460	2.010	33.600	14.700	712	30,80
2006	2.320	2.680	30.700	24.200	800	32,90
2007	3.530	2.690	54.600	37.200	1.190	32,90
2008	4.440	2.660	68.400	21.100	2.380	264
2009	4.530	1.750	34.200	14.600	1.370	1,70
2010	4.350	2.300	39.700	21.800	1.500	70,20
2011	3.870	2.560	36.100	22.900	1.460	160,00
2012	4.220	2.230	30.500	17.500	1.400	124,00
2013	6.800	2.080	28.400	15.000	1.620	68,70
2014	6.690	2.300	31.900	16.900	1.350	80,10
2015	6.500	1.940	29.600	11.800	1.210	87,60
2016	8.650	1.800	26.400	9.500	1.780	37,88
2017	13.900	2.200	58.600	10.100	1.900	60,00
Average	**4.560**	**2.063**	**35.378**	**15.672**	**1.219**	**64**

2. Lithium-Sulfur (Li-S) Batteries



Lithium sulfur (Li-S) provides an attractive battery product for traditional lithium-ion battery alternatives due to its excellent energy density, lightweight efficiency, cost reduction, and fast charging capability. For example, in the battery market such as electric vehicles, it also has certain advantages in its own batteries, which is expected to revolutionize the field of electric vehicles.

The prospects of LiSB lie in its impressive energy density and sulfur – a more abundant and less problematic material compared to the metals currently used in LIBs. With continuous progress in research and development in this field, lithium sulfur batteries are moving forward.

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2. Lithium-Sulfur (Li-S) Batteries

"0.1 C"

The term "0.1 C" in battery terminology refers to the charge/discharge rate relative to the battery's total capacity.

What Does "0.1 C" Mean?

•**Definition:**
A **C-rate** indicates how quickly a battery charges/discharges relative to its total capacity.

- **1 C** = Full capacity discharged in **1 hour** (e.g., 100Ah battery discharges at 100A).
- **0.1 C** = Discharges in **10 hours** (e.g., 100Ah battery discharges at 10A).

•**Formula:**

•Current (A)=C-rate × Battery Capacity (Ah)

Example: For a **50Ah battery**, 0.1 C = 0.1×50=5A

2. Lithium-Sulfur (Li-S) Batteries

"0.1 C"

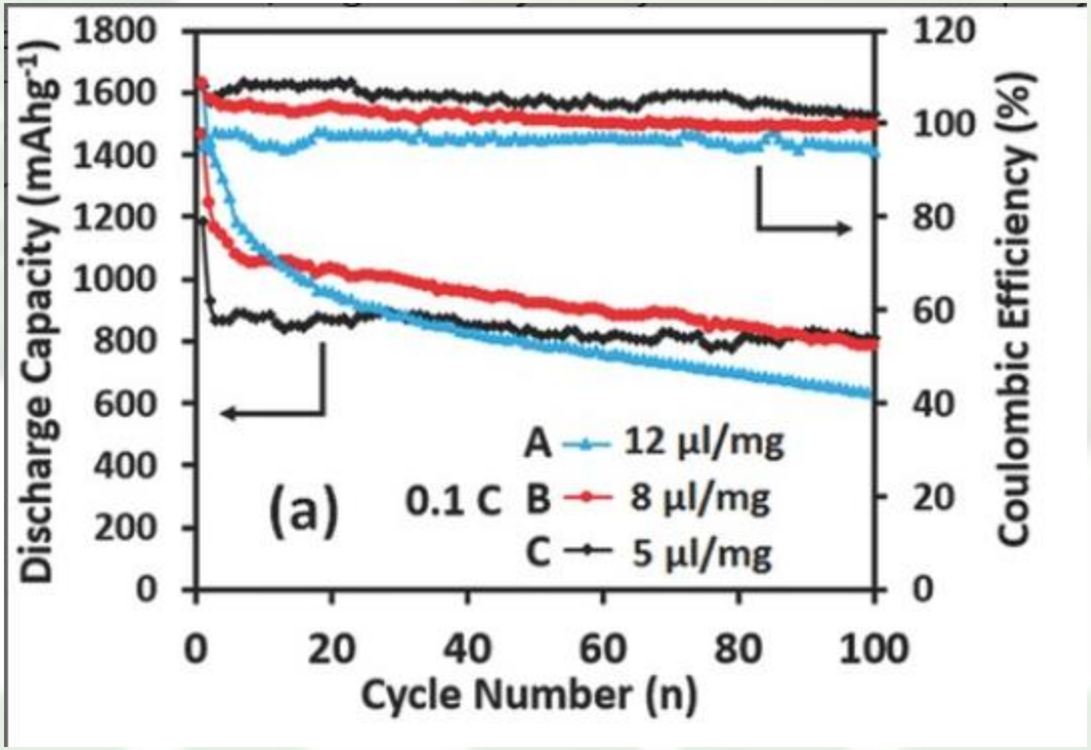
C-rate	Time to Discharge	Current (for 100Ah)	Use Case
0.1 C	10 hours	10A	Precision testing, long-life apps
1 C	1 hour	100A	EVs, power tools
2 C+	<30 mins	200A+	High-performance applications

Trade-off:

•**Higher C-rates** → More heat, lower efficiency, reduced lifespan.

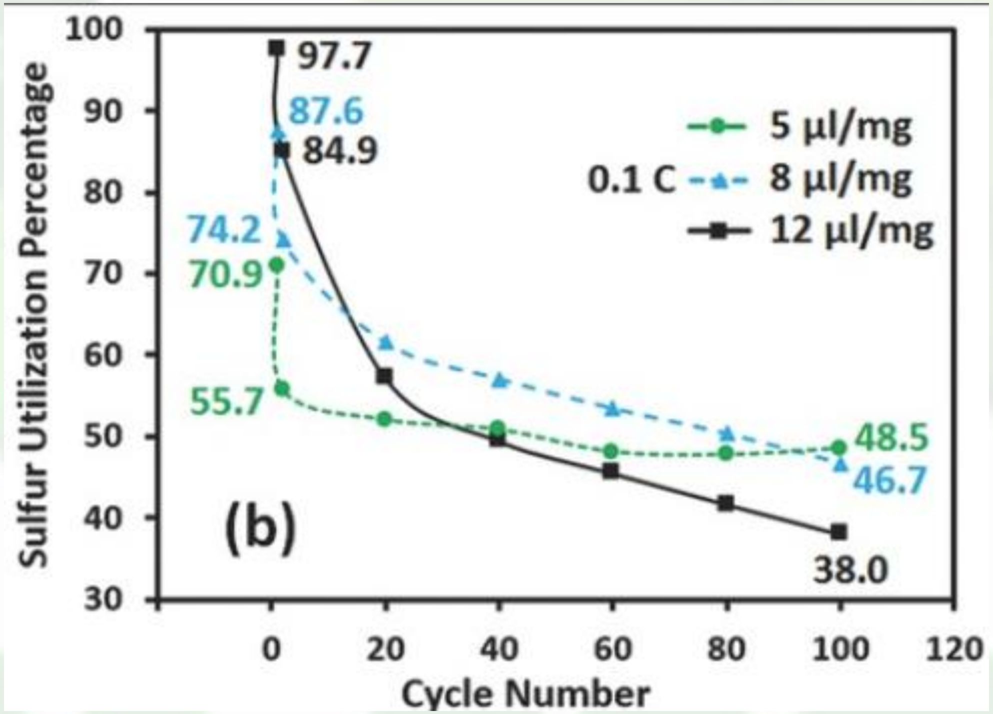
•**0.1 C** → Higher accuracy but impractical for fast charging.

2. Lithium-Sulfur (Li-S) Batteries



Long-cycle performance at 0.1 C, Li–S batteries employing different amounts of electrolytes.

2. Lithium-Sulfur (Li-S) Batteries



Sulfur utilization versus cycle numbers, Li–S batteries employing different amounts of electrolytes.

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New Battery Technologies for Electric Vehicles

3. Sodium-Ion (Na-Ion) Batteries

3. Sodium-Ion (Na-Ion) Batteries

Why Na-Ion Batteries Matter Now

•**Abundant Materials**: Sodium is 500x more common than lithium (2.6% of Earth's crust vs. 0.002%)

•**No Critical Minerals**: Eliminates need for cobalt, nickel, or lithium

•**Cost Advantage**: Projected to be 20-30% cheaper than Li-ion at scale

•**Safety Edge**: Lower fire risk due to stable chemistry

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3. Sodium-Ion (Na-Ion) Batteries

Performance Comparison: Na-Ion vs. Li-Ion

Parameter	Na-Ion	Li-Ion	Winner
Energy Density	100-160 Wh/kg	250-300 Wh/kg	Li-ion
Cycle Life	2,000-5,000 cycles	1,000-2,000 cycles	**Na-ion**
Cost ($/kWh)	$50-80 (projected)	$100-130	**Na-ion**
Cold Weather	Works to -30°C	Struggles below -20°C	**Na-ion**
Charge Time	15-30 min (fast)	20-40 min	Tie

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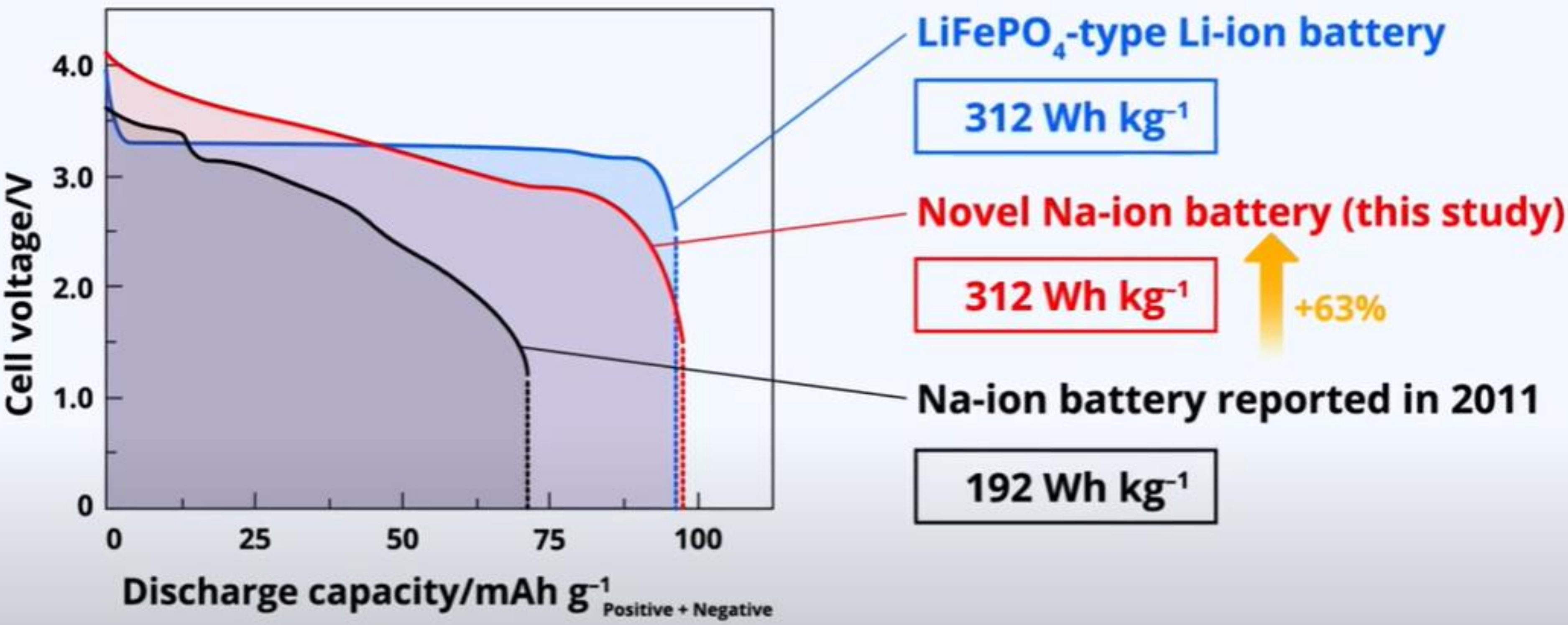
3. Sodium-Ion (Na-Ion) Batteries



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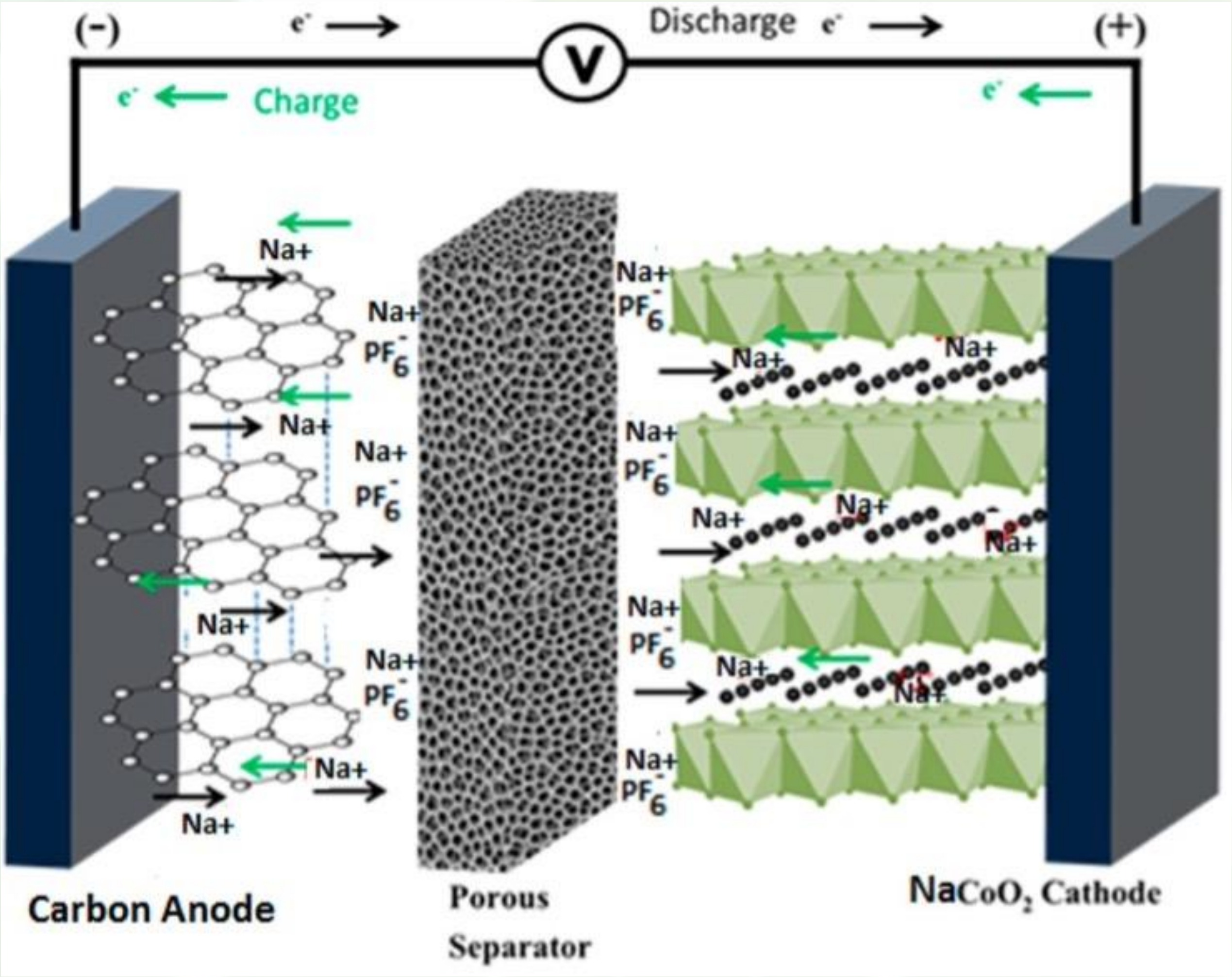

Representation of a sodium-ion battery cell

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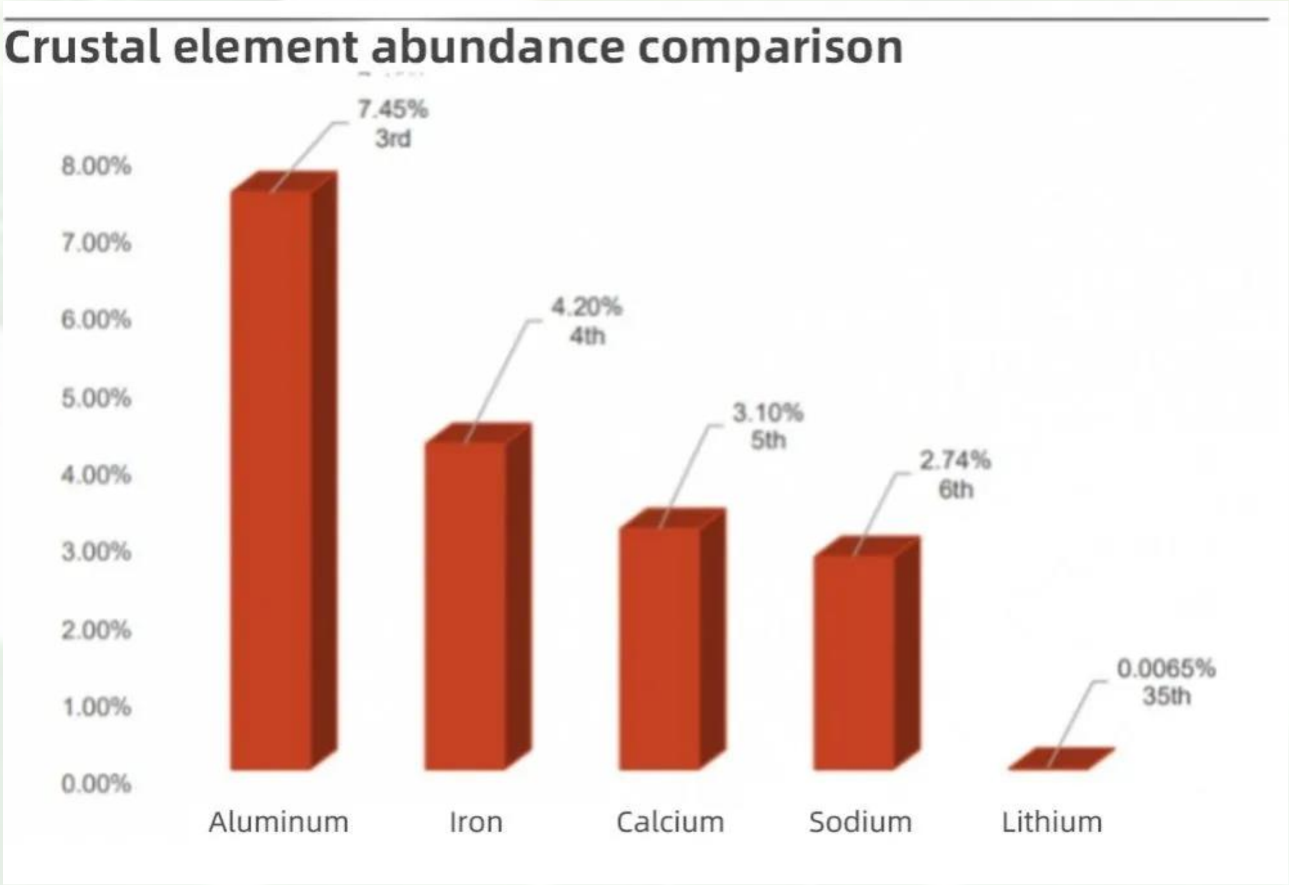

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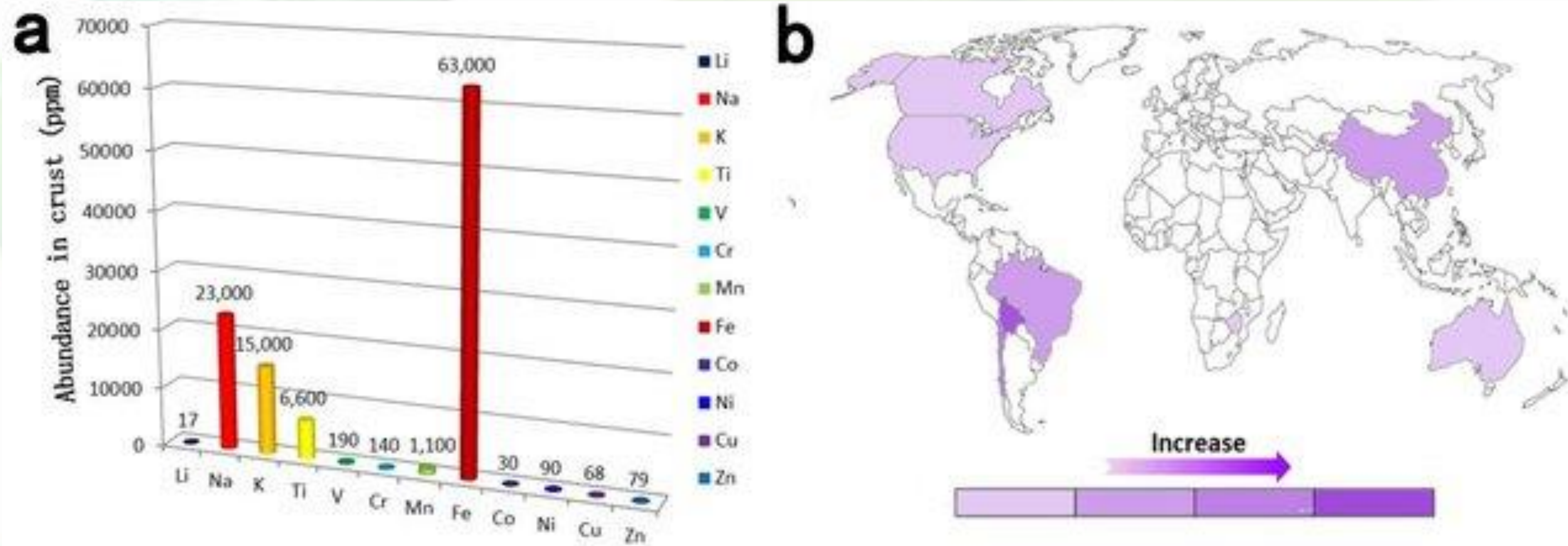

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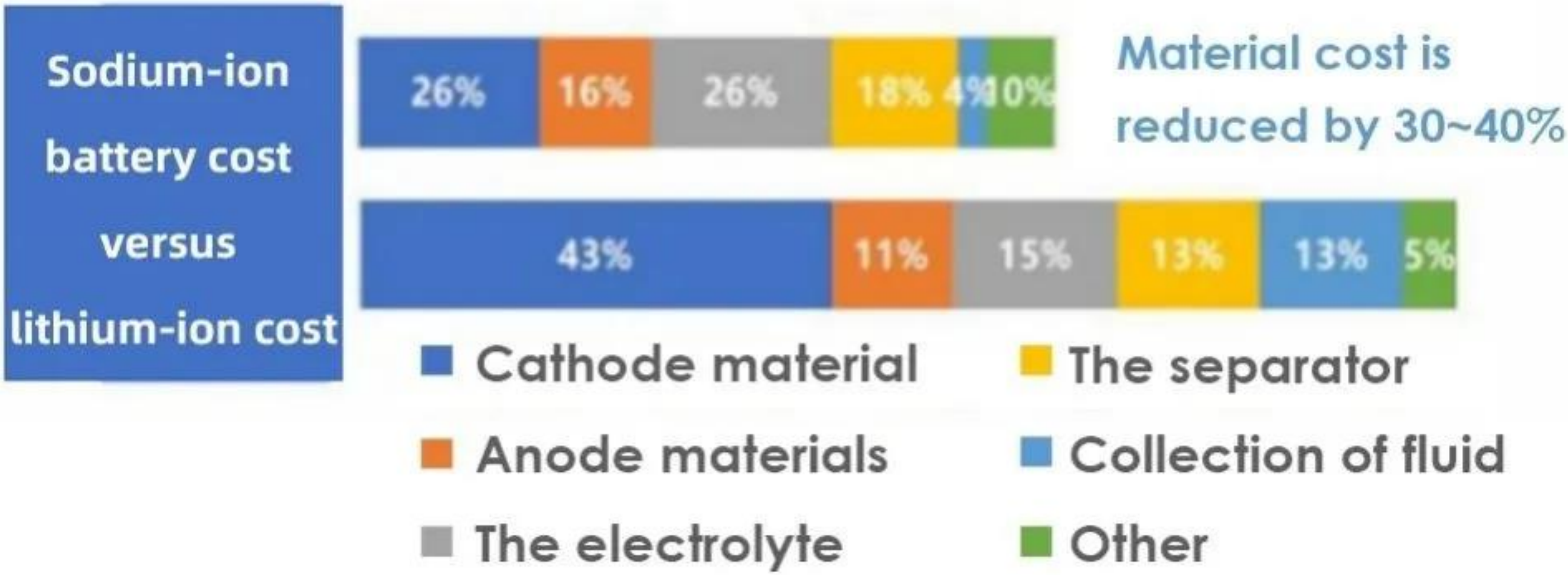
3. Sodium-Ion (Na-Ion) Batteries

The cost of sodium-ion batteries is in contrast to lithium-ion batteries



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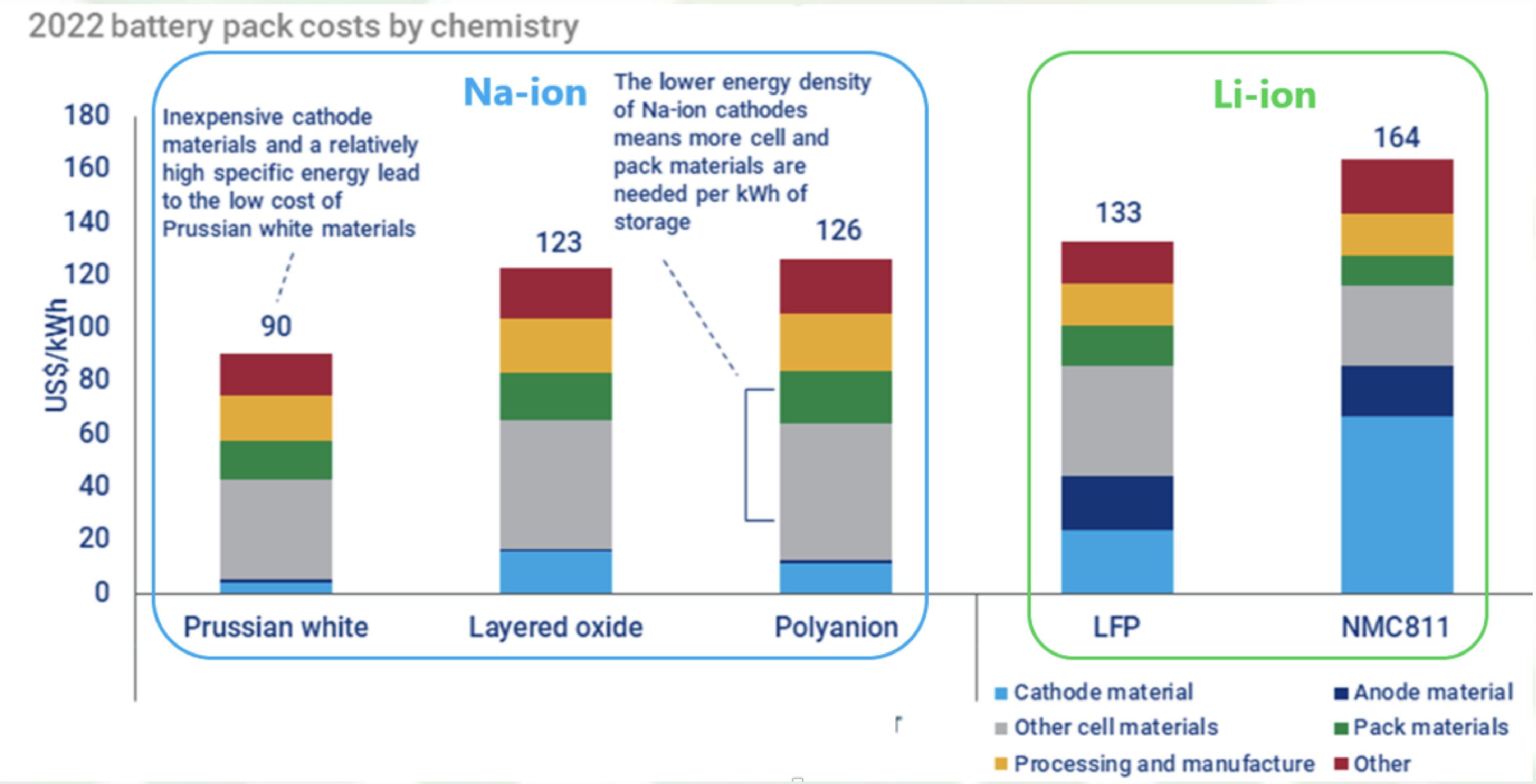
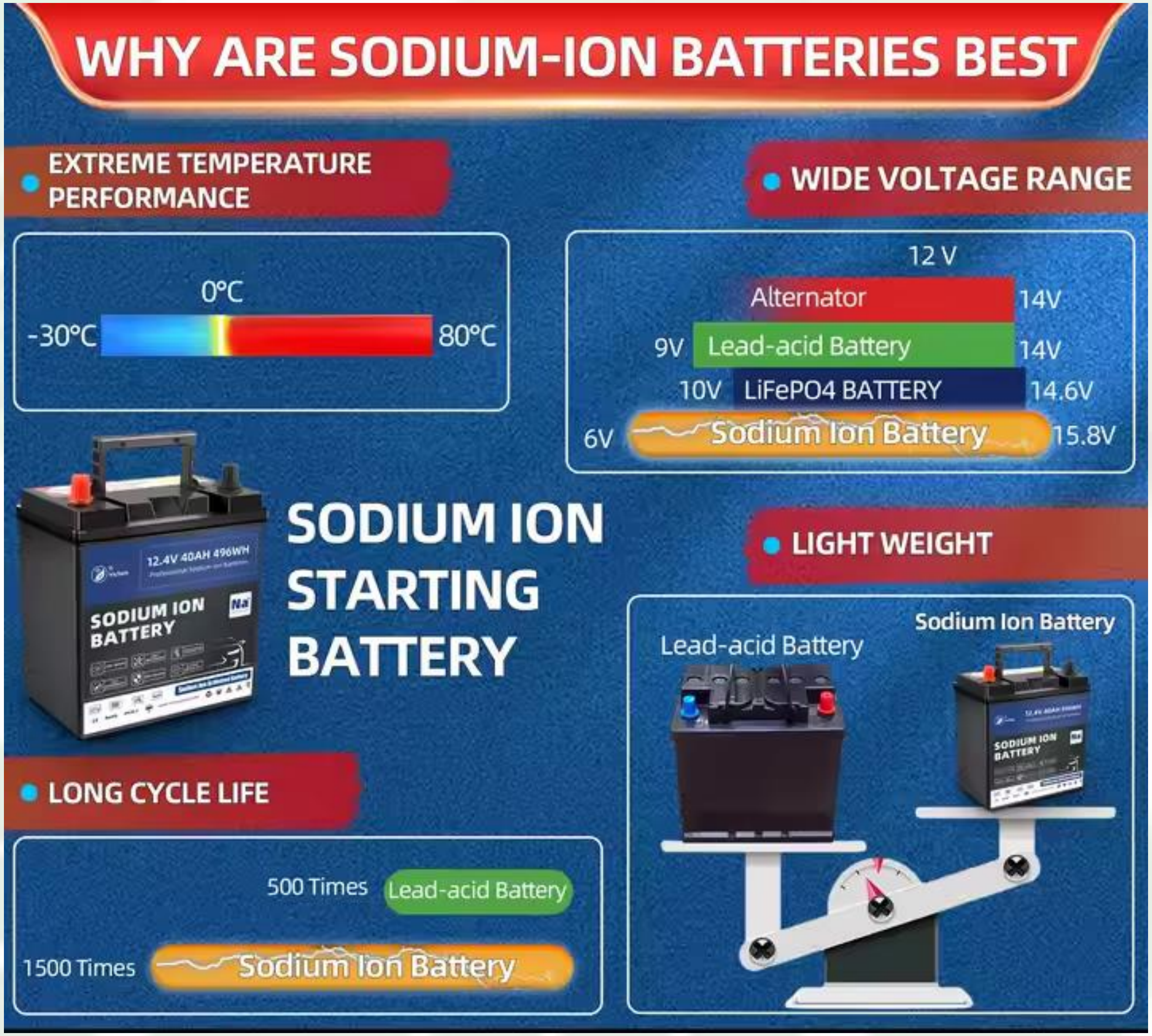


Prices for different types of batteries per energy unit

3. Sodium-Ion (Na-Ion) Batteries

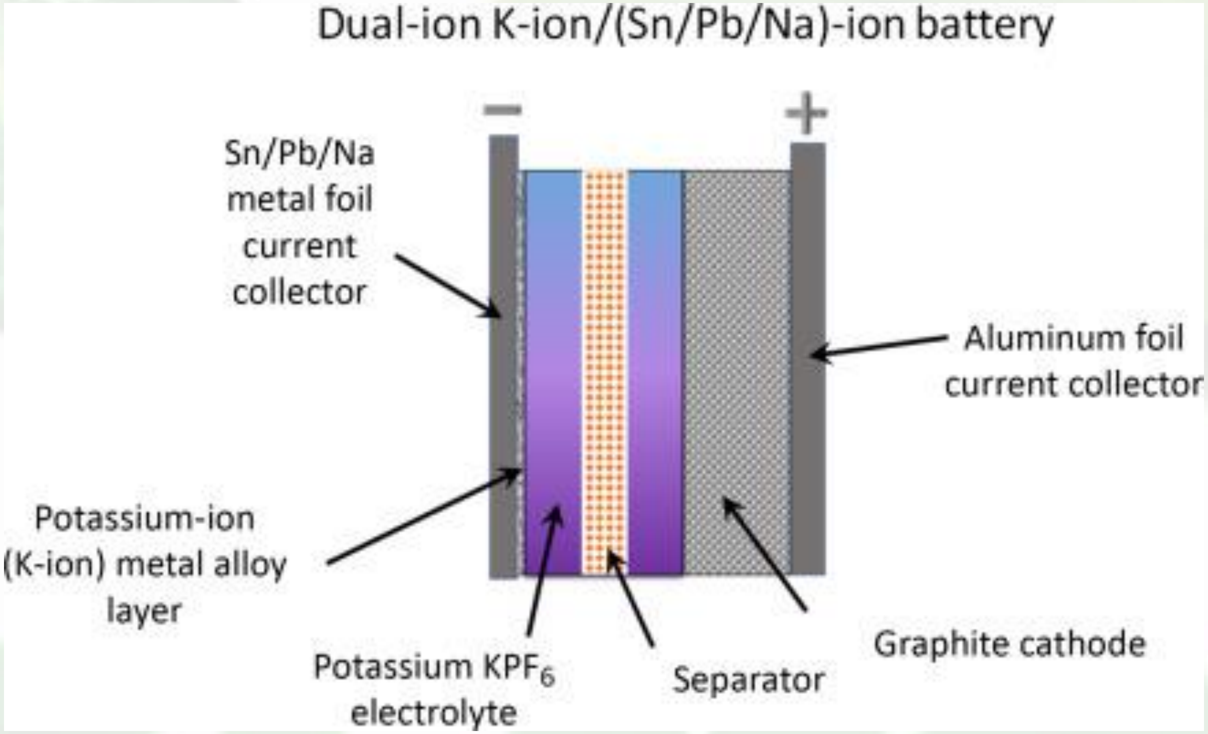


4. Potassium-Ion (K-Ion) Batteries

Why Potassium-Ion is Gaining Attention

- **Abundance:** Potassium is 880x more abundant than lithium (2.1% of Earth's crust)
- **Cost:** Potassium carbonate costs just 2/kg *vs*.30/kg for lithium carbonate
- **Voltage Potential:** K^+ has a -2.93V redox potential (close to Li^+'s -3.04V)
- **Sustainability:** Uses bio-derived materials for anodes (e.g., banana peel carbon)

4. Potassium-Ion (K-Ion) Batteries



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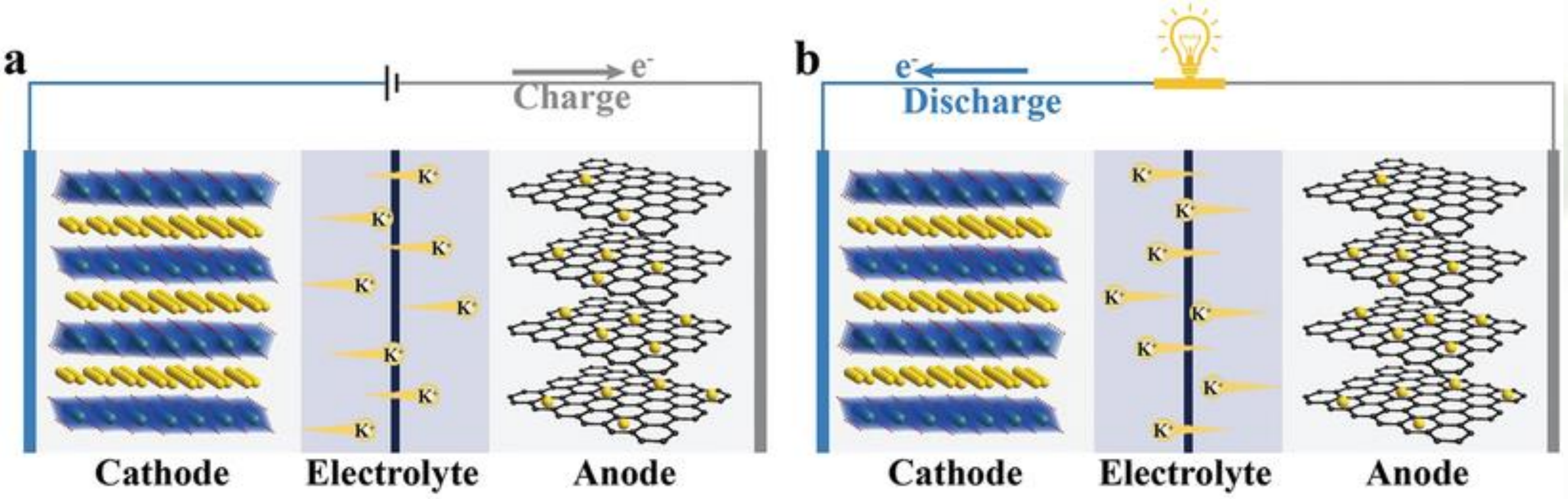
4. Potassium-Ion (K-Ion) Batteries



Schematic illustration of a typical potassium-ion battery with P2-type layered oxides as cathode and graphite as anode materials, respectively

4. Potassium-Ion (K-Ion) Batteries

Parameter	K-Ion	Na-Ion	Li-Ion
Energy Density	100-200 Wh/kg	100-160 Wh/kg	250-300 Wh/kg
Cycle Life	500-2,000 cycles	2,000-5,000	1,000-2,000
Cost Potential	$45-70/kWh	$50-80	$100-130
Ion Mobility	Faster than Na^+	Moderate	Fastest
Safety	Excellent	Good	Moderate

4. Potassium-Ion (K-Ion) Batteries

Key Advantages

1. **Faster Charging:**
   - K^+ moves 25% faster than Na^+ in electrolytes
   - Achieves 80% charge in <10 minutes in prototypes
2. **Material Flexibility:**
   - Uses conventional graphite anodes (unlike Na-ion)
   - Prussian blue cathodes avoid rare metals
3. **Temperature Resilience:**
   - Operates from -40°C to 60°C
   - Outperforms Li-ion in extreme cold

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4. Potassium-Ion (K-Ion) Batteries

Technical Challenges

- **Electrolyte Stability:**
  Potassium reacts violently with water (needs dry manufacturing)
- **Cathode Swelling:**
  K^+ is 55% larger than Li^+, causing structural stress
- **Energy Density:**
  Current prototypes only reach ~60% of Li-ion capacity

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4. Potassium-Ion (K-Ion) Batteries

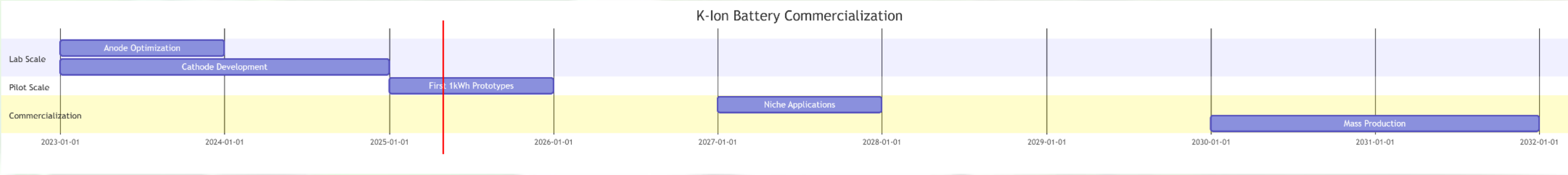
Research Breakthroughs (2023-2024)

1. **Anode Innovations:**
   - Nitrogen-doped carbon achieves 300 mAh/g capacity
   - Self-healing polymers prevent dendrites
2. **Cathode Advances:**
   - $KVPO_4F$ delivers 3.9V average voltage
   - Organic cathodes hit 500 cycles @ 90% retention
3. **Electrolytes:**
   - Concentrated "water-in-salt" electrolytes enable safety

Materials in Electrical Engineering

New Battery Technologies for Electric Vehicles

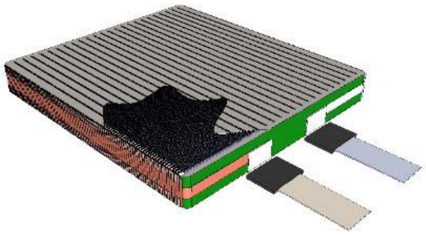
4. Potassium-Ion (K-Ion) Batteries



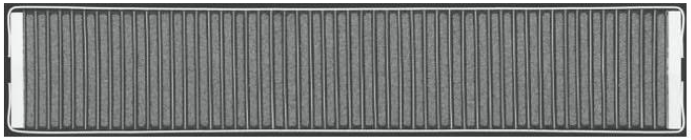
5. Silicon Anode Batteries

Silicon Anodes Improve Li-ion Batteries

Enovix 3D Silicon Lithium-ion Cell



Photomicrograph Cross-Section[1]



Silicon Anode Material Capacity

1800 mAh/cc[2]

Conventional **Wound** Lithium-ion Cell

Illustrated Cross-Section

Graphite Anode Material Capacity

800 mAh/cc[3]

[1]Source: Enovix Corporation. [2]De-rated from theoretical capacity of 2194 mAh/cc for Li trapping losses.
[3]Nominal capacity between host capacity of 841 mAh/cc and lithiated capacity of 719 mAh/cc.

5. Silicon Anode Batteries

Silicon Anodes Improve Li-ion Batteries

Francis Wang,

Si anodes have been heralded as one of the key future technology drivers for the performance of Li-ion batteries

Silicon has 10 times the gravimetric energy density of graphite anodes

5. Silicon Anode Batteries

What are Silicon Anode Lithium-Ion Batteries?

Silicon anode lithium-ion batteries are a type of rechargeable battery **where silicon replaces** the **conventional graphite in the anode**. These batteries aim to leverage the superior lithium storage capacity of silicon to achieve higher energy densities, thus offering potentially longer battery life and improved performance over traditional lithium-ion batteries.

Why is Silicon Used as an Anode?

Silicon is used as an anode material because of its exceptional theoretical capacity to store lithium ions. Silicon can hold approximately ten times more lithium than graphite, the traditional anode material. Specifically, silicon has a theoretical capacity of about 4200 mAh/g compared to graphite's 372 mAh/g. This substantial difference makes silicon a highly attractive material for enhancing the energy density of lithium-ion batteries.

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5. Silicon Anode Batteries

What is the Difference Between Silicon and Lithium Anodes?

Silicon and lithium anodes differ primarily in their material properties and performance characteristics. While lithium metal anodes offer high energy density, they are prone to dendrite formation, which can cause short circuits and safety issues. Silicon anodes, on the other hand, provide a much higher capacity for lithium-ion storage than graphite but come with their own set of challenges, such as significant volume expansion during charging cycles.

Why is Silicon Anode Battery?

Silicon anodes are considered better than traditional graphite anodes due to their higher energy storage capacity. Using a silicon anode improves energy density by allowing the battery to store more lithium ions per unit weight compared to graphite anodes. This higher capacity translates to potentially longer-lasting batteries and the ability to store more energy in a given volume, making them particularly attractive for applications requiring high energy density, such as electric vehicles and portable electronics. For electric vehicles, this translates to longer driving ranges on a single charge, and for consumer electronics, it means longer usage times between charges.

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6. Cobalt-Free Batteries

Cobalt-Free Batteries: The Future of Ethical and Affordable EVs

Cobalt-free batteries represent a major shift in lithium-ion (Li-ion) technology, eliminating **cobalt**—a costly, scarce, and ethically controversial material—while maintaining performance. Companies like **Tesla, CATL, and Panasonic** are aggressively developing these batteries to reduce costs, improve sustainability, and avoid supply chain risks.

6. Cobalt-Free Batteries

Cobalt-Free Batteries: The Future of Ethical and Affordable EVs

Why Eliminate Cobalt?

✓ **Ethical Concerns** – ~70% of cobalt comes from the **Democratic Republic of Congo (DRC)**, where mining involves child labor and unsafe conditions.

✓ **Cost Reduction** – Cobalt is expensive (~$30–50/kg), making up **10–20% of battery costs**.

✓ **Supply Chain Stability** – Cobalt is geopolitically sensitive (China controls most refining).

✓ **Performance** – New chemistries can match or exceed cobalt-based batteries.

Cobalt-Free Batteries: The Future of Ethical and Affordable

Chemistry	Cathode Material	Energy Density	Advantages	Challenges	Adoption Status
LFP (Lithium Iron Phosphate)	$LiFePO_4$	120–160 Wh/kg	Cheap, safe, long lifespan	Lower energy density	**Widely used** (Tesla Model 3, BYD)
LNMO (Lithium Nickel Manganese Oxide)	$LiNi_{0.5}Mn_{1.5}O_4$	~200 Wh/kg	High voltage (~4.7V), fast charging	Needs electrolyte optimization	**Pilot production** (CATL, LG)
NMA (Nickel Manganese Aluminum)	$LiNiMnAlO_2$	220–250 Wh/kg	Balanced performance, lower cost	Still needs refinement	**In development** (Panasonic, Tesla)
Lithium-Rich Layered Oxide	$Li_{1.2}Mn_{0.6}Ni_{0.2}O_2$	250–300 Wh/kg	Very high capacity	Voltage fade issues	**Lab stage**

6. Cobalt-Free Batteries

Green Cell CUBE LiFePO4 20Ah 12.8V 256Wh Lithium Iron Phosphate Battery for Tractor, Lawnmower, Electric Vehicles

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6. Cobalt-Free Batteries

6. Cobalt-Free Batteries

Cobalt-Free Batteries: The Future of Ethical and Affordable EVs

Advantages Over Cobalt-Based Batteries

✓ **Lower Cost** – LFP is **20–30% cheaper** than NMC ($LiNiMnCoO_2$).

✓ **Longer Lifespan** – LFP lasts **2–3x more cycles** than NMC.

✓ **Thermal Stability** – Less prone to overheating (safer for EVs).

✓ **Faster Charging** – LNMO supports **ultra-fast charging** (10–15 min).

6. Cobalt-Free Batteries

Challenges & Limitations

❌ **Energy Density Trade-Off** – Most cobalt-free batteries (except LNMO/NMA) have **lower energy density** than NMC/NCA.

❌ **Voltage & Power Limitations** – Some chemistries (like LFP) have **lower voltage (~3.2V vs. 3.7V for NMC)**.

❌ **Nickel Dependency** – Many alternatives (NMA, LNMO) still need **nickel**, which has its own supply risks.

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Who’s Leading Cobalt-Free Battery Development?

- **Tesla** – Using **LFP** in base Model 3/Y and energy storage (Megapack).
- **CATL** – Mass-producing **LFP** and developing **M3P** (Mn-enhanced LFP).
- **LG Energy Solution** – Working on **LNMO** for high-performance EVs.
- **BYD** – **Blade Battery (LFP)** with improved pack energy density.

6. Cobalt-Free Batteries

Future Outlook

•**2024–2026: LFP dominates budget EVs**, while **NMA/LNMO** enter premium markets.

•**2028–2030: Lithium-rich cathodes** could bridge the energy density gap.

•**Beyond 2030: Solid-state cobalt-free batteries** (e.g., lithium-sulfur) may emerge.

Will Cobalt Disappear Completely?

•**No**—it will still be used in niche applications (e.g., aerospace, high-end EVs).

•But **cobalt demand will drop by ~50% by 2030** (Benchmark Minerals).

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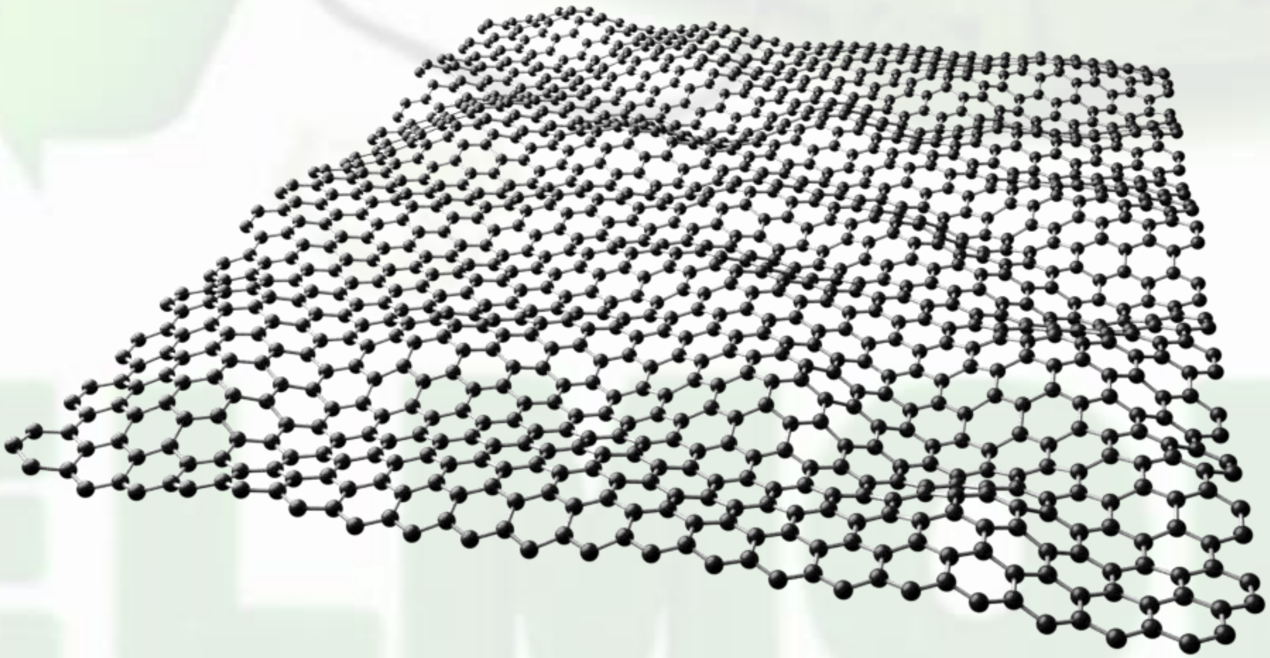
7. Graphene Batteries

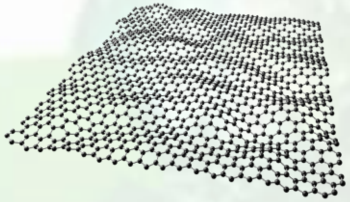
Graphene sheet: a single sheet of graphene is only one carbon atom thick.

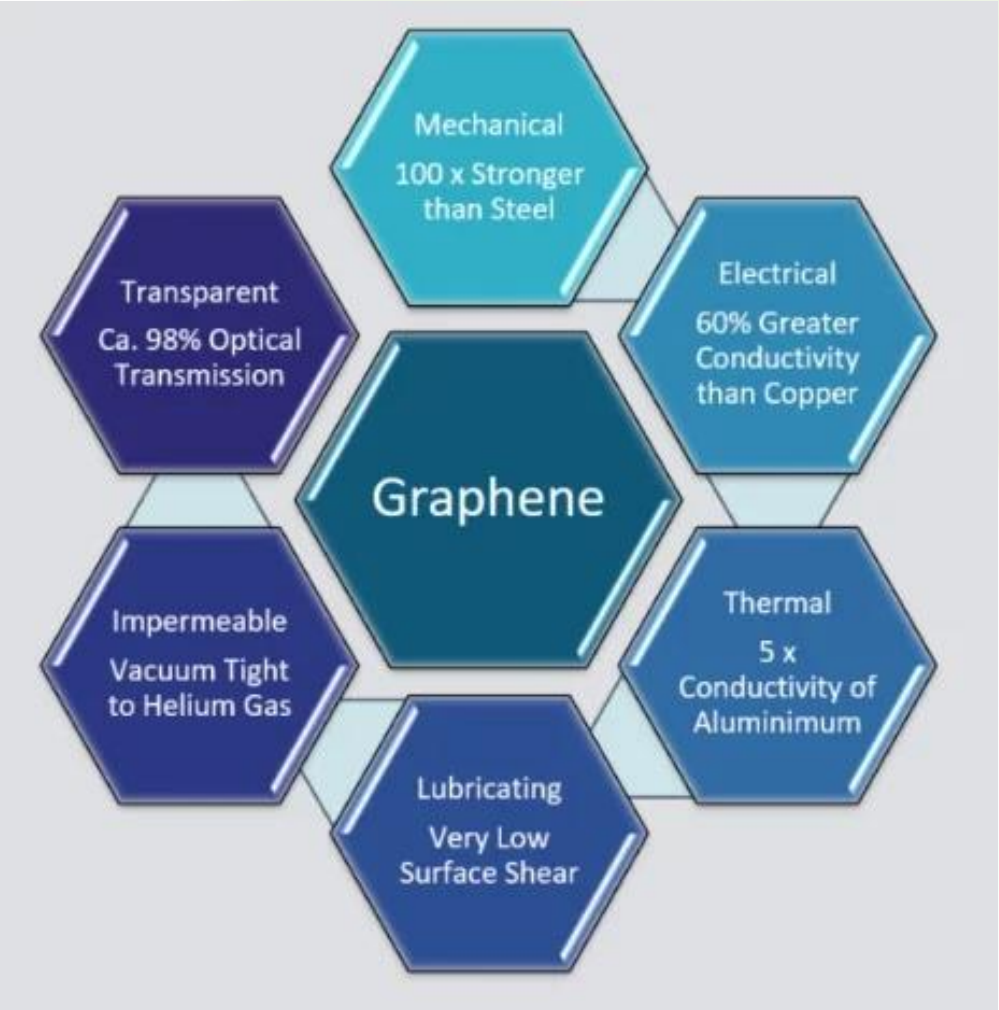
Graphene batteries are an emerging energy storage technology that leverages the unique properties of graphene—a single layer of carbon atoms arranged in a hexagonal lattice—to enhance performance over traditional lithium-ion or lead-acid batteries. Graphene's exceptional electrical conductivity, thermal stability, mechanical strength, and large surface area make it a promising material for next-generation batteries.



7. Graphene Batteries

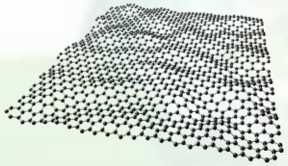
Graphen

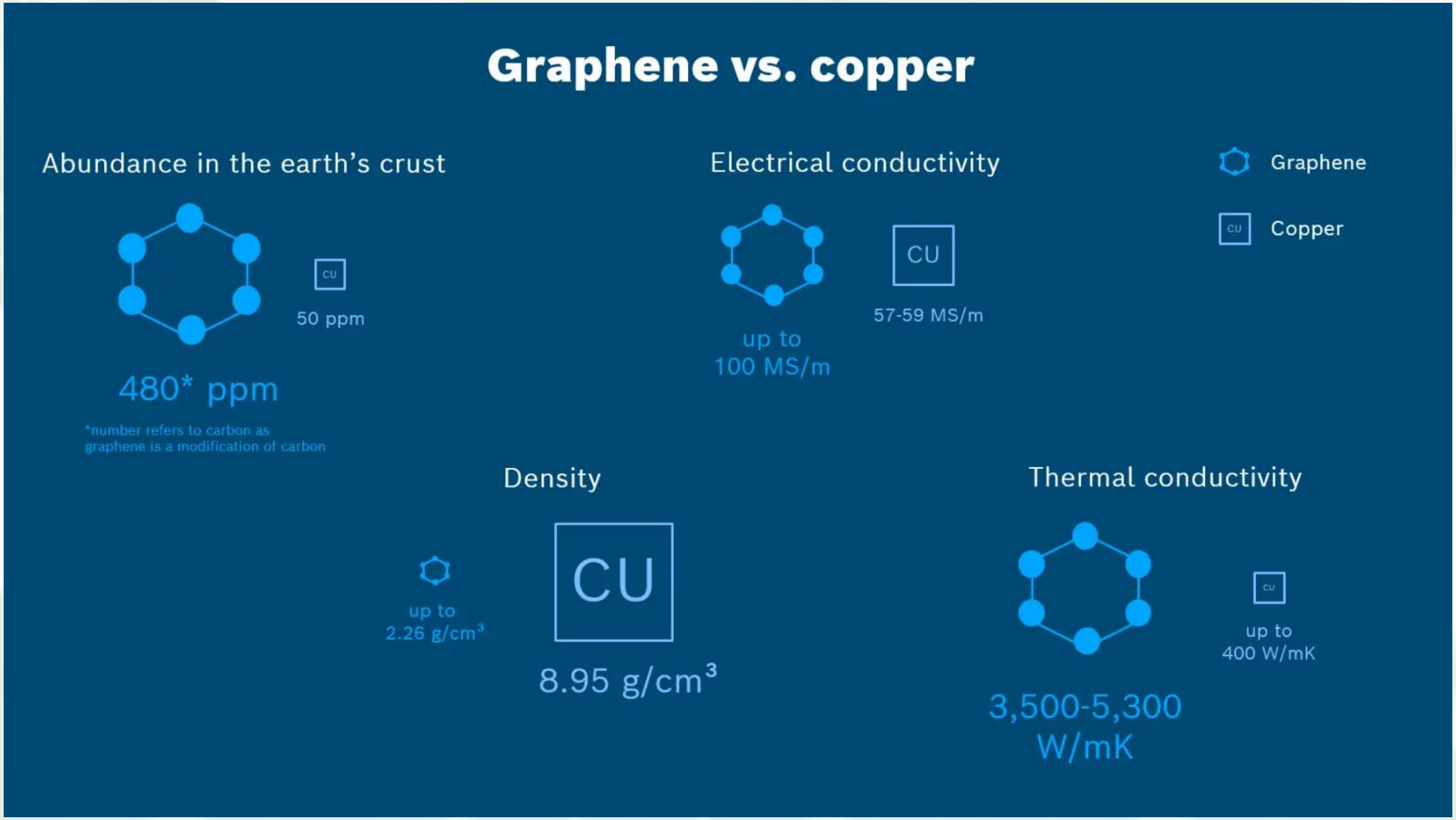




7. Graphene Batteries

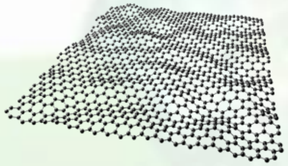
Graphen

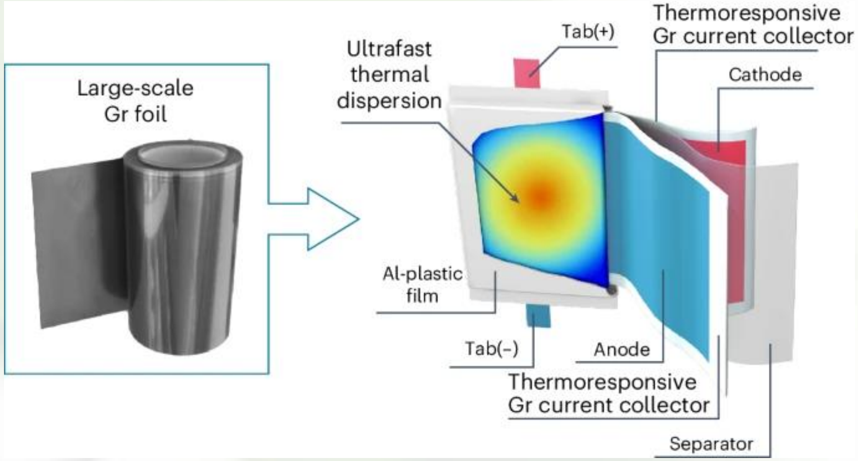




7. Graphene Batteries

Graphen Implication For Lithium-Ion Batteries





Lithium-ion batteries are vulnerable to a key risk, called thermal runaway. This happens when excessive heat accumulates in a part of the battery, often leading to battery failure with dangerous fires or explosions.

Thermal runaway mostly happens at the battery's current collectors, where the most power is concentrated. In current lithium-ion batteries, current collectors are usually made of aluminum or copper.

The graphene current collectors developed by the research with their graphene foil can display a thermal conductivity as high as 1,400.8 W m−1 K−1. For reference, **this is almost 10x higher than copper and aluminum-based current collectors.**

Because the graphene foil shows a very fast heat dissipation, it eliminates the risk of local heat concentration when the current is flowing.

In turn, this removes the risks of aluminothermic and hydrogen-evolution reactions which are the critical steps leading to propagation of the battery failure and fire hazard.

7. Graphene Batteries

Key Advantages of Graphene Batteries:

1.High Conductivity

- ✓ Graphene's high electron mobility allows for faster charging and discharging, reducing charging times significantly (e.g., from hours to minutes).

2.Increased Energy Density

- ✓ Graphene can store more energy per unit mass compared to conventional electrode materials, potentially leading to longer-lasting batteries.

3.Enhanced Lifespan

- ✓ Graphene's stability reduces degradation over charge cycles, extending battery life.

4.Improved Thermal Management

- ✓ Graphene dissipates heat efficiently, lowering the risk of overheating and improving safety.

5.Lightweight & Flexible

- ✓ Graphene-based batteries can be thinner, lighter, and even flexible, making them ideal for wearables and electric vehicles (EVs).

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7. Graphene Batteries

Advantages of Graphene Batteries Over Li-Ion Batteries

Graphene-based batteries offer several advantages over conventional Li-ion batteries, making them highly promising for the EV industry.

• **Faster Charging:** Graphene enables rapid electron movement, significantly reducing charging times. While Li-ion batteries take 30–60 minutes for a full charge, graphene batteries could potentially charge within a few minutes.[1,2]

• **Higher Energy Density:** Li-ion batteries have a limited energy storage capacity. With their high surface area and superior conductivity, graphene batteries can store more energy in the same volume, extending the EV range.[1,2]

• **Longer Lifespan:** Traditional batteries degrade with repeated charge cycles. Graphene batteries exhibit less wear and tear, resulting in a longer operational life and reducing the need for frequent replacements.[1,2]

• **Improved Efficiency:** Graphene enhances ion transport, reducing energy losses during charging and discharging. This leads to better overall battery performance and improved vehicle efficiency.[1,2]

• **Enhanced Safety:** Overheating and thermal runaway are common issues with Li-ion batteries. Graphene's superior thermal conductivity dissipates heat efficiently, minimizing the risk of fires and explosions.[1,2]

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7. Graphene Batteries

Performance comparison: Li-Ion vs Graphene Battery

	Definition	Lithium-Ion Battery	Graphene-Enhanced Battery
First device		1976	**2011**
Charge capacity (milliamp-hours / mAh)	The amount of chemical energy stored within the battery	~ 2700 - 3300 mAh	~ 1000 mAh
Charging speed	How fast the battery can be fully recharged	1-2 hours	**27 minutes**
Energy Density (watt-hours per kilogram / Wh kg^{-1})	The amount of energy the battery can store per unit mass.	~250 Wh kg^{-1}	**~1000 Wh kg^{-1}**
Lifetime	The number of times the battery can be fully recharged whilst maintaining at least 80% of its original capacity.	~ 500	**~ 2500**
Safety	Some batteries can overheat causing fires.	Flammable	**Non-flammable**
Sustainability	Many battery components include materials that must be mined and are hazardous, making recycling difficult.	Mined	Lab-grown

7. Graphene Batteries

Large surface area

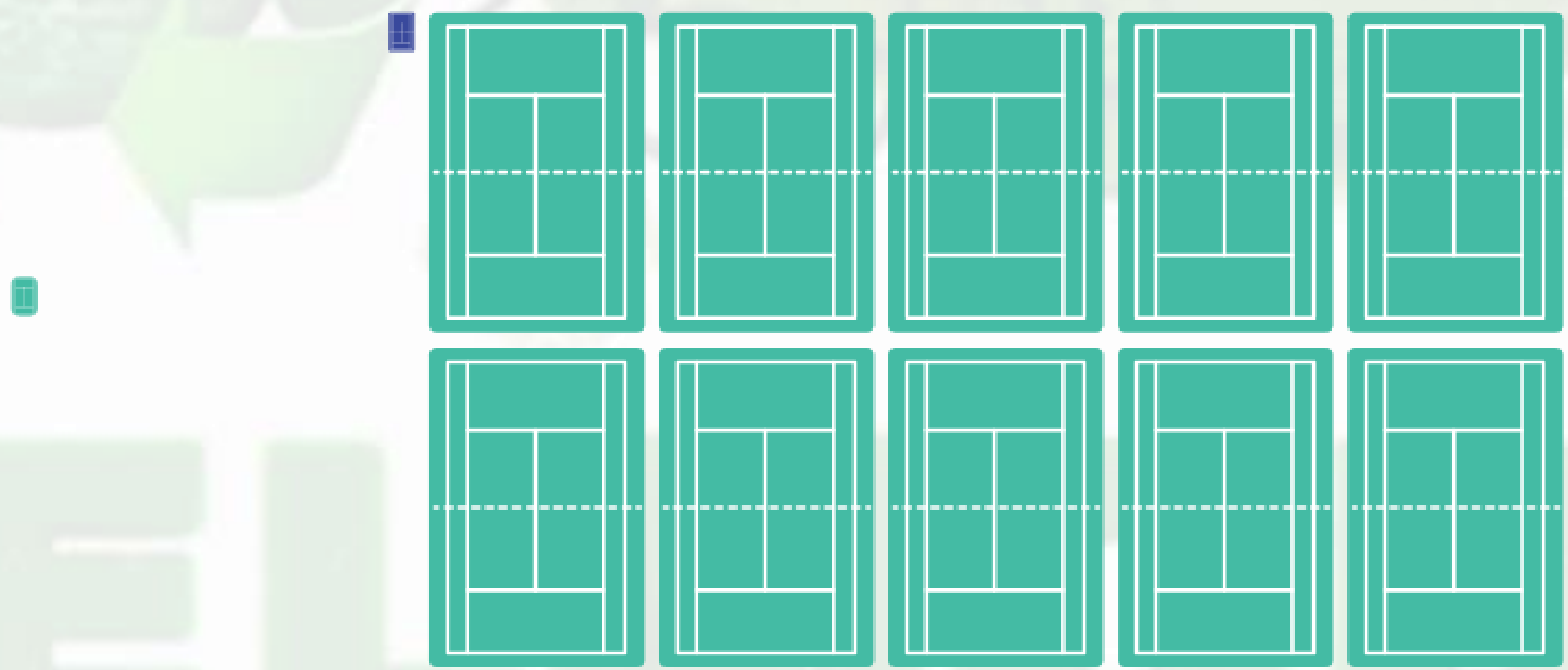
Graphene has a huge surface area of 2630 m2 per gram

Li 4 m^2g^{-1}

1 Table Tennis Top (2.74m x 1.525m)

Graphene 2630 m^2g^{-1}

10 Tennis Courts (23.774m x 10.973m Each)



Ossila

Graphene vs lithium surface area: 1 gram of graphene could be enough to cover 10 tennis courts

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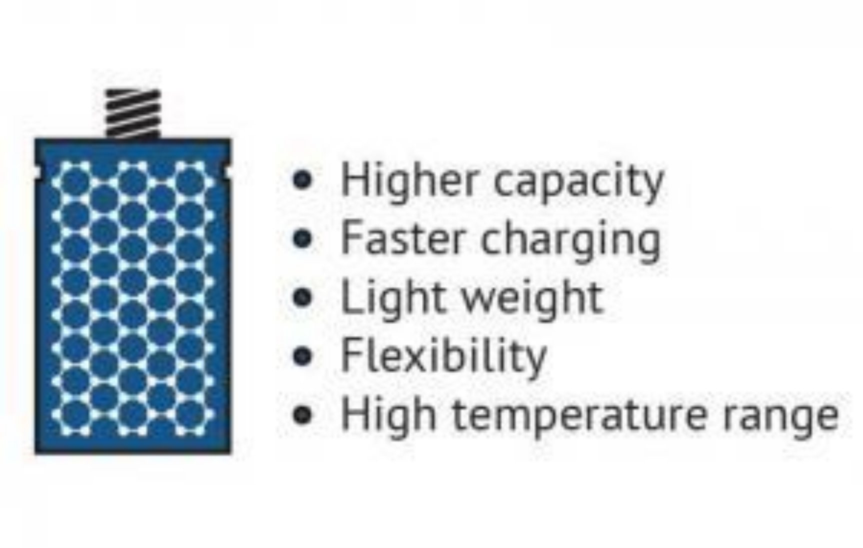
7. Graphene Batteries

Types of Graphene Batteries:

- **Graphene-Enhanced Lithium-Ion Batteries**
  - ✓ Graphene is used as an additive in electrodes to improve conductivity and capacity.
- **Graphene Supercapacitors**
  - ✓ Combine the rapid charge/discharge of supercapacitors with graphene's high energy storage.
- **Pure Graphene Batteries** (Still in R&D)
  - ✓ Theoretical batteries using graphene as the primary electrode material.

7. Graphene Batteries

Graphene batteries combine the advantages of both batteries and supercapacitors



A supercapacitor is used when energy is needed in short, sharp bursts. By combining the quick energy supply of supercapacitors and the high storage of batteries, the disadvantages of both can be overcome in a battery-supercapacitor hybrid (BSH). Li4Ti5O12 is often used as an electrode in capacitors. When coupled with N-doped graphene, a BSH can be formed and this has achieved storage of up to 70 Wh kg-1

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Battery-Supercapacitor Hybrids

A supercapacitor is used when energy is needed in short, sharp bursts. By combining the quick energy supply of supercapacitors and the high storage of batteries, the disadvantages of both can be overcome in a battery-supercapacitor hybrid (BSH). $Li_4Ti_5O_{12}$ is often used as an electrode in capacitors. When coupled with N-doped graphene, a BSH can be formed and this has achieved storage of up to 70 Wh kg^{-1}.

7. Graphene Batteries

Graphene Batteries

By incorporating graphene into Li-ion batteries, most often at the electrodes, many battery properties can be improved. Graphene batteries outperform traditional Li-ion batteries in terms of energy density and charging speed. Graphene batteries also offer new features such as being flexible and non-flammable.

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https://www.ossila.com/pages/lithium-ion-vs-graphene-batteries

7. Graphene Batteries

Disadvantages of Li-Ion Batteries

It’s clear from comparing Li-ion to graphene batteries, that Li-ion is inferior any several areas. Significant limitations of Li-ion batteries are their:

•lower energy density

•slower charging

•shorter lifetimes

•toxicity concerns

•flammability issues.

7. Graphene Batteries

The Benefits of Graphene Batteries

Vehicle performance

In the near future, the higher energy density of graphene batteries is expected to enable EVs to achieve significantly longer driving ranges on a single charge, making them more viable for extended journeys. As graphene technology advances, improved power output will likely enhance acceleration and overall efficiency, pushing EVs closer to the capabilities of high-performance sports cars.

Furthermore, graphene's superior conductivity is anticipated to ensure consistent energy delivery, reduce performance fluctuations, and optimize power management for a smoother and more reliable driving experience.

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7. Graphene Batteries

The Benefits of Graphene Batteries

Charging times

The ultra-fast charging capability of graphene batteries is one of their most significant advantages. With the ability to charge in minutes rather than hours, EV owners could experience a level of convenience comparable to refueling a traditional gasoline vehicle. This rapid charging would also reduce demand on charging infrastructure, improving accessibility and efficiency in EV networks.1,5

Sustainability

Graphene-based batteries could contribute to a more sustainable EV ecosystem. Their longer lifespan reduces battery waste, and they contain fewer environmentally harmful materials than Li-ion batteries. Graphene can also be derived from abundant carbon sources, potentially reducing reliance on rare earth metals and minimizing the environmental impact of battery production.[1,5]

7. Graphene Batteries

How Graphene Batteries Improve on 1C Charging

Graphene-enhanced batteries can **far exceed 1C charging** safely due to:

1. **Ultra-High Conductivity** – Graphene reduces internal resistance, allowing faster electron flow without overheating.
2. **Thermal Stability** – Graphene dissipates heat better than traditional materials, preventing damage at high currents.
3. **Longer Cycle Life** – Even at **5C–10C** (full charge in 6–12 minutes), graphene batteries degrade slower than conventional Li-ion.

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7. Graphene Batteries

Challenges and Limitations of Graphene Batteries

Despite its potential, several challenges hinder the widespread adoption of graphene batteries in EVs.

- **Manufacturing Costs:** Producing high-quality graphene remains costly, making large-scale manufacturing a significant challenge.[1]

- **Scalability Issues:** Scaling up graphene battery production to meet the demands of the EV industry requires major improvements in fabrication techniques.[1]

- **Integration into Existing Systems:** Most current EVs are built around lithium-ion batteries. Shifting to graphene-based systems would require battery management systems and charging infrastructure updates.

- **Supply Chain Constraints:** Graphene production relies on specialized materials and processes. A sudden spike in demand could strain the supply chain.[1]

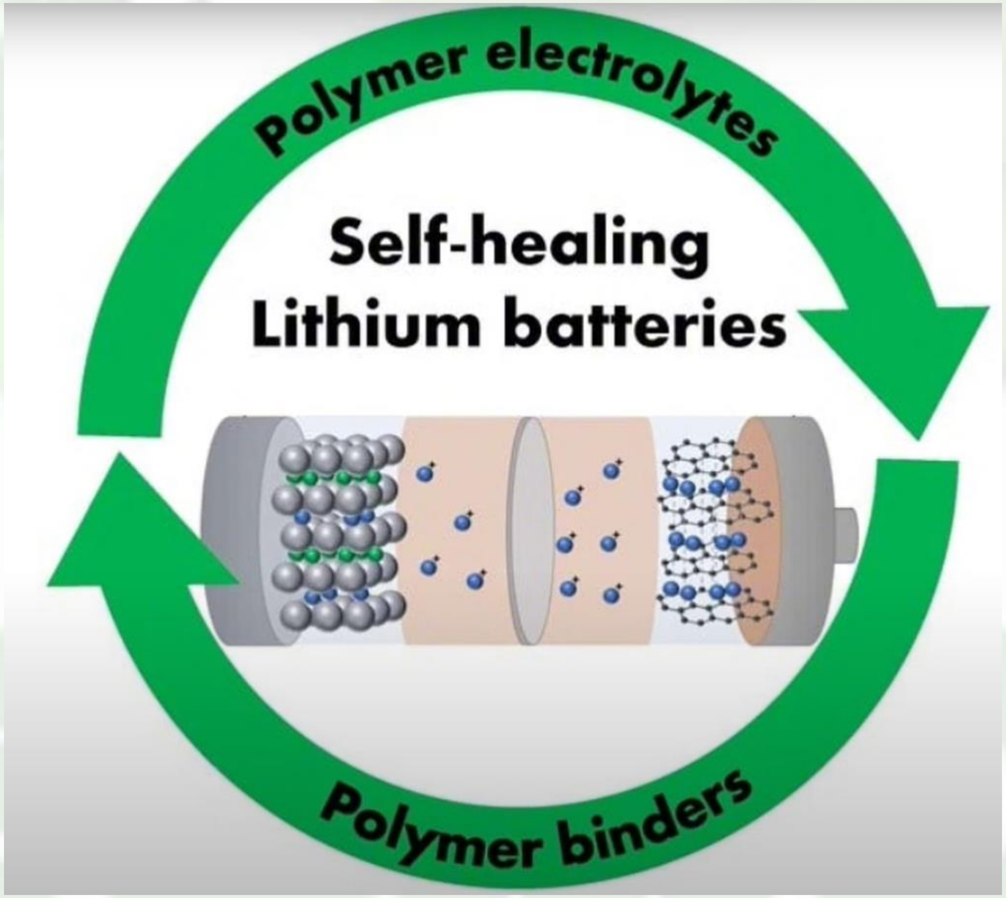
- **Commercialization Timeline:** Although research is advancing, it may still take several years before graphene batteries are ready for mass-market adoption, primarily due to the need for further testing and cost reduction.[1]

8. Self-Healing Batteries

Self-Healing Batteries: The Future of Durable Energy Storage

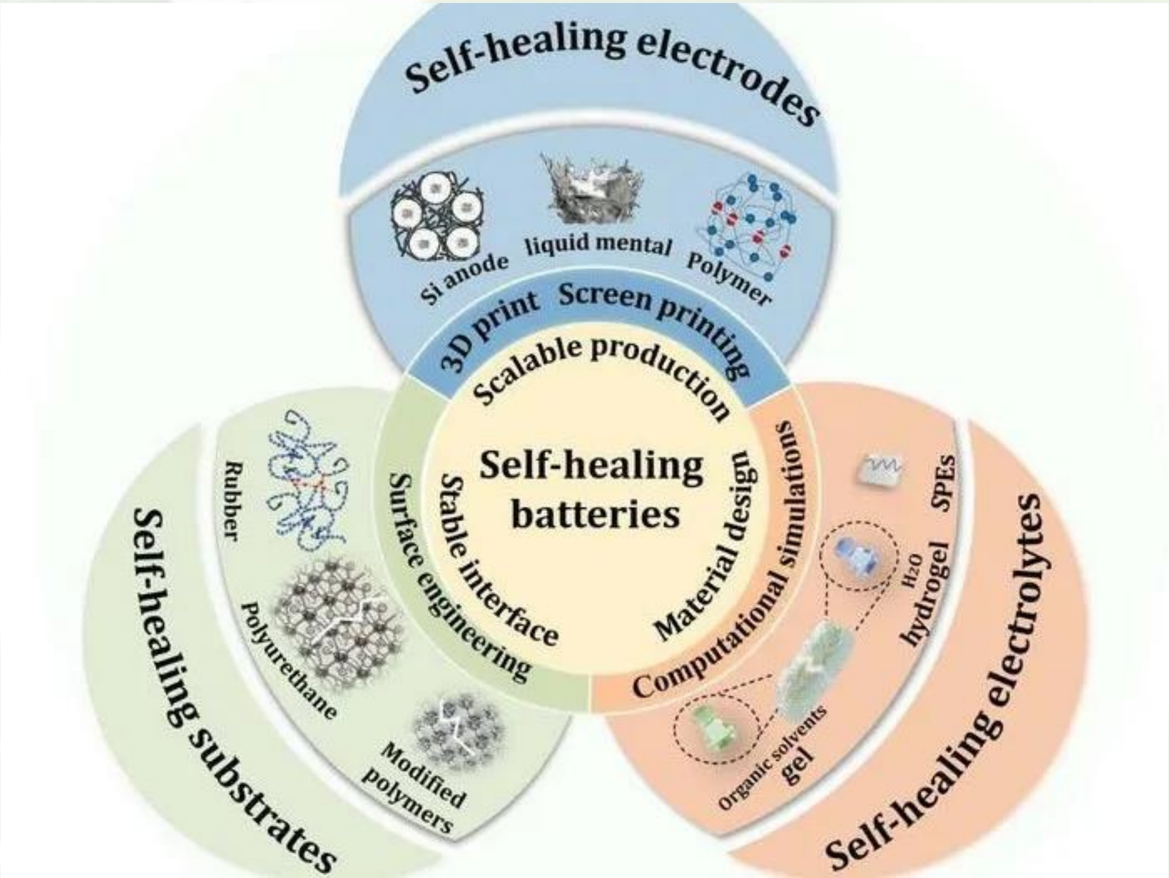
Self-healing batteries are an emerging technology **designed to automatically repair damage** (e.g., cracks, dendrite formation, or electrode degradation) that occurs during charging/discharging cycles. This innovation could extend battery lifespan, improve safety, and reduce waste.

Self-Healing Batteries: The Future of Durable Energy Storage



8. Self-Healing Batteries

Key Components and Design Strategies of Self-Healing Batteries



Core Components of Self-Healing Batteries

(A) Self-Healing Electrodes

•**Materials:**

- **Silicon Anodes:** Crack-resistant due to elastic binders.
- **Liquid Metals (e.g., Gallium):** Reflow to repair cracks.
- **Conductive Polymers (e.g., PEDOT:PSS):** Re-bond after damage.

•**Function:** Automatically repair cracks from volume expansion (common in Li-ion batteries).

8. Self-Healing Batteries

Core Components of Self-Healing Batteries

(B) Self-Healing Electrolytes

- **Materials:**
    - **Hydrogels:** Flexible and ion-conductive.
    - **Modified Polymers (e.g., Polyurethane):** Heal punctures.
    - **Solid-State Ceramics:** Resist dendrite penetration.
- **Function:** Prevent leakage, suppress dendrites, and maintain ion flow after damage.

8. Self-Healing Batteries

Core Components of Self-Healing Batteries

(C) Self-Healing Substrates

•**Materials:**

- **Graphene/CNT Layers:** Conduct electricity while flexing.
- **Elastomers (e.g., PDMS):** Stretchable and tear-resistant.

•**Function:** Protect battery structure from mechanical stress (e.g., bending, impacts).

8. Self-Healing Batteries

Design Strategies & Production Techniques

(A) Advanced Material Design

- **Dynamic Bonds:** Reversible chemical bonds (e.g., hydrogen, disulfide) that re-form after breaking.
- **Nanocomposites:** Embedding healing agents (e.g., microcapsules with conductive fillers).

(B) Computational Simulations

- **AI Modeling:** Predict failure points and optimize healing mechanisms.
- **Multiphysics Simulations:** Test stress/heat distribution under real-world conditions.

(C) Scalable Production

- **3D Printing:** Precise deposition of self-healing layers.
- **Screen Printing:** Low-cost, large-scale electrode fabrication.

8. Self-Healing Batteries

Benefits & Applications

•**Durability:** 2–3x longer lifespan vs. conventional batteries.

•**Safety:** Reduced risk of leaks/explosions.

•**Use Cases:**

- **EVs:** Survive extreme charging cycles.
- **Flexible Electronics:** Wearables, rollable phones.
- **Space/Aerospace:** Radiation-resistant, low-maintenance.

8. Self-Healing Batteries

How Do Self-Healing Batteries Work?

1. Self-Healing Electrodes

•**Microcapsules or Polymers** – Some batteries embed **healing agents** (e.g., conductive polymers or gels) that release when cracks form, sealing gaps.

•**Reversible Chemical Bonds** – Certain materials (e.g., **supramolecular polymers**) can **re-bond** after breaking, restoring conductivity.

2. Dendrite Suppression (For Lithium & Solid-State Batteries)

•**Lithium Dendrites** (branch-like growths) cause short circuits in Li-ion batteries.

•**Self-Healing Coatings** (e.g., graphene, elastomers) can **dissolve and re-deposit lithium**, preventing dendrite formation.

3. AI & Smart Battery Management

•Some systems use **sensors + AI** to detect damage and trigger healing mechanisms (e.g., heat, voltage adjustments).

8. Self-Healing Batteries

Advantages of Self-Healing Batteries

✓ **Longer Lifespan** – Can recover from wear, reducing replacement frequency.

✓ **Safer Operation** – Prevents dangerous failures (e.g., dendrite-induced fires).

✓ **Higher Energy Density** – More stable electrodes allow for more aggressive charging.

✓ **Sustainability** – Fewer dead batteries = less e-waste.

8. Self-Healing Batteries

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Current Research & Challenges

Technology	Researchers/Companies	Status
Self-Healing Li-ion	Stanford, U. of Illinois, Tesla (patents)	Lab-stage
Dendrite-Healing Solid-State	QuantumScape, Toyota	Prototyping
Graphene-Based Healing	Samsung, Huawei	Early R&D

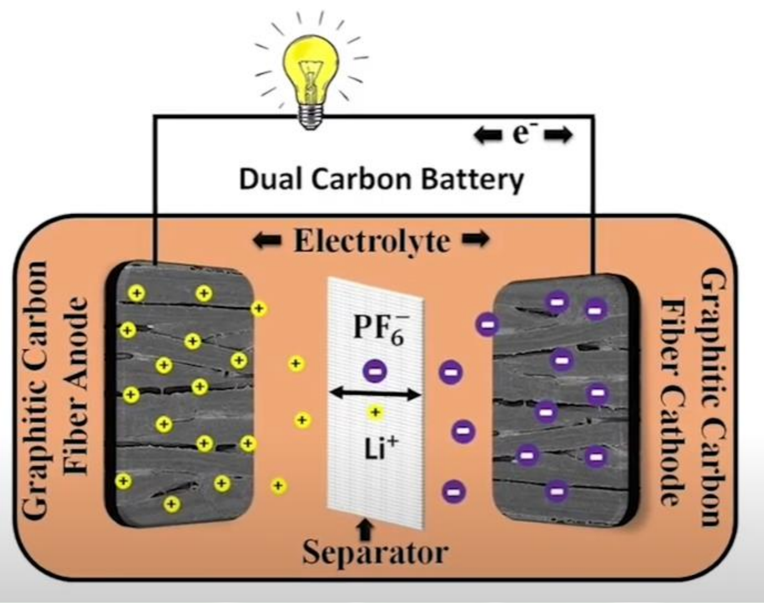
Challenges:

- **Cost** – Self-healing materials are expensive to produce.
- **Scalability** – Hard to mass-manufacture reliably.
- **Trade-offs** – Some healing mechanisms reduce energy density.

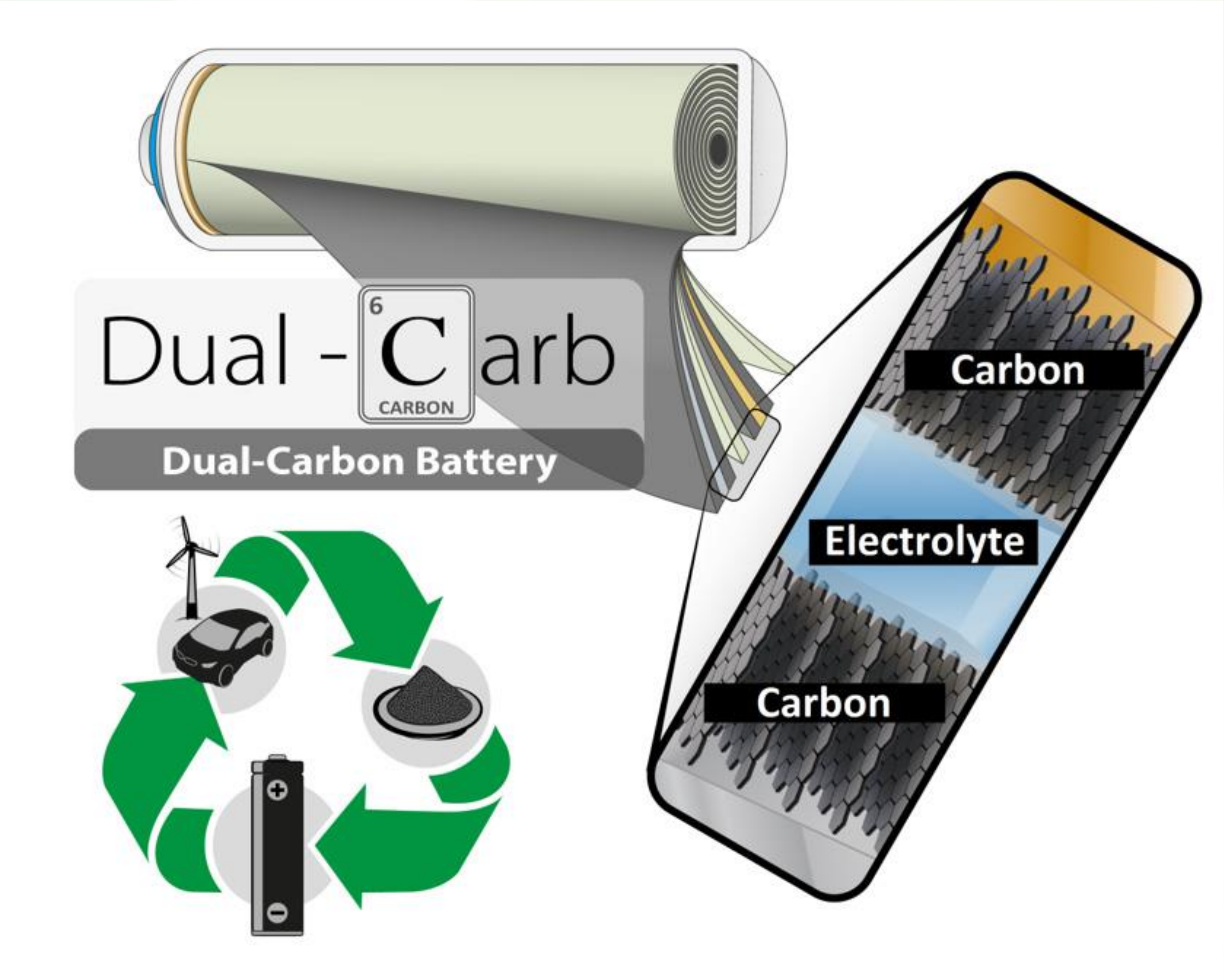
9. Dual-Carbon Batteries

Dual-Carbon Batteries: A Sustainable Alternative to Lithium-Ion

Dual-carbon batteries (also called **carbon-based batteries** or **all-carbon batteries**) are an emerging energy storage technology that uses **carbon-based materials for both the anode and cathode**, eliminating the need for metals like lithium, cobalt, or nickel. These batteries leverage **intercalation** (ion insertion) into carbon structures for energy storage, offering a **low-cost, eco-friendly, and fast-charging** alternative to conventional lithium-ion batteries.



9. Dual-Carbon Batteries



9. Dual-Carbon Batteries

How Dual-Carbon Batteries Work

1. Electrodes:

- ✓ **Anode & Cathode:** Both are made of **porous carbon** (e.g., graphite, graphene, or activated carbon).
- ✓ **Electrolyte:** Typically an **organic solvent with lithium or sodium salts** (e.g., $LiPF_6$, $NaPF_6$).

2. Charging/Discharging Mechanism:

- ✓ During charging, **anions (e.g., PF_6^-) intercalate into the cathode**, while **cations (Li^+/Na^+) intercalate into the anode**.
- ✓ Discharging reverses the process, releasing energy.

9. Dual-Carbon Batteries

Advantages Over Lithium-Ion Batteries

✓ **Fast Charging** – Can charge at **5C–10C** (e.g., 6–12 minutes for full charge) due to high carbon conductivity.

✓ **Long Lifespan – 50,000+ cycles** (vs. ~1,000 for Li-ion) because carbon degrades minimally.

✓ **Safety** – No flammable liquid electrolytes or dendrite risks.

✓ **Eco-Friendly** – No rare metals (Li, Co, Ni); easier to recycle.

✓ **Wide Temperature Range** – Works from **-30°C to 100°C** (better than Li-ion).

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9. Dual-Carbon Batteries

Challenges & Limitations

❌ **Lower Energy Density** (~100–200 Wh/kg vs. 250–300 Wh/kg for Li-ion).

❌ **Voltage Limitations** (~3.8V max, vs. 4.2V for Li-ion).

❌ **Scalability** – Still in early commercialization (few mass-produced models).

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9. Dual-Carbon Batteries

Future Outlook & Potential Applications

- **Consumer Electronics** – Fast-charging phones/laptops.
- **EVs & Grid Storage** – Long-life, low-cost storage for renewable energy.
- **Medical Devices** – Safe, long-lasting implantable batteries.

Expected Commercialization: 2025–2030 for niche uses, with broader adoption if energy density improves.

General Conclusions on Next-Gen Battery Technologies for Electric Vehicles (EVs)

The future of EV batteries is rapidly evolving, with multiple emerging technologies competing to replace conventional **lithium-ion (Li-ion)** batteries. Below is a high-level comparison of key technologies, their advantages, challenges, and projected timelines for mass adoption in EVs.

Materials in Electrical Engineering

New Battery Technologies for Electric Vehicles

Technology Comparison Table

Technology	Energy Density	Charging Speed	Lifespan	Safety	Cost	Commercialization
Solid-State	**★★★★★ (400–500 Wh/kg)**	**★★★★ (Fast)**	**★★★★ (Long)**	**★★★★★ (Very Safe)**	**$$$$ (High)**	**2026–2030**
Lithium-Sulfur (Li-S)	**★★★★ (500+ Wh/kg)**	**★★★ (Moderate)**	**★★ (Short)**	**★★ (Dendrites)**	**$$ (Medium)**	**2025–2028**
Sodium-Ion (Na-Ion)	**★★ (100–160 Wh/kg)**	**★★★ (Moderate)**	**★★★ (Good)**	**★★★★ (Safe)**	**$ (Low)**	**Now (China)**
Potassium-Ion (K-Ion)	**★★ (Similar to Na-Ion)**	**★★ (Slow)**	**★★ (Moderate)**	**★★★ (Safe)**	**$ (Low)**	**2030+**
Silicon Anode (Li-Ion)	**★★★★ (350–400 Wh/kg)**	**★★★★ (Fast)**	**★★★ (Moderate)**	**★★★ (Good)**	**$$$ (Medium)**	**2024–2026**
Cobalt-Free (Li-Ion)	**★★★ (250–300 Wh/kg)**	**★★★ (Moderate)**	**★★★★ (Long)**	**★★★ (Good)**	**$$ (Medium)**	**Now (Tesla, CATL)**
Graphene Batteries	**★★★★ (300–500 Wh/kg)**	**★★★★★ (Ultra-Fast)**	**★★★★ (Long)**	**★★★★ (Safe)**	**$$$$ (High)**	**2025–2030**
Self-Healing	**★★★ (Depends on base tech)**	**★★★ (Depends)**	**★★★★★ (Very Long)**	**★★★★ (Safe)**	**$$$ (High)**	**2028–2035**
Dual-Carbon	**★★ (100–200 Wh/kg)**	**★★★★★ (Ultra-Fast)**	**★★★★★ (50k+ cycles)**	**★★★★★ (Very Safe)**	**$$ (Medium)**	**2025–2030**

General Conclusions on Next-Gen Battery Technologies for Electric Vehicles (EVs)

Key Trends & Takeaways

A. Energy Density Leaders (Longer Range EVs)

- **Solid-State, Li-S, and Graphene** lead in energy density (~400–500+ Wh/kg), enabling **800–1000 km ranges**.
- **Silicon Anodes** (in Li-ion) offer a near-term boost (~350–400 Wh/kg).

B. Fast-Charging Solutions (5–15 Minute Charging)

- **Graphene, Dual-Carbon, and Solid-State** support ultra-fast charging (5C–10C rates).
- **Current Li-ion with silicon anodes** can achieve **15–20 min charging**.

C. Cost & Sustainability Winners

- **Sodium-Ion & Cobalt-Free Li-ion** are **low-cost, ethical alternatives** (no rare metals).
- **Dual-Carbon** is highly recyclable and safe but has lower energy density.

General Conclusions on Next-Gen Battery Technologies for Electric Vehicles (EVs)

Key Trends & Takeaways

D. Safety & Longevity

•**Solid-State, Dual-Carbon, and Self-Healing** excel in safety (no fires/leaks).

•**Self-Healing and Dual-Carbon** promise **50,000+ cycles**, ideal for grid storage.

E. Commercialization Timeline

•**2024–2026:** Silicon anodes, cobalt-free Li-ion, Na-ion (China).

•**2026–2030:** Solid-state, graphene, Li-S, dual-carbon.

•**2030+:** Potassium-ion, advanced self-healing.

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General Conclusions on Next-Gen Battery Technologies for Electric Vehicles (EVs)

Final Verdict: Which Tech Will Dominate EVs?

- **Short-Term (2024–2028): Silicon Anode Li-ion + Cobalt-Free** (Tesla, CATL).
- **Mid-Term (2028–2035): Solid-State** (Toyota, QuantumScape) and **Graphene** (Samsung, Huawei).
- **Long-Term (2035+): Li-S or Self-Healing** if durability improves.
- **Niche Roles: Na-ion for budget EVs, Dual-Carbon for fast-charging applications.**