ECE 398GG – ELECTRICAL VEHICLES

4. EV Batteries and Their Management

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Battery energy and power density

- Energy stored per unit mass and per unit volume are key measures for batteries.
- Energy rate (power) per unit mass and volume or also important.
- The capacity rate ($C$ rate) sets a reference point for energy and power.
- Also vital: Cycle life, cycle efficiency, self discharge, thermal capability.
Global battery market in 2019 was more than $100 billion. (http://www.grandviewresearch.com/industry-analysis/battery-market)

Of this, about 30% lead acid and about 30% lithium ion.

Familiar use for lead-acid batteries: vehicle starting, lighting, and ignition (SLI).

Massive use: Backup and auxiliary power for telecommunications and computing.
Rechargeable batteries (secondary batteries) have been around for more than 150 years.

Lead-acid batteries date to 1859. The overall reaction involves metallic lead, lead oxide, and sulfuric acid on the one side, with lead sulfate and water on the other side.

Nickel-iron batteries (1901) were favored by Edison and used in Detroit Electric and other electric cars.
Rechargeable types

- Nickel cadmium batteries (NiCd) (1899) can have high specific power, with common commercial devices rated to 20C.
- Cadmium is extremely toxic, and NiCd batteries are phasing out.
- Nickel-metal-hydride (NiMH) batteries (1967) avoid cadmium but are near-drop-in replacements for NiCd.
- They are still common in hybrid cars because the power density can be higher than for lithium cells.
## A few types (various sources, includes [www.powerstream.com](http://www.powerstream.com))

<table>
<thead>
<tr>
<th>Type</th>
<th>Cell voltage (room temp)</th>
<th>Energy density</th>
<th>Power density</th>
<th>Self discharge</th>
<th>Charge efficiency (typical)</th>
<th>Cycle life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead acid</td>
<td>2.04 V</td>
<td>35 Wh/kg</td>
<td>600 W/kg</td>
<td>16% per month</td>
<td>80%</td>
<td>200</td>
</tr>
<tr>
<td>Nickel cadmium</td>
<td>1.30 V</td>
<td>60 Wh/kg</td>
<td>600 W/kg</td>
<td>10% per month</td>
<td>70%</td>
<td>&gt;5000</td>
</tr>
<tr>
<td>Nickel metal hydride</td>
<td>1.35 V</td>
<td>100 Wh/kg</td>
<td>600 W/kg</td>
<td>10% per month (but 20% first day)</td>
<td>75%</td>
<td>500</td>
</tr>
<tr>
<td>Sodium sulfur</td>
<td>2.08 V (350°C)</td>
<td>110 Wh/kg</td>
<td>150 Wh/kg</td>
<td>--</td>
<td>85%</td>
<td>4500</td>
</tr>
<tr>
<td>Vanadium redox</td>
<td>1.41 V</td>
<td>20 Wh/kg</td>
<td>--</td>
<td>--</td>
<td>75%</td>
<td>&gt;20,000</td>
</tr>
<tr>
<td>Lithium ion</td>
<td>Variable to 4.1 V</td>
<td>200 Wh/kg</td>
<td>300 W/kg</td>
<td>2% per month</td>
<td>90%+</td>
<td>2000</td>
</tr>
<tr>
<td>Lithium ion (polymer)</td>
<td>Variable to 4.1 V</td>
<td>200 Wh/kg</td>
<td>400 Wh/kg</td>
<td>5% per month</td>
<td>90%+</td>
<td>500</td>
</tr>
</tbody>
</table>
Ragone Plot

- Specific power vs. specific energy
- Notice the log-log scales

www.powerstream.com
Present, future

- Although there are many rechargeable battery chemistries, lead acid, NiMH, and lithium-ion cells are the only ones in broad commercial application.
- Lead-acid batteries for SLI, NiMH for power-dense applications, Li-ion for energy dense applications.
- Future? Dozens of chemistries in various lab stages.
  - The ultimate could be related to a combination of lithium (the most electropositive element) and fluorine (the most electronegative element. Could yield a 6 V cell.
  - Mg-ion and Na-ion cells. Both in active development.
  - Lithium-air batteries are more akin to fuel cells. As batteries, they need much improvement on reversibility, efficiency, and other challenges.
Cylindrical battery construction

- NiCd example

S. Revankar, *Chemical Energy Storage*, Elsevier, 2019
Li-ion configuration

- **Cathode**: As the source of lithium ions, determines the capacity and the average voltage of a battery.
- **Anode**: Stores and releases lithium ions from the cathode, allowing the pass of currents through an external circuit.
- **Separator**: Prevents contact between cathode and anode.
- **Electrolyte**: The medium which helps the movement of ions.

www.samsungsdi.com
General issues

- Any electrochemical reaction follows an Arrhenius relation, in which the rate is proportional to \( e^{-E_a/kT} \) where \( E_a \) is an activation energy, \( k \) is Boltzmann's constant, and \( T \) is temperature.

- The effect is roughly a doubling of reaction rate for each 10°C rise.

- Impacts on battery performance are fundamental.
Li-ion challenges

- The high cell voltage (up to 4.1 V) rules out water-based electrolytes.
  - Lead acid: sulfuric acid
  - Nickel cells: potassium hydroxide solution
  - Li-ion: organic liquids, usually with dissolved lithium salts
- Thermal runaway: If a local hotspot gets above a certain point, it can start an exothermic reaction with the electrolyte degrading.
- Local damage or fire can follow.
- Case penetration can initiate this, https://www.youtube.com/watch?v=hCDkjOak3E0
Recycling infrastructure really is not in place.
There might need to be economic or regulatory incentives for recycling.
In the U.S., about 99% of lead-acid batteries are recycled.
Lead recycling is more profitable than lead mining.
Li-ion configuration

- The key in Li-ion cells is that lithium is bound in an ionic state rather than available as a pure metal.

Graphite is typical as the anode (negative electrode).

The cathode is a lithium compound.
- Lithium cobalt oxide
- Lithium iron phosphate
- Lithium manganese oxide
- Others

Electrolyte: a lithium salt in ethylene carbonate or dimethyl carbonate.

In any battery (or fuel cell), ions or protons diffuse through the electrolyte and electrons are directed through the external circuit.

This works if the external circuit requires less voltage than the inherent open-circuit electrochemical potential.

Electrolytes in general can be liquid (water based on carbonate based) or solid (polymers or some ceramics).

Ionic conductivity limits current rate capabilities.
Mechanical stresses

- It is typical for mass densities to differ between the two sets of end products in a secondary battery.
- Usually this means that a cell expands during charging.
- The change produces cyclic mechanical stress.
- It also produces pressure in the package.
- Vital to manage this for packaging, mounting, and physical management.
- If charging produces gases (e.g. hydrogen), internal pressure is an important issue.
Li-ion cells

- Good consumer-grade Li-ion cells will include internal thermal cutouts, fuses, and extra space for expansion.
- Although the maximum voltage is about 4.1 V, usually 3.6 V is taken as the nominal value. A 3 Ah cell therefore has nominal capacity of 10.8 Wh.
- Almost all practical uses involve series and parallel connection of cells. The typical notation is nSmP, e.g. 99S60P for an early Tesla pack.
Cell configurations

- Cylindrical cells (common)
  - Typical size 18650, 18 mm diameter, 65 mm long.
  - AA battery is size 14500, for example
- Prismatic cells (rectangular shape)
- Typical polymer pouch


[Image of battery cell and internal components]

[Image of battery cell with dimensions labeled]

[Image of battery cell with internal components labeled]

[Image of battery cell with 'http://www.batteryspace.com']
Comparing power and energy cell ratings

- All are for name-brand 18650 Li-ion cells (45-51 g).
Others

- Tesla making 21700 cylinders.
- New 46800 cells, some reporting 25 Ah capacity.
- Typical large-format prismatic cell, 72 Ah, 31 mm x 136 mm x 222 mm, 1.78 kg. Rated to 2C.

voltaplex.com
Modules

- A group of cells packaged together with a single output terminal set comprises a module.
- Most familiar: 12 V lead-acid battery, a module with 6 series cells, nominal 12 V.
- Sometimes used alone, or assembled into a complete battery pack.

www.onesourcebatteries.com
**Multi-cell modules, self contained**

2S2P Leaf module

- Modules can be from cylindrical or prismatic cells.
- Often provide coolant channels and sensors.

evbatterycenter.com

7S20P module

Tesla 6S74P Model S module

Phys.org (10/1/2009)

www.greentecauto.com
For lead-acid cells, most common: 12 V modules, 24 V packs (called 28 V in the industry), 48 V packs.

For Li-ion, no standards, but 20 V packs (5S) and 48 V packs (12S), are increasingly common.

www.bestgobattery.com
Packs

- A pack will include complete sensing and management electronics.

www.bestgobattery.com
Car packs need full moisture seals and comprehensive structural integration.

www.greenoptimistic.com
Battery operating phases

- Charge
- Discharge
- Idle
- Trickle (not used for Li-ion)

- Charge and discharge might not be symmetric.
Battery operating phases

- NiMH example

Battery operating phases

- Reduction in charge power density at the high end limits regeneration: energy acceptance drops above 60% SOC.
- Active balancing required 20% and 40% SOC, and between 60% and 80% SOC.
- Braking strategy must limit charge power at the high end.

“Harding Handbook for Quest Batteries,” Fig. 3.7.2, available http://www.hardingenergy.com/pdfs/NiMH.pdf
Monitoring

- Notice the wide section of flat voltage.
- Voltage measurements alone cannot estimate SOC.
- Voltage is more favorable for lead acid and Li-ion cells.
Monitoring

- Li-ion cells have almost linear open-circuit voltage above 20% SOC.
- Can we measure open circuit voltage?

![Graph showing open cell voltage vs. capacity for different pack types.](image)
**Drawbacks**

- Li-ion cells are intolerant of overcharge.
- Extremely important to stop at 4.1 V – for *any* cell.
- Temperature compensation is vital: It is 4.1 V at 25°C.
- Open circuit voltage takes time to settle down. Do we have the ability to turn a pack on and off to check SOC?

![Typical cell electrical model](image)
**Charge sequence**

- Best charging practice is “CCCV sequence.”
- This means charge at constant current until a voltage limit is reached, and then continue to charge at reduced current, maintaining this voltage.
Charge sequence

- For lead-acid batteries, the constant voltage interval can continue indefinitely.
- Lead-acid final voltage might be adjusted based on the specific cell type and strategy (always temperature).
- For Li-ion, charging stops when current gets below a certain value (such as $C/100$).
Charge sequence

- The ideal current might be $C/5$ or even less.

- Within the most linear part of the range, higher current might be feasible.
- Example: $3C$ when SOC is between 20% and 80%.
- You can imagine the hype: “Can recharge to 80% in less than 20 minutes.”
- Fast charging always implies extra $I^2R$ loss, more heat, and life reduction.
Charge acceptance

- A situation with recharge from a source other than a charger, such as regenerative braking or downhill driving is called charge acceptance.
- This is an important limiting factor: Can a fully charged car immediately accept regeneration energy?
- Generic answer is “no.” Coming downhill in a parking structure after fully charging can be a problem.
- Alternatives:
  - Disable regeneration above a certain battery voltage.
  - Include a resistive braking unit to avoid brake thermal stress.
Idle

- Are there “key off” loads that will discharge a battery over time?
- Self-discharge is also important.
- Rule of thumb in the industry: Three weeks parked at the airport with no risk of not starting up.
- For an all-electric car, what storage reduction might be acceptable over three weeks?
- For Li-ion cells, key off loads are almost always more important than self discharge.
  - Security systems
  - Sensors and computers
  - Communications
Discharge

- In passenger cars, the discharge details are essentially impossible to predict.
- About all we know is that it will be rare for a driver to push toward power limits.
- Drive cycles are about all we can hope for in terms of testing out discharge.
Discharge
Discharge and life

- Cycle life is usually based on “100% depth of discharge” complete discharge cycles.
- In transportation, these are rare.
- The effect is nonlinear, but a very rough guide is the notion of “total lifetime discharge.”
- What does this mean? If a battery can manage 1000 cycles at 100% DoD, it is providing 1000Q, when Q is the rated charge capacity for 100% discharge.
- We might expect 10,000 cycles at 10% DoD based on this total lifetime discharge.
- Actual results seem to be better than this.
Optimum range

- NiMH batteries work best (most efficient, longest cycle life) when maintained close to 50% DoD.
- A NiMH pack managed to 50% ± 10% can perform for hundreds of thousands of miles.
- Li-ion packs have some similarity.
- Roughly speaking, managing a Li-ion pack to 55% ± 35% seems to give excellent results.
- Notice the implied derating:
  - The NiMH pack performs best when only 20% of the capacity is used.
  - An Li-ion pack performs well over about 70% of the capacity range.
Balancing

- Consider a large pack, such as 99S60P in a Tesla.
- For both charge and discharge, how do we ensure even energy flows and balanced use of cells?
- For parallel cells, the voltages will match but perhaps not the current.
- For series cells, the currents will match but perhaps not the voltages.
- Does it matter?
Battery balancing

- In the end, we need cells to be matched in terms of state of charge.
- Why?
  - Charge voltage is limited to 4.1 V for any cell.
  - We need to shift to CV charging when even one cell hits the limit.
  - If any cell is low, how can it be recharged? Over time, will it drag down the others?
- For parallel connections, this is a modest issue:
  - Voltage is linear in SOC.
  - Matched voltage implies matched SOC.
Battery balancing

- For series connections, there is a problem.
- A weak cell that hits the voltage limit early will slow down charging for an entire pack.
- In Li-ion applications, external circuit management is essential to deal with this.
Battery testing

- What about testing? Voltage, current, temperature, SOC monitoring, what else?
- Gold standard is *impedance spectroscopy* (EIS), the complex impedance over a frequency range.

More about EIS

- Notice the range: 0.01 Hz (100 s) to 100 kHz.
- This is a slow measurement that takes tens of minutes.
- It provides a lot of information, but is really not possible for real-time testing and monitoring of EV batteries.
- It is very hard to interpret at the pack level.
Battery models

- Remember that in EV applications, we have pretty accurate energy analysis, and can predict what a vehicle will use.
- With good battery models, we can analyze how the power and energy in a drive cycle will affect batteries.
Battery models

- That is correct – We can estimate quite accurately the currents, voltages, stresses, and SOC on a battery pack given a drive cycle.
- This sort of analysis provides opportunities for control optimization.