**Common and Alternative Battery Chemistries**  
As compiled by the BCI Technical Committee

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**Lead acid (Pb)**  
Lead-acid batteries consist of a lead-dioxide cathode, a sponge metallic lead anode and a sulfuric acid solution electrolyte that can be sealed or flooded. The cell voltage is 2.1 Volts. They are mainly used in starter batteries for internal combustion engine (ICE) vehicles. Because of their high lead content, these batteries give lower energy density.  

Because of it is robust and low cost, this battery is still the prevailing chemistry in use. It has good high-rate performance over a wide temperature range and low self discharge. Failure occurs from several hundred to over a thousand capacity cycles. In starting service, lead-acid batteries can provide many thousands of shallow cycles.  

In addition to its usage as a starting battery, lead-acid is also used for deep cycle operations and standby power.  

While their lead content makes them toxic and improper disposal can be hazardous to the environment, lead-acid batteries are easily and almost totally recycled.

**Nickel Cadmium (NiCd)**  
Nickel Cadmium batteries use nickel hydroxide Ni(OH)$_2$ for the cathode, cadmium Cd as the anode and an alkaline solution of potassium hydroxide (KOH) for an electrolyte that can be sealed recombinant or flooded.  

NiCd batteries have been used for storing electrical energy in a wide variety of applications. They have a long cycle life and good high-rate performance over a wide temperature range with rapid recharge capability. The batteries suffer from memory effect and high self-discharge at high temperature. Cost is higher than lead acid.  

Because cadmium metal is highly toxic and yields soluble compounds, its use in batteries is restricted or banned in many countries.
**Nickel Metal Hydride (NiMH)**
NiMH batteries use nickel hydroxide $\text{Ni(OH)}_2$ for the cathode. Hydrogen in a hydride form absorbed on lanthanum is used as the anode. The sealed recombinant electrolyte is alkaline, usually potassium hydroxide (KOH).

Nickel Metal Hydride batteries share similarities with NiCd batteries but they have higher capacity. They can be recharged rapidly but their high rate performance is less than that of nickel-cadmium. They also suffer because of poor charge retention and higher cost anodes. They have been used successfully in hybrid vehicles, computers, cell phones and other consumer electronic applications where they provide a safer operation than many lithium ion variations. Cost is much higher than lead acid, but they usually have longer life.

There are minimal environmental problems.

**Zebra – Sodium (Na-NiCl$_2$)**
The zebra battery is a molten salt battery that operates at 270–350°C. The cathode is nickel in the discharged state and nickel chloride in the charged state. The anode is molten sodium. Molten sodium aluminum chloride (NaAlCl$_4$), which has a melting point of approximately 157°C, is used as the electrolyte. Separators are made from beta-alumina ceramic.

The zebra battery has an attractive specific energy and good cycle life but is somewhat limited in power (90 Wh/kg and 150 W/kg). Its cost is higher than lead acid.

When not in use, zebra batteries typically require to be left on charge, in order to be ready for use when needed. If shut down, the reheating process lasts 24 hours, and then a normal charge process of 6-8 hours is required for a full charge. This is a major issue for EV customers who may not use their vehicle every day or forget to put the vehicle on charge. It is also inefficient as it consumes energy when not in use.

**Lithium-ion**
Lithium, because of its low weight and high voltage, can provide over three times the energy density of traditional rechargeable batteries. The technology is still advancing with extensive research to increase energy density, high-rate capability, cycle life, increased charging rates and cost reduction. Despite the fact that it has higher energy density than other battery systems, it still is not suited for long range electric vehicles. It is therefore targeted toward shorter range EVs, PHEVs and HEVs.

Lithium-ion batteries normally use carbon anodes or a lithium titanate variation. There is no single chemistry lithium-ion battery. The cathode can consist of a variety of compounds, each with different characteristics and electrochemical performance. The electrolyte normally consists of a lithium salt dissolved in a non-aqueous organic solvent that is flammable at elevated temperatures.
The energy of the battery is limited by the specific capacity of the electrodes, and the cathode in particular. Much investment and research has therefore been devoted to replacement cathode materials.

The cost of the lithium systems is still high and there is limited recycling.
### Comparison of Common Cell Chemistries

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit of Measurement</th>
<th>Lead Acid</th>
<th>NiMH</th>
<th>Lithium-Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Voltage</td>
<td>Volts</td>
<td>2.1</td>
<td>1.2</td>
<td>3.2-3.6</td>
</tr>
<tr>
<td>Energy Density</td>
<td>Wh/Kg</td>
<td>30-40</td>
<td>50-80</td>
<td>100-200</td>
</tr>
<tr>
<td>Power Density</td>
<td>W/Kg</td>
<td>100-200</td>
<td>100-500</td>
<td>500-8000</td>
</tr>
<tr>
<td>Maximum Discharge</td>
<td>C</td>
<td>6 -10</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>Useful Capacity</td>
<td>Depth of Discharge%</td>
<td>50</td>
<td>50-80</td>
<td>&gt;80</td>
</tr>
<tr>
<td>Charge Efficiency</td>
<td>%</td>
<td>60-80</td>
<td>70-90</td>
<td>~100</td>
</tr>
<tr>
<td>Self Discharge</td>
<td>%/Month</td>
<td>3-4</td>
<td>30</td>
<td>2-3</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>ºC</td>
<td>-40 +60</td>
<td>-30 +60</td>
<td>-40 +60</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>Number of Cycles</td>
<td>600-900</td>
<td>&gt;1000</td>
<td>&gt;2000</td>
</tr>
<tr>
<td>Micro-cycle Tolerant</td>
<td></td>
<td>Deteriorates</td>
<td>Yes</td>
<td>Yes Needs BMS</td>
</tr>
<tr>
<td>Robust (Over/Under Voltage)</td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Needs BMS</td>
</tr>
</tbody>
</table>

### Lithium variants

**Lithium Cobalt Oxide – LiCoO$_2$**

While Lithium Cobalt Oxide has been the most widely used cathode material in lithium batteries for computers and cell phones, it has a number of drawbacks compared to the new chemistries. While it provides moderate cycle life (>500 cycles) and energy density, it is less thermally stable than other transition metal oxide or phosphate chemistries making it highly combustible under extreme abuse conditions. These characteristics restrict their use in EV and HEV applications.

**Lithium Iron Phosphate – LiFePO$_4$ (and LiMnPO$_4$)**

Due to the ability not to release oxygen during abusive conditions, phosphate-based cathodes have superior thermal stability than other Lithium-ion technologies. While Lithium phosphate cells are incombustible or resist thermal breakdown in the event of mishandling during charge, discharge, overcharge or short circuit conditions, they have lower operating voltage than other cathode chemistries thereby giving a lower energy density. Lithium iron phosphate batteries offer a longer cycle life and can support higher currents and thus greater power. They are a significant improvement over lithium cobalt oxide cells in terms of the cost, safety and toxicity. The use of manganese increases the operating voltage of the phosphate system compared with iron.

**Lithium Manganese Oxide Spinel – LiMn$_2$O$_4$**

In comparison with cobalt based cathodes, Lithium Manganese Oxide Spinel provides a higher cell voltage and is more thermally stable. Manganese, unlike Cobalt, is also a safe and more environmentally benign cathode material. Other benefits include lower cost and higher temperature performance. It does however suffer from less (20%) energy density.

**Lithium (NCM) – Nickel Cobalt Manganese – LiNi$_x$Co$_y$Mn$_z$O$_2$**

Using a mixed metal content of nickel, cobalt and manganese in the cathode gives energy density superior to LiCoO$_2$ and LiFePO$_4$ at a lower cost. Power density performance is better than LiCoO$_2$ but not as high as LiFePO$_4$. This chemistry is increasingly seen as a viable alternative solution to LiFePO$_4$ for high energy density packs for EV and HEV applications.
**Lithium Titanate Oxide (LTO) – Li₄Ti₅O₁₂**
Lithium titanate can replace the graphite anode and work with the various cathode materials. This anode is compatible with any of the above cathodes, but is generally used with high voltage Manganese-based systems. They display superior high-rate capability and power over a wide operating temperature range and are also safer than the graphite anode. Unlike graphite, they do not form a passivating layer with the electrolyte thus increasing cycle life. However, lithium titanate batteries tend to have a slightly lower energy density than graphite-based systems.

<table>
<thead>
<tr>
<th>Main Lithium Variants</th>
<th>Energy Density (Wh/kg)</th>
<th>Energy Density (Wh/l)</th>
<th>Cycle Life (100% DOD)</th>
<th>Price ($/Wh)</th>
<th>Power</th>
<th>Thermal Runaway Onset Temperature °C</th>
<th>Voltage</th>
<th>Temperature Range °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCoO₂</td>
<td>170-185</td>
<td>450-490</td>
<td>500</td>
<td>0.31-0.46</td>
<td>1C</td>
<td>170</td>
<td>3.6</td>
<td>-20 to 60</td>
</tr>
<tr>
<td>LiFePO₄ (EV/PHEV)</td>
<td>90-125</td>
<td>130-300</td>
<td>2000</td>
<td>0.3-0.6</td>
<td>5C cont. 10C pulse</td>
<td>270</td>
<td>3.2</td>
<td>-20 to 60</td>
</tr>
<tr>
<td>LiFePO₄ (HEV)</td>
<td>80-108</td>
<td>200-240</td>
<td>&gt;1000</td>
<td>0.8-1.2</td>
<td>30C cont. 50C pulse</td>
<td>270</td>
<td>3.2</td>
<td>-20 to 60</td>
</tr>
<tr>
<td>NCM (HEV)</td>
<td>150</td>
<td>270-290</td>
<td>1500</td>
<td>0.5-0.58</td>
<td>20C cont. 40C pulse</td>
<td>215</td>
<td>3.7</td>
<td>-20 to 60</td>
</tr>
<tr>
<td>NCM (EV/PHEV)</td>
<td>155-190</td>
<td>330-365</td>
<td>1500</td>
<td>0.5-0.58</td>
<td>1C cont. 5C pulse</td>
<td>215</td>
<td>3.7</td>
<td>-20 to 60</td>
</tr>
<tr>
<td>Titanate vs NCM/LMO</td>
<td>65-100</td>
<td>118-200</td>
<td>12000</td>
<td>1-1.7</td>
<td>10C cont. 20C pulse</td>
<td>Not susceptible</td>
<td>2.5</td>
<td>-50 to 75</td>
</tr>
<tr>
<td>Manganese Spinel (EV/PHEV)</td>
<td>90-110</td>
<td>280</td>
<td>&gt;1000</td>
<td>0.45-0.55</td>
<td>3-5C cont.</td>
<td>255</td>
<td>3.8</td>
<td>-20 to 50</td>
</tr>
</tbody>
</table>

**Chemistry development**

There is considerable room for the development of new materials for electrode chemistries that would offer the possibility of increasing the energy density of cells, thus making them more attractive for automotive applications. Some potential replacement cell chemistries are outlined below.
**Transition Metal Oxide (TMO)/Silicon Alloy**
Silicon-Alloy materials are particularly attractive as replacements for a graphite anode, as they offer higher energy density than graphite (up to three times as much) and would be potentially much cheaper to manufacture than both soft, hard and semi-gra hitized carbons.

When used in conjunction with an advanced transition metal oxide (TMO) or even silicate-based cathodes then cells using these anode and cathode combinations have a theoretical energy density of over 300Wh/kg, depending on the exact materials used.

**Zinc-Air cells**
Discharge is powered by the oxidation of zinc with oxygen from the air. Using a free external source of energy (oxygen) makes the energy density very attractive. Rechargeable cells use a catalyst to allow the reverse process of discharge to occur and make the cell rechargeable.

Although they offer high energy density, the downside is slow discharge rates and low power density; in other words the energy cannot be accessed fast.

**Lithium-Sulfur cells**
These have a high capacity, but many years of development have not solved the main problems--poor cycle life and high self-discharge.

**Lithium-Air cells**
Lithium-air cells potentially offer 5 to 10 times the energy density of existing lithium-ion cells.

A porous composite carbon and catalyst positive electrode is used to achieve recharge with selective membranes that allow selective oxygen transfer but no water and electrolyte. Cells in development have demonstrated only limited cycling.
<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Energy Density (Wh/kg)</th>
<th>Energy Density (Wh/l)</th>
<th>Power Density (W/kg)</th>
<th>Power Density (W/l)</th>
<th>Voltage</th>
<th>Cycle Life</th>
<th>Temperature Range</th>
<th>Self discharge</th>
<th>Environmental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Acid</td>
<td>30-45</td>
<td>50-100</td>
<td>200-700</td>
<td>800-1400</td>
<td>2.1</td>
<td>low-med</td>
<td>-40 to +80</td>
<td>Low</td>
<td>Good (recycled)</td>
</tr>
<tr>
<td>Nickel Cadmium</td>
<td>40-60</td>
<td>100-160</td>
<td>140-160</td>
<td>250-300</td>
<td>1.2</td>
<td>v.good</td>
<td>-20 to +50</td>
<td>High</td>
<td>Poor (cadmium)</td>
</tr>
<tr>
<td>Nickel Metal Hydride</td>
<td>60-90</td>
<td>200-280</td>
<td>200-250</td>
<td>550-700</td>
<td>1.2</td>
<td>good</td>
<td>-20 to +60</td>
<td>High</td>
<td>OK</td>
</tr>
<tr>
<td>Lithium Ion</td>
<td>100-160</td>
<td>270-350</td>
<td>250-350</td>
<td>600-850</td>
<td>2.3-4.0</td>
<td>good</td>
<td>-20 to +60</td>
<td>Low</td>
<td>OK</td>
</tr>
<tr>
<td>Lithium Polymer</td>
<td>130-200</td>
<td>250-350</td>
<td>260-450</td>
<td>600-800</td>
<td>3.7</td>
<td>OK-good</td>
<td>20 to +60</td>
<td>Low-medium</td>
<td>OK</td>
</tr>
<tr>
<td>Sodium Nickel Chloride</td>
<td>80-100</td>
<td>130-170</td>
<td>80-120</td>
<td>180-220</td>
<td>2.6</td>
<td>OK</td>
<td>Molten salt</td>
<td>High</td>
<td>OK</td>
</tr>
</tbody>
</table>

**Cost**

- **Lead Acid**: Low (1X) - SLI, motive power, standby, HEV (lower voltage)
- **Nickel Cadmium**: Medium (2X) - SLI, motive power, small power
- **Nickel Metal Hydride**: Medium (3-4X) - SLI, motive power, small power
- **Lithium Ion**: Medium (4-10X) - SLI, motive power, small power
- **Lithium Polymer**: High (6-10X) - SLI, motive power, small power
- **Sodium Nickel Chloride**: Medium (3X) - SLI, motive power, small power

**Applications**

- **Lead Acid**: HEV, small power
- **Nickel Cadmium**: Small power, EV, PHEV, HEV
- **Nickel Metal Hydride**: Small power, EV, PHEV, HEV
- **Lithium Ion**: High voltage, light weight, cycle life
- **Lithium Polymer**: High voltage, light weight, cycle life
- **Sodium Nickel Chloride**: High voltage, light weight, cycle life

**Weaknesses**

- **Lead Acid**: Weight, life, sulfation SLI, motive power, standby, HEV (lower voltage)
- **Nickel Cadmium**: Cadmium, memory effect, weight, low voltage, cost SLI, motive power, small power
- **Nickel Metal Hydride**: Self discharge, weight, over discharge, low voltage, cost HEV, small power
- **Lithium Ion**: Safety, cost, life, multiple chemistries, cost, temperature Small power, EV, PHEV, HEV
- **Lithium Polymer**: Safety, cost, life, cost, temperature Small power, EV, PHEV, HEV
- **Sodium Nickel Chloride**: Power, restricted to large capacity, maintaining molten salt Large motive power, large HEV

**Strengths**

- **Lead Acid**: Low cost, robust, mature, wide temperature, recycling, power
- **Nickel Cadmium**: Robust, cycle life, high charge rate, power
- **Nickel Metal Hydride**: Robust, cycle life, high charge rate
- **Lithium Ion**: High voltage, light weight, cycle life
- **Lithium Polymer**: High voltage, light weight, cycle life
- **Sodium Nickel Chloride**: Robust, safety, operating condition

**References:**

1. Electropaedia.com
2. Axeon
3. Midtronics, Inc.