Lithium-ion battery

A **lithium-ion battery** or **Li-ion battery** (abbreviated as **LIB**) is a type of [rechargeable battery](https://en.wikipedia.org/wiki/Rechargeable_battery). Lithium-ion batteries are commonly used for [portable electronics](https://en.wikipedia.org/wiki/Portable_electronics) and [electric vehicles](https://en.wikipedia.org/wiki/Electric_vehicle) and are growing in popularity for military and [aerospace](https://en.wikipedia.org/wiki/Aerospace) applications

Research areas for lithium-ion batteries include extending lifetime, increasing energy density, improving safety, reducing cost, and increasing charging speed,[[18]](https://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-18) among others. Research has been under way in the area of non-flammable electrolytes as a pathway to increased safety based on the flammability and volatility of the organic solvents used in the typical electrolyte. Strategies include [aqueous lithium-ion batteries](https://en.wikipedia.org/wiki/Aqueous_Lithium-ion_Battery), ceramic solid electrolytes, polymer electrolytes, ionic liquids, and heavily fluorinated systems

# Types of Lithium-ion

## Lithium Cobalt Oxide(LiCoO2) — LCO

ts high specific energy makes Li-cobalt the popular choice for mobile phones, laptops and digital cameras. The battery consists of a cobalt oxide cathode and a graphite carbon anode. The cathode has a layered structure and during discharge, lithium ions move from the anode to the cathode. The flow reverses on charge. The drawback of Li-cobalt is a relatively short life span, low thermal stability and limited load capabilities (specific power). Figure 1 illustrates the structure.

The drawback of Li-cobalt is a relatively short life span, low thermal stability and limited load capabilities (specific power). Like other cobalt-blended Li-ion, Li-cobalt has a graphite anode that limits the cycle life by a changing [solid electrolyte interface (SEI)](http://batteryuniversity.com/learn/article/how_to_prime_batteries), thickening on the anode and lithium plating while fast charging and charging at low temperature. Newer systems include nickel, manganese and/or aluminum to improve longevity, loading capabilities and cost.

**Li-cobalt excels on high specific energy but offers only moderate performance specific power, safety and life span.**

**Summary Table**

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| **Lithium Cobalt Oxide:** LiCoO2 cathode (~60% Co), graphite anode                                       Short form: LCO or Li-cobalt.                                                                                                             Since 1991 | |
| **Voltages** | 3.60V nominal; typical operating range 3.0–4.2V/cell |
| **Specific energy (capacity)** | 150–200Wh/kg. Specialty cells provide up to 240Wh/kg. |
| **Charge (C-rate)** | 0.7–1C, charges to 4.20V (most cells); 3h charge typical. Charge current above 1C shortens battery life. |
| **Discharge (C-rate)** | 1C; 2.50V cut off. Discharge current above 1C shortens battery life. |
| **Cycle life** | 500–1000, related to depth of discharge, load, temperature |
| **Thermal runaway** | 150°C (302°F). Full charge promotes thermal runaway |
| **Applications** | Mobile phones, tablets, laptops, cameras |
| **Comments**   **2019 update:** | Very high specific energy, limited specific power. Cobalt is expensive. Serves as Energy Cell. Market share has stabilized.  Early version; no longer relevant. |

## 2. Lithium Manganese Oxide (LiMn2O4) — LMO

# Li-ion with manganese spinel was first published in the Materials Research Bulletin in 1983. In 1996, Moli Energy commercialized a Li-ion cell with lithium manganese oxide as cathode material. The architecture forms a three-dimensional spinel structure that improves ion flow on the electrode, which results in lower internal resistance and improved current handling. A further advantage of spinel is high thermal stability and enhanced safety, but the cycle and calendar life are limited. Low internal cell resistance enables fast charging and high-current discharging. In an 18650 package, Li-manganese can be discharged at currents of 20–30A with moderate heat buildup. It is also possible to apply one-second load pulses of up to 50A. A continuous high load at this current would cause heat buildup and the cell temperature cannot exceed 80°C (176°F). Li-manganese is used for power tools, medical instruments, as well as hybrid and electric vehicles.

# Although moderate in overall performance, newer designs of Li-manganese offer improvements in specific power, safety and life span.

**Summary Table**

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| **Lithium Manganese Oxide:** LiMn2O4 cathode. graphite anode                                                               Short form: LMO or Li-manganese (spinel structure)                                                                    Since 1996 | |
| **Voltages** | 3.70V (3.80V) nominal; typical operating range 3.0–4.2V/cell |
| **Specific energy (capacity)** | 100–150Wh/kg |
| **Charge (C-rate)** | 0.7–1C typical, 3C maximum, charges to 4.20V (most cells) |
| **Discharge (C-rate)** | 1C; 10C possible with some cells, 30C pulse (5s), 2.50V cut-off |
| **Cycle life** | 300–700 (related to depth of discharge, temperature) |
| **Thermal runaway** | 250°C (482°F) typical. High charge promotes thermal runaway |
| **Applications** | Power tools, medical devices, electric powertrains |
| **Comments**   **2019 update:** | High power but less capacity; safer than Li-cobalt; commonly mixed with NMC to improve performance.  Less relevant now; limited growth potential. |

## 3. Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2)

# One of the most successful Li-ion systems is a cathode combination of nickel-manganese-cobalt (NMC). Similar to Li-manganese, these systems can be tailored to serve as [Energy Cells](http://batteryuniversity.com/learn/article/discharge_characteristics_li) or [Power Cells](http://batteryuniversity.com/learn/article/discharge_characteristics_li). For example, NMC in an 18650 cell for moderate load condition has a capacity of about 2,800mAh and can deliver 4A to 5A; NMC in the same cell optimized for specific power has a capacity of only about 2,000mAh but delivers a continuous discharge current of 20A. A silicon-based anode will go to 4,000mAh and higher but at reduced loading capability and shorter cycle life. Silicon added to graphite has the drawback that the anode grows and shrinks with charge and discharge, making the cell mechanically unstable.

# NMC is the battery of choice for power tools, e-bikes and other electric powertrains. The cathode combination is typically one-third nickel, one-third manganese and one-third cobalt, also known as 1-1-1. This offers a unique blend that also lowers the raw material cost due to reduced cobalt content. Another successful combination is NCM with 5 parts nickel, 3 parts cobalt and 2 parts manganese (5-3-2). Other combinations using various amounts of cathode materials are possible.

# NMC has good overall performance and excels on specific energy. This battery is the preferred candidate for the electric vehicle and has the lowest self-heating rate

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| **Lithium Nickel Manganese Cobalt Oxide:** LiNiMnCoO2. cathode, graphite anode Short form: NMC (NCM, CMN, CNM, MNC, MCN similar with different metal combinations) Since 2008 | |
| **Voltages** | 3.60V, 3.70V nominal; typical operating range 3.0–4.2V/cell, or higher |
| **Specific energy (capacity)** | 150–220Wh/kg |
| **Charge (C-rate)** | 0.7–1C, charges to 4.20V, some go to 4.30V; 3h charge typical. Charge current above 1C shortens battery life. |
| **Discharge (C-rate)** | 1C; 2C possible on some cells; 2.50V cut-off |
| **Cycle life** | 1000–2000 (related to depth of discharge, temperature) |
| **Thermal runaway** | 210°C (410°F) typical. High charge promotes thermal runaway |
| **Cost** | ~$420 per kWh (Source: RWTH, Aachen) |
| **Applications** | E-bikes, medical devices, EVs, industrial |
| **Comments**   **2019 update:** | Provides high capacity and high power. Serves as Hybrid Cell. Favorite chemistry for many uses; market share is increasing.  Leading system; dominant cathode chemistry. |

## 3. Lithium Iron Phosphate(LiFePO4) — LFP

# Li-phosphate offers good electrochemical performance with low resistance. This is made possible with nano-scale phosphate cathode material. The key benefits are high current rating and long cycle life, besides good thermal stability, enhanced safety and tolerance if abused.

# Li-phosphate is more tolerant to full charge conditions and is less stressed than other lithium-ion systems if kept at high voltage for a prolonged time. As a trade-off, its lower nominal voltage of 3.2V/cell reduces the specific energy below that of cobalt-blended lithium-ion. With most batteries, cold temperature reduces performance and elevated storage temperature shortens the service life, and Li-phosphate is no exception. Li-phosphate has a higher self-discharge than other Li-ion batteries, which can cause balancing issues with aging. This can be mitigated by buying high quality cells and/or using sophisticated control electronics, both of which increase the cost of the pack. Cleanliness in manufacturing is of importance for longevity. There is no tolerance for moisture, lest the battery will only deliver 50 cycles. Figure 9 summarizes the attributes of Li-phosphate.

# Li-phosphate is often used to replace the lead acid starter battery. Four cells in series produce 12.80V, a similar voltage to six 2V lead acid cells in series. Vehicles charge lead acid to 14.40V (2.40V/cell) and maintain a topping charge. Topping charge is applied to maintain full charge level and prevent  n lead acid batteries. With four Li-phosphate cells in series, each cell tops at 3.60V, which is the correct full-charge voltage. At this point, the charge should be disconnected but the topping charge continues while driving. Li-phosphate is tolerant to some overcharge; however, keeping the voltage at 14.40V for a prolonged time, as most vehicles do on a long road trip, could stress Li-phosphate. Time will tell how durable Li-Phosphate will be as a lead acid replacement with a regular vehicle charging system. Cold temperature also reduces performance of Li-ion and this could affect the cranking ability in extreme cases.  Li-phosphate has excellent safety and long life span but moderate specific energy and elevated self-discharge.

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| **Lithium Iron Phosphate:** LiFePO4 cathode, graphite anode                                                    Short form: LFP or Li-phosphate                                                                                                       Since 1996 | |
| **Voltages** | 3.20, 3.30V nominal; typical operating range 2.5–3.65V/cell |
| **Specific energy (capacity)** | 90–120Wh/kg |
| **Charge (C-rate)** | 1C typical, charges to 3.65V; 3h charge time typical |
| **Discharge (C-rate)** | 1C, 25C on some cells; 40A pulse (2s); 2.50V cut-off (lower that 2V causes damage) |
| **Cycle life** | 2000 and higher (related to depth of discharge, temperature) |
| **Thermal runaway** | 270°C (518°F) Very safe battery even if fully charged |
| **Cost** | ~$580 per kWh (Source: RWTH, Aachen) |
| **Applications** | Portable and stationary needing high load currents and endurance |
| **Comments**   **2019 update:** | Very flat voltage discharge curve but low capacity. One of safest Li-ions. Used for special markets. Elevated self-discharge.  Used primarily for energy storage, moderate growth. |

## 4. Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2) — NCA

# Lithium nickel cobalt aluminum oxide battery, or NCA, has been around since 1999 for special applications. It shares similarities with NMC by offering high specific energy, reasonably good specific power and a long life span. Less flattering are safety and cost. Figure 11 summarizes the six key characteristics. NCA is a further development of lithium nickel oxide; adding aluminum gives the chemistry greater stability.

# High energy and power densities, as well as good life span, make NCA a candidate for EV powertrains. High cost and marginal safety are negatives.

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| **Lithium Nickel Cobalt Aluminum Oxide:**LiNiCoAlO2 cathode (~9% Co), graphite anode                Short form: NCA or Li-aluminum.                                                                                                     Since 1999 | |
| **Voltages** | 3.60V nominal; typical operating range 3.0–4.2V/cell |
| **Specific energy (capacity)** | 200-260Wh/kg; 300Wh/kg predictable |
| **Charge (C-rate)** | 0.7C, charges to 4.20V (most cells), 3h charge typical, fast charge possible with some cells |
| **Discharge (C-rate)** | 1C typical; 3.00V cut-off; high discharge rate shortens battery life |
| **Cycle life** | 500 (related to depth of discharge, temperature) |
| **Thermal runaway** | 150°C (302°F) typical, High charge promotes thermal runaway |
| **Cost** | ~$350 per kWh (Source: RWTH, Aachen) |
| **Applications** | Medical devices, industrial, electric powertrain (Tesla) |
| **Comments**  **2019 update:** | Shares similarities with Li-cobalt. Serves as Energy Cell.  Mainly used by Panasonic and Tesla; growth potential. |

## 5. Lithium Titanate (Li2TiO3) — LTO

Batteries with lithium titanate anodes have been known since the 1980s. Li-titanate replaces the graphite in the anode of a typical lithium-ion battery and the material forms into a spinel structure. The cathode can be lithium manganese oxide or NMC. Li-titanate has a nominal cell voltage of 2.40V, can be fast charged and delivers a high discharge current of 10C, or 10 times the rated capacity. The cycle count is said to be higher than that of a regular Li-ion. Li-titanate is safe, has excellent low-temperature discharge characteristics and obtains a capacity of 80 percent at –30°C (–22°F).  
  
LTO (commonly Li4Ti5O12) has advantages over the conventional cobalt-blended Li-ion with graphite anode by attaining zero-strain property, no SEI film formation and no lithium plating when fast charging and charging at low temperature. Thermal stability under high temperature is also better than other Li-ion systems; however, the battery is expensive. At only 65Wh/kg, the specific energy is low, rivalling that of NiCd. Li-titanate charges to 2.80V/cell, and the end of discharge is 1.80V/cell. Figure 13 illustrates the characteristics of the Li-titanate battery. Typical uses are electric powertrains, UPS and solar-powered street lighting.

**Li-titanate excels in safety, low-temperature performance and life span. Efforts are being made to improve the specific energy and lower cost.**

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| **Lithium Titanate:** Cathode can be lithium manganese oxide or NMC; Li2TiO3 (titanate) anode Short form: LTO or Li-titanate                                              Commercially available since about 2008. | |
| **Voltages** | 2.40V nominal;  typical operating range 1.8–2.85V/cell |
| **Specific energy (capacity)** | 50–80Wh/kg |
| **Charge (C-rate)** | 1C typical; 5C maximum, charges to 2.85V |
| **Discharge (C-rate)** | 10C possible, 30C 5s pulse; 1.80V cut-off  on LCO/LTO |
| **Cycle life** | 3,000–7,000 |
| **Thermal runaway** | One of safest Li-ion batteries |
| **Cost** | ~$1,005 per kWh (Source: RWTH, Aachen) |
| **Applications** | UPS, electric powertrain (Mitsubishi i-MiEV, Honda Fit EV), solar-powered street lighting |
| **Comments**   **2019 update:** | Long life, fast charge, wide temperature range but low specific energy and expensive. Among safest Li-ion batteries.  Ability to ultra-fast charge; high cost limits to special application. |

