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D5.4 Undergraduate/Master Curricula Implemented

Title of Course

Materials in Electrical Engineering

Title of the presentation

Battery Technologies for Electric Vehicles

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

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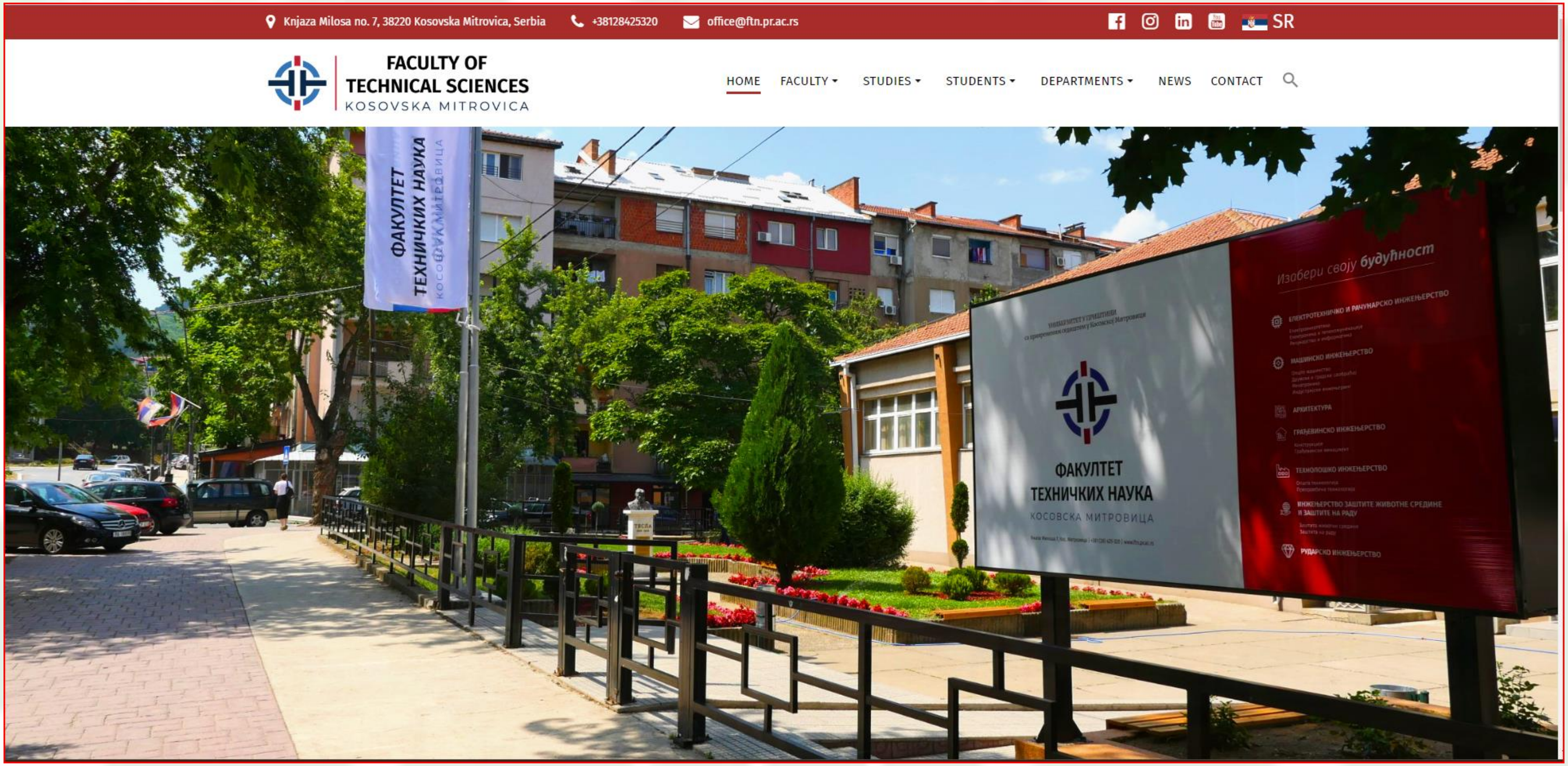

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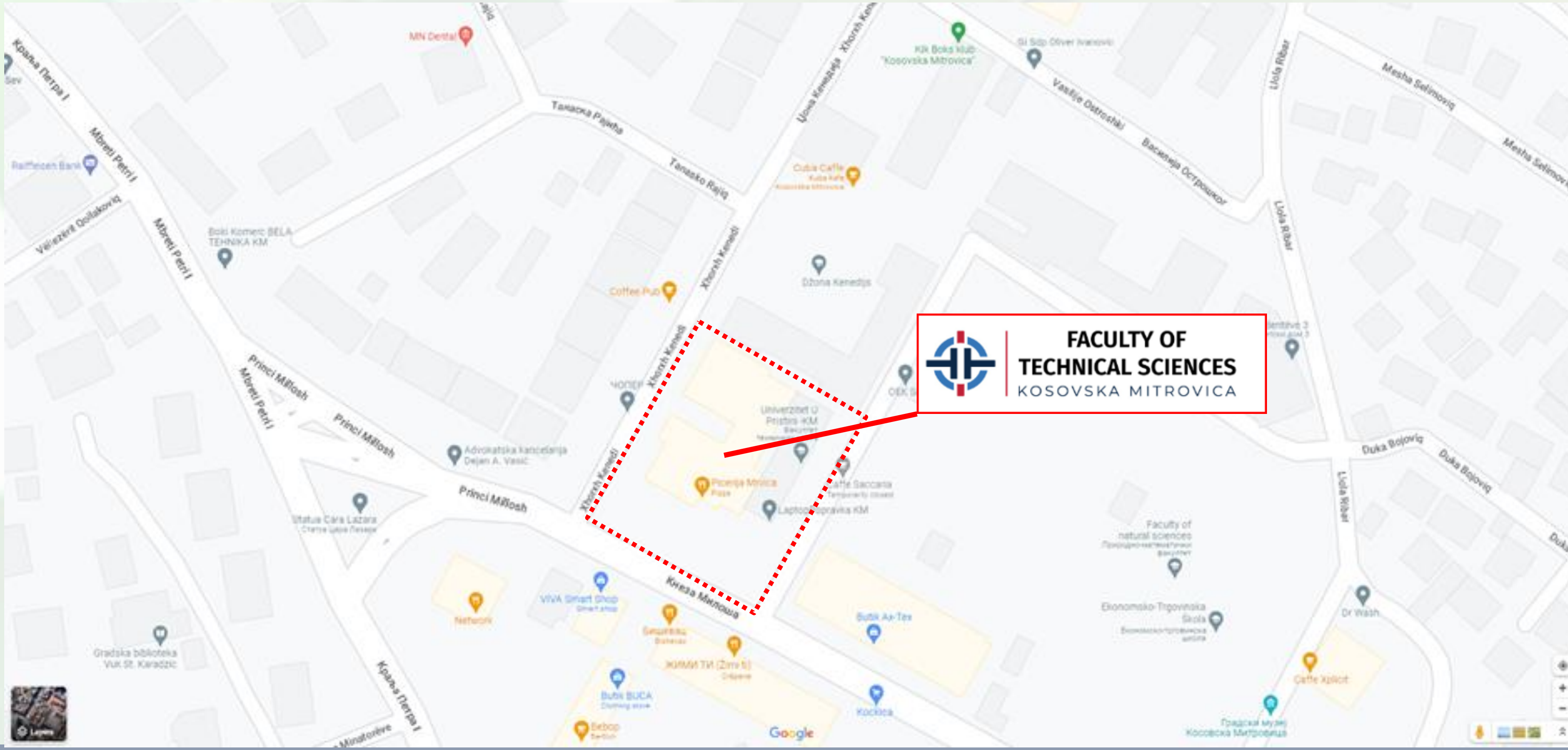

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Lithium-ion batteries advantages for EVs

Lithium-ion (Li-ion) batteries are the dominant energy storage technology in electric vehicles (EVs) due to their superior performance compared to other battery types.

1. High Energy Density

- Li-ion batteries store a large amount of energy per unit weight and volume, enabling EVs to achieve longer driving ranges (300–500+ km on a single charge).
- This is crucial for reducing vehicle weight while maintaining performance.

2. High Power Density

- They deliver strong acceleration by providing high power output when needed, improving EV performance.
- Efficient energy discharge supports regenerative braking, recapturing energy during deceleration.

3. Long Cycle Life

- Modern Li-ion batteries can endure **1,000–2,000+ charge cycles** before significant degradation (losing ~20% capacity).
- Advances in battery chemistry (e.g., LFP batteries) further enhance longevity.

Lithium-ion batteries advantages for EVs

4. Fast Charging Capability

- Li-ion batteries support **DC fast charging**, allowing EVs to recharge to **80% in 20–30 minutes** (depending on battery size and charger power).
- Newer designs (e.g., silicon anodes, ultra-fast charging tech) aim to reduce this further.

5. Lightweight & Compact

- Compared to alternatives like lead-acid or nickel-metal hydride (NiMH) batteries, Li-ion batteries are much lighter, improving vehicle efficiency and handling.

6. Low Self-Discharge Rate

- They lose only **~1–2% charge per month** when idle, unlike older battery types that drain faster.
- This ensures EVs retain charge when parked for extended periods.

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Lithium-ion batteries advantages for EVs

7. High Efficiency

- Li-ion batteries have **90–95% charge/discharge efficiency**, meaning minimal energy is wasted as heat.
- This maximizes the usable energy from the grid to the wheels.

8. Scalability & Flexibility

- Used in all EV segments, from small cars (e.g., Nissan Leaf) to large trucks (e.g., Tesla Semi).
- Modular designs allow manufacturers to adjust battery size for different models.

9. Declining Costs

- Prices have dropped **~90% since 2010** (from ~1,200/kWhto 1,200/*kWhto* 100–130/kWh in 2024).
- Economies of scale and tech improvements continue to drive costs down.

10. Environmental Benefits

- Zero tailpipe emissions when used in EVs.
- Recyclability is improving with dedicated battery recycling programs (e.g., Redwood Materials, Li-Cycle).

Lithium-ion batteries advantages for EVs

Future Improvements

- **Solid-state batteries**: Higher energy density, faster charging, and improved safety.
- **Silicon anodes**: Increase capacity and reduce charging times.
- **LFP (Lithium Iron Phosphate)**: Cheaper, longer-lasting, and cobalt-free (used in Tesla Model 3, BYD EVs).

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Comparison of Key Li-ion Battery Chemistries for EVs

1. NMC (Nickel Manganese Cobalt Oxide)

Advantages ✓

- **High energy density** → Longer driving range (ideal for premium EVs).
- **Good power output** → Strong acceleration and performance.
- **Balanced chemistry** (nickel boosts energy, manganese improves stability).

Disadvantages ✗

- **Contains cobalt** → Ethical concerns (child labor in mining) and high cost.
- **Moderate lifespan** (~1,000–2,000 cycles) degrades faster than LFP.
- **Thermal risk** → Requires advanced cooling systems to prevent overheating.

Comparison of Key Li-ion Battery Chemistries for EVs

2. NCA (Nickel Cobalt Aluminum Oxide)

Advantages ✅

- **Highest energy density** among commercial batteries → Maximizes range (e.g., Tesla Long Range).
- **Good fast-charging capability** → Works well with Superchargers.
- **Lighter weight** than NMC for the same capacity.

Disadvantages ❌

- **Less stable** than NMC → Higher risk of thermal runaway if damaged.
- **Still uses cobalt** → Expensive and ethically problematic.
- **Shorter lifespan** (~1,000–1,500 cycles) than LFP.

Comparison of Key Li-ion Battery Chemistries for EVs

3. LFP (Lithium Iron Phosphate)

Advantages ✅

- **No cobalt/nickel** → Cheap, ethical, and environmentally friendly.
- **Extremely long lifespan** (~3,000–5,000+ cycles) → Lasts longer than the car itself.
- **Ultra-safe** → Resists fires/explosions even under abuse.
- **Can charge to 100% daily** without significant degradation.

Disadvantages ❌

- **Lower energy density** → Heavier batteries or shorter range (used in Tesla Standard Range, BYD).
- **Poor cold-weather performance** → Loses ~20–30% range in freezing temps.
- **Lower power density** → Slightly slower acceleration than NMC/NCA.

Comparison of Key Li-ion Battery Chemistries for EVs

4. Solid-State (Future Tech – Not Yet in Mass Production)

Advantages ✅

- **2–3× energy density** → Potential 500+ mile ranges.
- **Faster charging** → Could recharge in minutes.
- **Zero fire risk** → No liquid electrolyte.

Disadvantages ❌

- **Decades away** from mass adoption (likely post-2030).
- **Extremely expensive** today due to manufacturing challenges.
- **Durability issues** → Still unstable in real-world testing.

Comparison of Key Li-ion Battery Chemistries for EVs

Quick Summary

Chemistry	Best For	Biggest Pro	Biggest Con
NMC	Performance EVs	Balance of energy & power	Cobalt dependency
NCA	Long-range EVs	Highest energy density	Safety concerns
LFP	Budget/Urban EVs	Cheap, safe, long-lasting	Lower range in cold weather
Solid-State	Future EVs	Revolutionary potential	Not yet viable

Comparison of Key Li-ion Battery Chemistries for EVs

Biggest Pro

This means that this battery type can store a large amount of energy relative to its size and weight, which significantly enhances the range of electric vehicles. A higher energy density allows EVs to travel longer distances on a single charge, making them more practical and appealing for consumers. This is especially important for users who prioritize long-range travel without frequent charging stops.

Biggest Con

This refers to the risk of overheating and potentially catching fire, especially if the battery is damaged or improperly handled. While safety measures are continuously improving, incidents related to battery fires can raise concerns among consumers and manufacturers alike. Ensuring safe operation and mitigating these risks is a critical aspect of battery design and usage.

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Comparison of Key Li-ion Battery Chemistries for EVs

Trends in EV Battery Chemistries

1. **LFP Dominance in Entry-Level EVs** – Tesla, BYD, and others are shifting to LFP for cheaper, longer-lasting batteries.
2. **High-Nickel NMC/NCA for Premium EVs** – For maximum range (e.g., Lucid Air, Tesla Long Range).
3. **Cobalt Reduction** – Automakers are moving to NMC 811 or zero-cobalt LFP.
4. **Solid-State Coming (2030+)** – Toyota, BMW, and startups are investing heavily.

Cobalt - Ethical Concerns

1. Human Rights Abuses in Mining

- **Child labor & unsafe conditions**:
  - ~70% of the world's cobalt comes from the **Democratic Republic of Congo (DRC)**, where:
    - **40,000+ children** work in hazardous artisanal mines (UNICEF).
    - Miners (including kids) dig by hand with no safety gear, risking cave-ins and toxic exposure.
  - Wages are often **less than $2/day**, and workers face exploitation.
- **Modern slavery risks**:
  - Reports link cobalt mining to **forced labor** and human trafficking.

2. Environmental Damage

- **Pollution from mining**:
  - Cobalt extraction contaminates water and soil with **sulfuric acid, heavy metals, and radioactive uranium** (often found alongside cobalt).
  - Deforestation and ecosystem destruction in the DRC.
- **Carbon footprint**:
  - Refining cobalt is energy-intensive, increasing the **battery's overall emissions**.

Cobalt - Ethical Concerns

3. Geopolitical & Supply Risks

- **DRC dominates supply** (70%+ of global cobalt), creating:
  - **Price volatility** (e.g., cobalt prices spiked 300% in 2017–2018).
  - **Political instability** risks (corruption, conflict minerals).
- **China controls refining** (~80% of processed cobalt), raising dependency concerns for Western automakers.

The Steep Decline in Lithium-Ion Battery Costs

The cost of lithium-ion (Li-ion) batteries has plummeted by ~90% over the past decade, from around 1,200$/kWh in 2010 to just 100–130 $/kWh in 2024. This dramatic price drop is one of the key reasons EVs are becoming more affordable and mainstream.

1. Why Have Battery Prices Fallen So Much?

A. Economies of Scale

- **Mass production**: As EV sales surged (from ~50,000 EVs sold globally in 2010 to **10+ million in 2023**), battery manufacturers scaled up production.
  - Example: Tesla's **Gigafactories** (Nevada, Shanghai, Berlin) reduced costs through **high-volume output**.
- **Supply chain optimization**: Larger orders for raw materials (lithium, nickel, graphite) led to bulk discounts.

The Steep Decline in Lithium-Ion Battery Costs

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B. Technological Improvements

- **Higher energy density**:
  - New chemistries (e.g., **NMC 811, LFP**) store more energy per kg, reducing material costs per kWh.
- **Manufacturing innovations**:
  - **Dry electrode coating** (Tesla's 4680 cells) cuts production steps and energy use.
  - **Cell-to-pack (CTP) designs** (BYD's Blade Battery) eliminate modules, saving space and materials.

C. Falling Raw Material Costs (Until 2022)

- **Lithium, cobalt, nickel prices dropped** (2010–2020) due to:
  - Increased mining output (e.g., lithium from Australia, Chile).
  - Reduced cobalt usage (switching from NMC 111 to NMC 811 or LFP).
- **2022–2023 spike (temporary)**:
  - Post-COVID demand surge and geopolitical issues caused short-term price hikes, but **long-term trend remains downward**.

The Steep Decline in Lithium-Ion Battery Costs

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D. Competition & Industry Investments

- **More players**: CATL, LG Energy Solution, Panasonic, and BYD compete fiercely, driving innovation and cost-cutting.
- **Government subsidies**:
  - China's **EV and battery subsidies** accelerated domestic production.
  - U.S. **Inflation Reduction Act (IRA)** incentivizes local battery manufacturing.

2. Price Trends Over Time

Year	Avg. Price per kWh	Key Developments
2010	~$1,200	Early EV batteries (Nissan Leaf, Tesla Roadster)
2015	~$350	Gigafactory 1 opens, Tesla Model 3 launch planned
2020	~$137	LFP adoption rises, economies of scale kick in
2022	~$150	Post-COVID supply chain disruptions
2024	$100–130	LFP dominates budget EVs; Tesla 4680 cells ramp up

Projections for 2030:

- **$60–80/kWh** (BloombergNEF) as solid-state and sodium-ion batteries enter mass production.

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The Steep Decline in Lithium-Ion Battery Costs

3. Impact on EV Adoption

A. Cheaper EVs

- **Price parity with ICE vehicles**:
- At **100$/kWh**, a **60kWh** battery pack costs **6,000$ (vs. ~72,000$ in 2010).**
- EVs like the BYD Seagull (**10,000$**) and TeslaModel3 (**10,000$**) and TeslaModel3 (**35,000$**) are now affordable.

B. Longer Range for Same Cost

- In 2010: **$1,200/kWh** = ~24 kWh battery (Nissan Leaf, 73 miles range).
- In 2024: **$100/kWh** = **100 kWh battery** (Tesla Model S, 400+ miles range).

C. Grid Storage Becomes Viable

- Low battery prices enable large-scale **solar/wind energy storage** (e.g., Tesla Megapack).

The Steep Decline in Lithium-Ion Battery Costs

4. Challenges Ahead

A. Raw Material Volatility

- **Lithium prices fluctuated wildly** (2021–2023), but recycling and new mines (e.g., in Nevada) will stabilize supply.

B. Geopolitical Risks

- **China dominates battery production** (~75% of global capacity), prompting U.S./EU to build local supply chains.

C. Next-Gen Batteries Needed

Solid-state and sodium-ion must scale to push prices below **$60/kWh**

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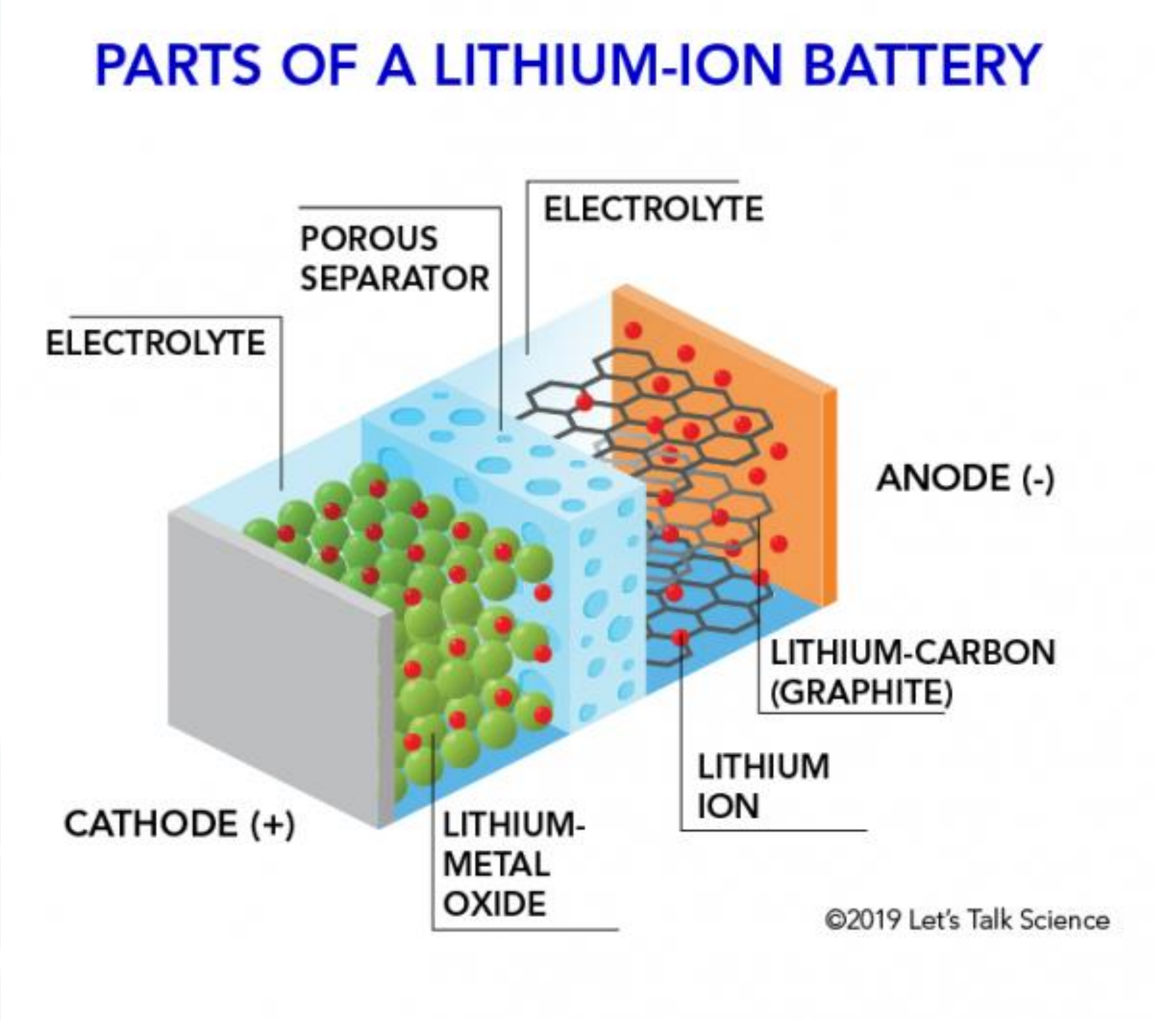
Various components of Li-ion battery



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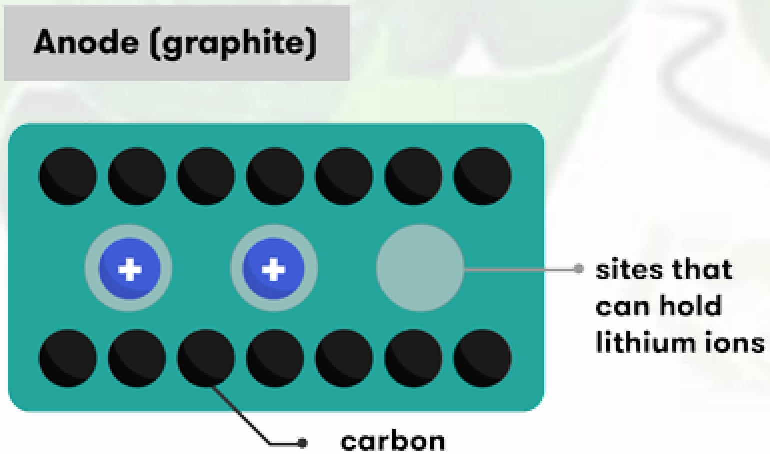
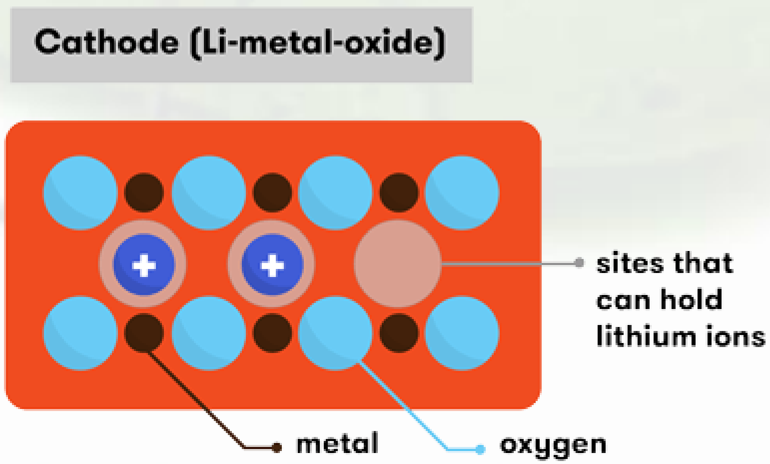
Various components of Li-ion battery





Materials in Electrical Engineering

Battery Technologies for Electric Vehicles

Various components of Li-ion battery

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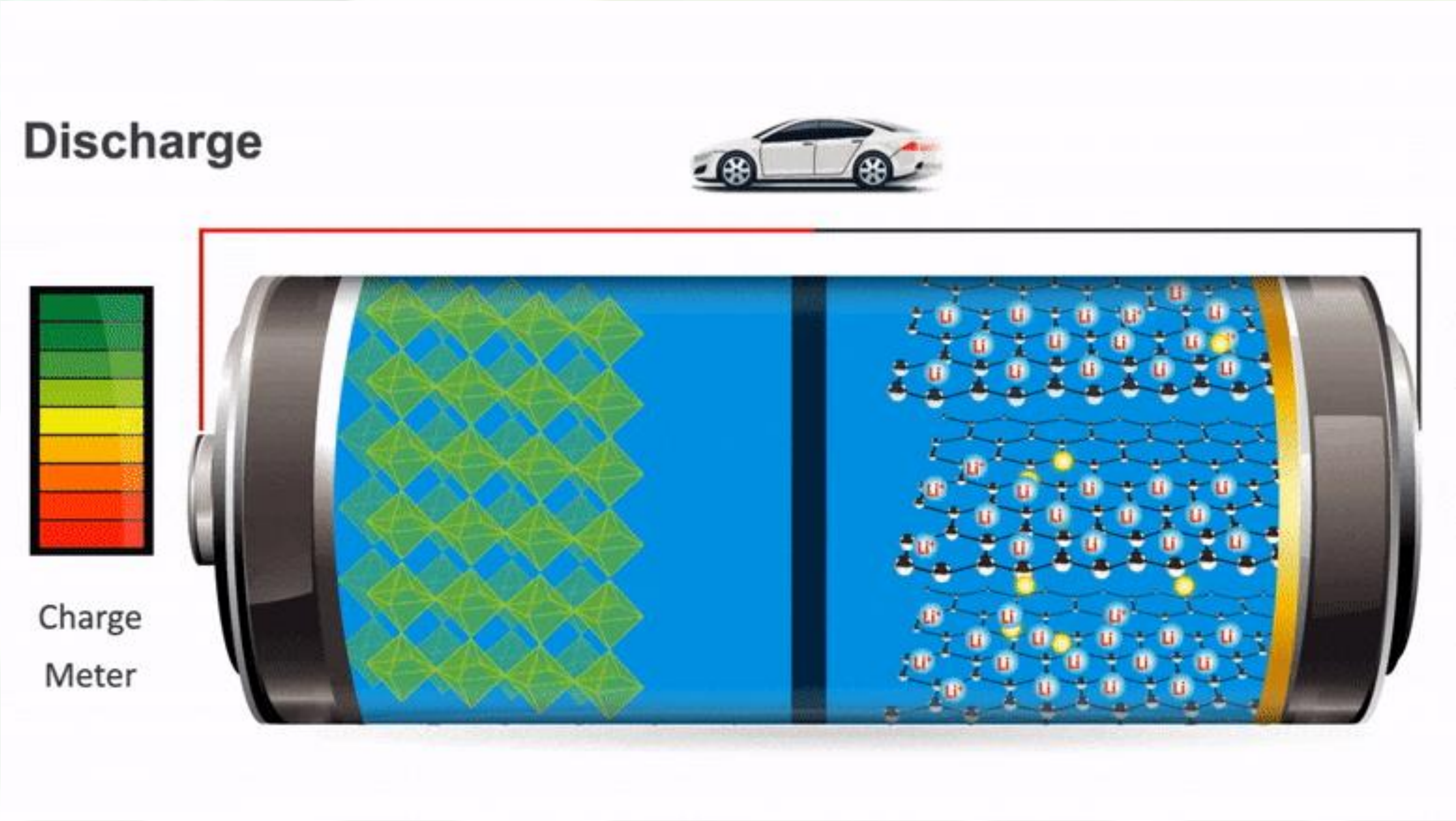
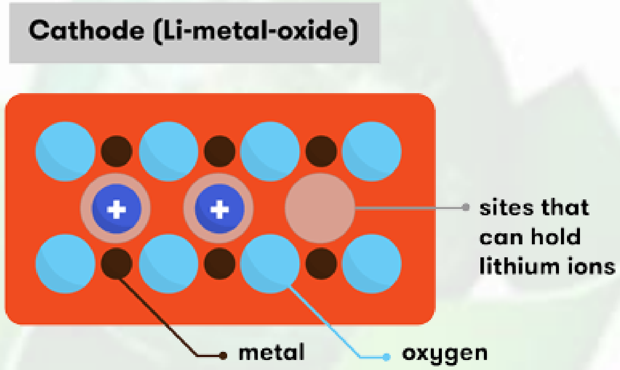


Various components of Li-ion battery

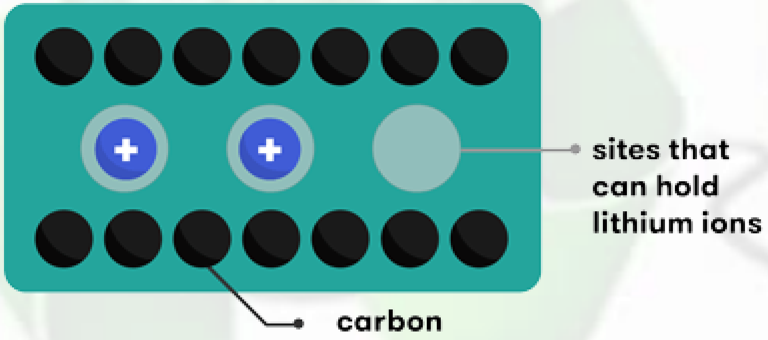


Various chemical compositions used in cathode are,

- LCO-Lithium Cobalt Oxide ($LiCoO_2$)
- LFP-Lithium Iron Phosphate ($LiFePO_4$)
- LMO-Lithium Manganese Oxide ($LiMn_2O_4$)
- NMC-Lithium Nickel Manganese Cobalt oxide ($LiNiMnCoO_2$)
- NCA-Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$)
- LTO-Lithium Titanium Oxide ($LiTiO_3$)

Various components of Li-ion battery

Anode (graphite)



The anode materials are usually,

Graphite.

Hard carbon.

Lithium Titanate.

Tin/cobalt alloy.

Silicon/carbon.

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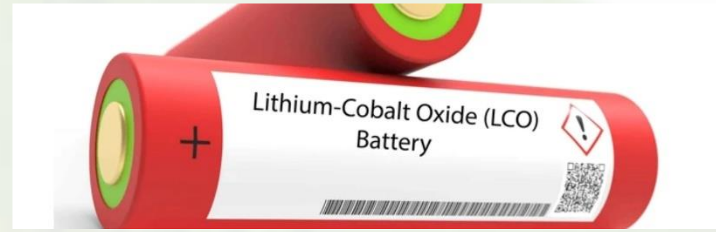
(1) LCO (Lithium Cobalt oxide):



At anode:

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

At cathode:

$$CoO_2 + Li^+ + e^- \rightarrow LicoO_2$$

Overall relation:

$$LicoO_2 + C_6 \rightarrow LiC_6 + CoO_2$$

Materials in Electrical Engineering

Battery Technologies for Electric Vehicles

(1) LCO (Lithium Cobalt oxide)

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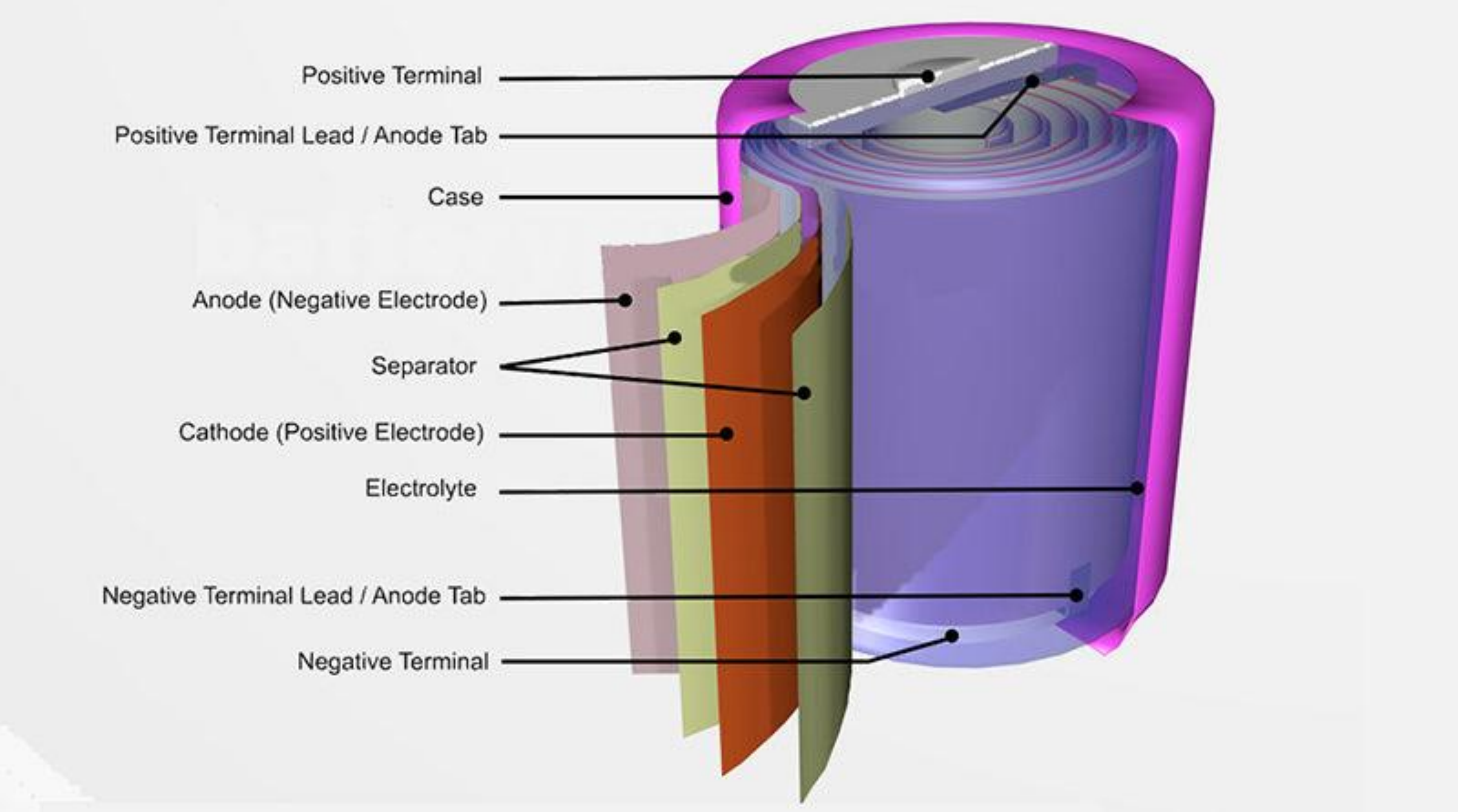
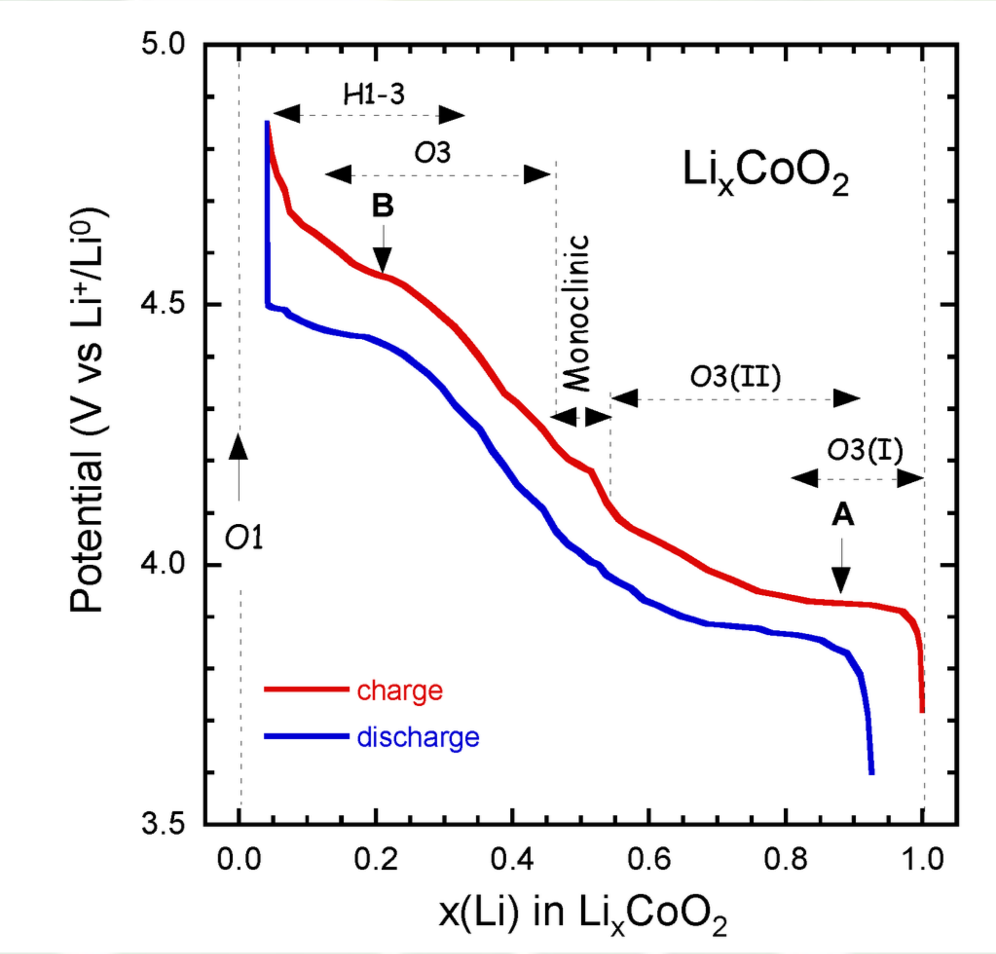


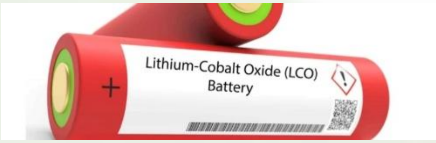
Materials in Electrical Engineering

Battery Technologies for Electric Vehicles

(1) LCO (Lithium Cobalt oxide)

Charge-discharge curves LixCoO2 at C/24 rate in the range 3.6–4.85 V vs. Li0/Li+





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(1) LCO (Lithium Cobalt oxide)

Nominal voltage: 3.6V

Typical operating range: 3.0 - 4.2 V/cell.

Specific energy(Capacity): 150-200Wh/Kg. Its seems to be high from above figure.

Specific Power: It is the ability to provide high current,which is operating in moderate level in these types of batteries.

Charge (C-rate): 0.7C-1C rate charge in 3 hrs (typical case). Charge upto 4.2V. Charge current above 1C shorten battery life.

Discharge (C-rate): 1C. Cutoff voltage at 2.5V and Discharge current above 1C shorten battery life.

Cycles life: 500-1000 cycles. This related to depth of discharge, load and temperature.

Thermal runaway: Full charge promotes thermal runaway condition and its maximum value is 150 deg C.

Cost: Coastwise Cobalt is expensive so these batteries are somewhat costlier.

It has high specific energy capacity but having less specific power, lesser life span makes them less popular over higher load operations.

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Various components of Li-ion battery

(2) LMO (Lithium Manganese Oxide, Li-MnO2):

At anode:

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

At cathode:

$MnO_2 + Li^+ + e^- \rightarrow LiMnO_2$

Overall relation:

$LiMnO_2 + C_6 \rightarrow LiC_6 + MnO_2$

Various components of Li-ion battery

(2) LMO (Lithium Manganese Oxide, Li-MnO2):

Nominal Voltage: 3.7V.

Typical operating range: 3.0-4.2V/cell.

Specific energy (Capacity): 100-150Wh/kg.

Charge(C-rate): 0.7-1C typical, maximum up to 3C. Charge up to 4.2V (Typical level).

Discharge (C-rate): 1C. Cutoff Voltage at 2.5V. Discharge possible up to 10C with some cells.

Cycle life: 300-700 times related to depth of discharge and temperature.

Thermal runaway: 250 deg C at typical condition. High charge promotes thermal runaway.

Higher power but lesser capacity. These battery types are safer than Li-Cobalt batteries. They are commonly mixed with NMC for better performance.

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Various components of Li-ion battery

(3) NCA (Lithium Nickel Cobalt Aluminium Oxide

At anode:

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

At cathode:

$NiCoAlO_2 + Li^+ + e^- \rightarrow LiNiCoAlO_2$

Overall relation:

$C_6Li + NiCoAlO_2 \rightarrow LiCoAlO_2 + C_6$

Various components of Li-ion battery

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(3) NCA (Lithium Nickel Cobalt Aluminium Oxide

Typical operating range: 3.0-4.2V/cell

Specific energy capacity: 200-260Wh/kg. Upto 300Wh/Kg.

Charge(C-rate): 0.7C,Charge up to 4.2V(most cells), Charge duration as 3Hr(typical case). Fast charge are possible.

Discharge(C-rate): 1C typical, Cutoff voltage to 3.0V. High discharge rate shorten the battery life.

Cycle life: 500 (Related to DOD and temperature)

Thermal runaway: 150 deg C(Typical), High charge promotes thermal runaway.

Cost: Approx.$350/KWh.

(4) NMC -Lithium Nickel Manganese Cobalt oxide, Li-NMC

At anode:

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

At cathode:

$$NiMnCoO_2 + Li^+ + e^- \rightarrow LiNiMnCoO_2$$

Overall relation:

$$LiC_6 + NiMnCoO_2 \rightarrow LiNiMnCoO_2 + C_6$$

(4)NMC - Lithium Nickel Manganese Cobalt oxide, Li-NMC

Nominal Voltage: 3.6-3.7 V.

Typical voltage range: 3.0 -4.2V/cell and higher too.

Specific energy: 150-220Wh/kg.

Charge(C-rate): 0.7-1C.Maximum charge upto 4.2V and also to 4.3V. Charge current above 1C shorten the battery life.

Discharge(C-rate): 1C-2C.Cutoff voltage as 2.50V.

Cycle life: 1000-2000 times (Related to DOD and temperature).

Thermal runaway:210 deg C.High charge promotes thermal runaway.

Cost: Approx.$420/KWh.

(4)NMC - Lithium Nickel Manganese Cobalt oxide, Li-NMC

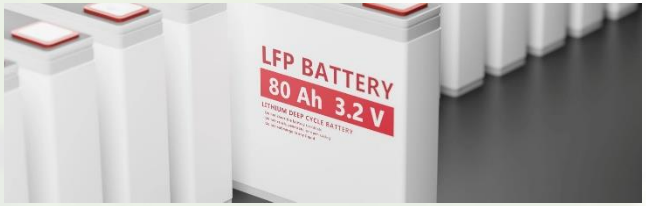
cathode

NMC 111: Equal parts of Ni, Mn, and Co.

cathode

NMC 811:
8 parts nickel,
1 part manganese, and
1 part cobalt,

Various components of Li-ion battery



(5) LFP(Lithium Iron Phosphte):

At anode:

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

At cathode:

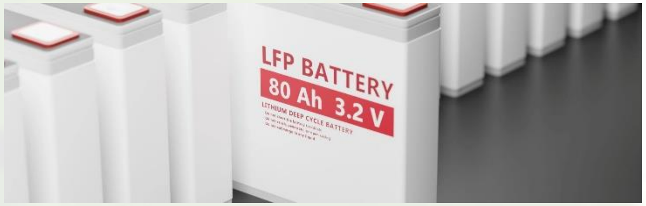
$$FePo_4 + Li^+ + e^- \rightarrow LiFePO_4$$

Overall relation:

$$LiC_6 + FePo_4 \rightarrow LiFePO4 + C_6$$

Various components of Li-ion battery

(5) LFP (Lithium Iron Phosphte):



Nominal Voltage: 3.20-3.30V.

Typical operating range: 2.5-3.65V/cell.

Specific energy: 90-120Wh/kg.

Charge(C-rate): 1C typical. Charge upto 3.65V. Charging duration as 3Hr.

Discharge (C-rate): 1C-25C on some cells. Cutoff voltage as 2.50V. Less than 2V causses damage.

Cycle life: 2000 and higher (Related to depth of discharge and temperature).

Thermal runaway: 270 deg C (Fully safe even at full charge)

Cost: Approx. $580/KWh.

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Various components of Li-ion battery

(6) LTO(Lithium Titanium Oxide)

At anode:

$$Li_2TiO_3 \rightarrow TiO_2 + Li^+ + e^-$$

At cathode:

$$Mn_2O_4 + Li + e^- \rightarrow LiMn_2O_4$$

Overall relation:

$$Li_2TiO_3 + 2\ Mn_2O_4 \rightarrow 2LiMn_2O_4 + TiO_3$$

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Various components of Li-ion battery

(6) LTO (Lithium Titanium Oxide)

Nominal Voltage: 2.4V.

Typical operating range: 1.8-2.85 V/cell.

Specific energy: 50-80Wh/kg.

Charge(C-rate): 1C-5C maximum .Charge upto 2.85V.

Discharge (C-rate): 10C. Cutoff voltage as 1.80V on LCO/LTO.

Cycle life: 3000-7000 times.

Thermal runaway: One of the safest among all Li-ion batteries.

Cost: Approx. $1,005/KWh.

Various components of Li-ion battery

Reaction type	LCO	LMO	NCA	NMC	LFP	LTO
Anode	Graphite	Graphite	Graphite	Graphite	Graphite	Lithium Titnium Oxide
Cathode	Lithium cobalt oxide	Lithium Manganese Oxide	Lithium Nickel Cobalt Oxide	Lithium Nickel Manganese Cobalt Oxide	Lithium Iron Phosphate	Manganese Oxide
Electrolyte	Ethylene Carbonate +Li Salt	Methyle Carbonate +Li Salt	Propylene Carbonate +Li Salt	Methyle Carbonate +Li Salt	Propylene Carbonate +Li Salt	Propylene Carbonate +Li Salt
Seperators	Polyolefin	Polyolefin	Polyolefin	Polyolefin	Polyolefin	Polyolefin
Nominal Voltage	3.6V	3.7V	3.6V	3.6V-3.7 V	3.2V-3.3V	2.4V
Applicatio ns	Mobiles,Lapt ops,Cameras	Power tools,Medical devices,Power trains	Electrical power trains,medical devices,Industr ies	E-bikes,EV's ,Medical devices,industrial uses.	High load current and endurance needed equipments	