Li-Ion battery Model

Octavio Salazar
Energy Storage - Lithium Ion Batteries

DC Hydropower

DC Wind Power

PV

Other Renewables

DC-DC Converter

DC-DC Converter

DC-DC Converter

External Grid

C-PCS: Control and Power Conditioning System
Energy Storage - Lithium Ion Batteries

Energy density (W h kg⁻¹)

Smaller size

Lighter weight

Ni-MH

Ni-Cd

Lead-acid

Li ion

Li metal ('unsafe')

Ni-MH/Ni-Cd (1.2V)

Ni-MH/Ni-Cd (1.2V)

Ni-MH/Ni-Cd (1.2V)

Li-ion (3.6V)
Battery Capacity
A battery's capacity is measured in Amp-hours, called "C". This is the *theoretical* amount of current a battery delivers when discharged in one hour to the point of 100% depth of discharge.

C-Rate (a.k.a. Charge rate, Hourly Rate)
The C rate is often used to describe battery loads or battery charging. 1C is the capacity rating (Amp-hour) of the battery.

<table>
<thead>
<tr>
<th>C-Rate</th>
<th>C-Rate</th>
<th>Hours of Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1C (1 hour rate)</td>
<td>1C</td>
<td>1 hour</td>
</tr>
<tr>
<td>C/4 (4 hour rate)</td>
<td>0.25C</td>
<td>4 hours</td>
</tr>
<tr>
<td>C/10 (10 hour rate)</td>
<td>0.1C</td>
<td>10 hours</td>
</tr>
</tbody>
</table>

Example:
Battery capacity= 1500mAh
1C=1500mA
2C=3000mA
0.5C=750mA

BMS = Battery Monitoring System
SoC=State of Charge
CC = Coulomb Counter (Accumulated Charge)
UUC = Unusable Charge
FCC = Full Charge Capacity of Battery
OCV = open-circuit voltage
PC = Battery Percentage Charge
RUC = Remaining Usable Charge
RC = Remaining Charge
Battery basics—lithium-ion batteries

Intercalation process

Lithium Ion batteries take advantage of the structure of graphite to intercalate Li Ions without drastically changing its initial structure.

Cathode materials [2]
- Layered oxides (LiCoO2)
- Transition metal phosphates (LiFePO4)
- Spinels (LiMn2O4)

Basic Li-Ion battery lithiation Principle

Current commercial Battery performance
LiCoO2, C680mAh [1]
Commercially available Li-Ion batteries (LiCoO$_2$)

LiCoO$_2$
- Layered structure
- 160 mAh/g
- 2d diffusion
- Industry used material

Charge: 1150mA(1lA)/4.2V(CC-CV)/2.5h
Discharge: 0.2lA, 0.5lA, 1lA (E.V.=2.75V)
Temperature: 25 deg. C

Charge: 1150mA(1lA)/4.2V(CC-CV)/2.5h/25 deg. C
Discharge: 230mA(0.2lA) (E.V.=2.75V)
Li-Ion batteries (LiCoO$_2$) thermal runaway

Thermal runaway:

- **80°C**: SEI layer dissolved, electrolyte reacts with electrode creating new SEI layer (exothermic reaction) increasing temp
- **80°C**: flammable gases are released from electrolyte, increase pressure (Oxygen release~110)
- **135°C**: polymer separator melt allows internal short circuit
- **200°C**: increased temperature allows metal oxide (cathode LiCoO$_2$) breakdown releasing Oxygen enabling combustion
- Cathode breakdown is an exothermic reaction increasing temperature more
Li-Ion High temperature applications
(Oil drilling, medical- heat sterilizing)

Rechargeable high temperature lithium-ion battery
VL 32600-125

Cylindrical, D-sized spiral cell
Reusable up to 200 times
in demanding >100°C environments.
More than 1000 typical oil drilling surveys up to 125°C.

Operating conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge method</td>
<td>Constant Current/Constant Voltage</td>
</tr>
<tr>
<td>Maximum charge voltage</td>
<td>4.10 +/- 0.05 V</td>
</tr>
<tr>
<td>Recommended charge voltage range</td>
<td>3.8 V to 4.0 V</td>
</tr>
<tr>
<td>Maximum recommended charge current</td>
<td>0.9 A (C/5 rate) at 20°C to 125°C</td>
</tr>
<tr>
<td>Charge temperature range</td>
<td>0/125°C</td>
</tr>
<tr>
<td>Maximum continuous discharge current</td>
<td>2.3 A (C/2 rate)</td>
</tr>
<tr>
<td>Pulse discharge current</td>
<td>up to 3.4 A for 2 seconds</td>
</tr>
<tr>
<td>Discharge temperature range</td>
<td>0/125°C</td>
</tr>
</tbody>
</table>

High temperature operation:
- Initial effect improves reaction rate
- High discharge rate increases power dissipation increasing temperature
Theoretical specific capacity and working potential of Lithium-Ion electrode materials

\[ V_{cell} = \left| \frac{\mu_{\text{cath}}^{Li} - \mu_{\text{an}}^{Li}}{F} \right| \]

- **Positive electrodes**
  - LiMnP\(_x\) (Me = Mn, Ni, Co, Cr)
  - LiMn\(_{2-x}\)Me\(_x\)O\(_4\) (Me = Mn, Co, Cr, Ni, Al)
  - LiCo\(_{1-x}\)MeO\(_2\) (Me = Co, Ni, Cr, Al)
  - LiFePO\(_4\)
  - Vanadium oxides

- **Negative electrodes**
  - Li\(_4\)Ti\(_5\)O\(_12\)
  - Me\(_x\)O\(_y\) (Me = Mn, Ni, Co, Cr)
  - Sn
  - Si/C composites
  - Si

**Graphite**

**Theoretical capacity, mA h/g**

- 600
- 1200
- 1800
- 3800
- 4200

**Fig. 1.** A schematic of power parameters (theoretical specific capacity and working potential) of active materials for lithium-ion batteries.
Li-Ion batteries ($\text{LiCoO}_2$)

**Charge Characteristics**

- **Increased C-rate**
  - Heat induced by power dissipation
  - Lithium plating (impede intercalation)
  - Capacity loss
  - Dendrite creation (preferential sites)

- **High voltage**
  - Electrolyte breakdown

Charge: $1150 \text{mA}(1 \times \text{A})/4.2 \text{V} (\text{CC-CV})$

Temperature: $25 \text{deg. C}$

LiCoO$_2$/C; $1150 \text{mAh}$ (Maxell-ICP553450SR)
• End of charge is based exclusively on cut-off voltage
• Premature cutoff due to uncertain capacity measurement results in large quantity of unused capacity
• For multi-media applications, over 25% capacity unused usually
State of Charge (SOC) - Fuel gauging Li-Ion battery management

**Li-Ion Battery Management**

- **Battery Fuel Gauge** Uses a sense resistor to measure current in and out of the battery and calculates the battery’s remaining energy. (Coulomb counting)

- **Protection IC** Ensures that a Li-Ion battery stays within safe voltage/current limits

- **Charge Management IC** converts the DC input power to a voltage/current level need to quickly and safely charge a battery.
State of Charge (SOC) - Fuel gauging battery management

Charge Management

Li-Ion

Protection IC

Battery Fuel Gauge

Water supply

\[ f \text{ flow} \]

\[ \int f \, dt = \text{volume} \]

Octavio Salazar
State of Charge (SOC) - Coulomb counting battery characterization - weighted tables

Practical SOC estimation based on coulomb counting and look up tables

Characteristics
- Cycle life
- Temperature
- Charge/discharge rate
- Self discharge

Sources of error
- Sample size validity
- In dynamic applications constant monitoring is needed
- Cumulative error build up
- Data points and algorithm
- Columbic efficiency - energy lose (as heat) due to chemical reaction
Li-Ion battery electric circuit model

(a) OCV $\rightarrow$ $V$

(b) $R_s$ $\parallel$ $C_d$

(c) $R_s$ $\parallel$ $R_{d1}$ $\parallel$ $R_{d2}$ $\parallel$ $C_{d1}$ $\parallel$ $C_{d2}$

Graphs:
- Real part ($\Re$) vs. Imaginary part ($\Im$)
- Current ($I$) vs. Time ($t$)
- OCV - $\Delta V$ vs. Time ($t$)
State of Charge (SOC) - Coulomb counting

(a) Usable Capacity vs Cycle Number

(b) Usable Capacity vs Temperature (°C)

(c) Usable Capacity vs I_{batt} (A)

(d) Usable Capacity vs Time (Month)

(e) Open-Circuit Voltage (V_{oc})

(f) Short Time Constant vs Long Time Constant

Octavio Salazar
Battery diffusion model

- **Electrical**
  - cathode
  - Conductive additives
  - Current collectors
  - Electrical taps

- **Ionic**
  - Electrode
  - Electrolyte

- **Interfacial**
  - Electrolyte/electrode
  - Additives/electrode
  - Electrode/current collector

---

**Fig. 3.** Conduction phenomena in cathode particle (LiFePO₄) during charge.
SOC, current capacity and runtime is calculated through a capacitor ($C_{Capacity}$) and a current-controlled current source, from runtime-based models.

The RC network, similar to that in Thevenin-based models, simulates the transient response. To bridge SOC to open-circuit voltage, a voltage-controlled voltage source is used.
State of Charge (SOC)- Cell balancing

Consequences of cell unbalance

- Premature cells degradation through exposure to overvoltage
- Safety hazards from overcharged cells
- Early charge termination resulting in reduced capacity
- Cell health detection issues

Causes of Cell unbalancing

- State of Charge (SOC) unbalance
- Total capacity differences
- Impedance differences and gradient

Multi-cell battery pack accentuates the need of SOC estimation and creates cell balancing issues.
State of Charge (SOC): Cell balancing

- **Efficient grouping** - Cell matching helps minimize manufacturing variations

- **Dissipative cell balancing** is less efficient due to inherent losses associated with the balancing strategy

**Current bypass**: Cell balancing set-up using bypass FETs.

- **Non-dissipative balancing** minimizes losses but suffers from longer time required for balancing

**Charge redistribution**: each capacitor continuously switches between two adjacent cells, so current flows to equalize the voltage of the cells and capacitors
  - C charges to 63% in one time constant to 99% in 4T (time constant $T=RC$)

---

Improved shared transformer cell balancing for Li-ion batteries

- uses a single magnetic core with primary coils for each cell in the stack.
- The secondary of the transformer is switched to connect with the cell array.
- Can balance a multi-cell pack relatively fast, and with low energy losses
  - inductor reaches 63% max current in one time constant, to 99% in $4T(T=R/L)$
Research opportunities

- Adjust the electrical model based on SOC
- Accuracy improvement needs to be quantified
- Temperature impact on impedance
Backup slides
Energy Storage - Current state of Lithium Ion Batteries

Lithium Ion batteries take advantage of the structure of graphite to intercalate Li ions without drastically changing its initial structure.

Typical Industry Li-Ion Battery performance

- Anode material
  - Graphite theoretical capacity: 372mAh/g [1]

- Cathode materials [2]
  - Layered oxides (LiCoO2)
  - Transition metal phosphates (LiFePO4)
  - Spinels (LiMn2O4)

- Intercalation process [2]

  - 80% capacity @ ~600 cycles

**Positive Electrode**  
LiCoO2  
Charge  
Discharge  
\[Li_{1-x}CoO_2 + xLi^+ + xe^-\]

**Negative Electrode**  
\[C + xLi^+ + xe^-\]

**Battery as a Whole**  
LiCoO2 + C  
Charge  
Discharge  
\[Li_{1-x}CoO_2 + CLix\]

---

Octavio Salazar
State of Charge (SOC) - Coulomb counting

![Graphs showing State of Charge (SOC) over time with different current profiles and resistance models.](image-url)
State of Charge (SOC)- Coulomb counting

Fig 1. The battery equivalent internal impedance.

Battery Lifetime

Voltage-Current Characteristics
Electrochemical impedance spectroscopy (EIS)

- induces a small perturbation near the target
- measures the AC impedance from the response to the perturbation
- fits the curve using an equivalent impedance model that can physically explain the measured AC impedance, and models the target.

State of Charge (SOC)- estimation using EIS

Impedance spectra of the BNK lithium polymer battery at each SOC

- SOC can be estimated using $R_{ct}$ and Time constant
- Time constant is the product of $R_{ct}$ and $C_{dl}$
- Adjust the electrical model based on SOC

System power management (architecture)

Charge Management

Li-Ion

Protection IC

Battery Fuel Gauge

DC/DC

35V
150mA

3 cell Li-Ion
7.5V to 12.6V

2 cell Li-Ion
5.0V to 8.4V

1 cell Li-Ion
2.5V to 4.2V

5V
800mA
5V

3.3V
2.0A

2.85V
2.5A

1.8V
2.5A

1.2V
400mA

0.95V
1A

Flash LED
Back light
LED string
Display

RF, Audio,
Data Acquisition
Disk Drive, etc.

Portable System

USB, Memory, I/O,
System,
Expansion

DSP, MCU, ASIC
Cores

DC

Battery Fuel
Gauge

12V Power Rail
5V Power Rail
3.3V Power Rail

Charge Management

Portable System

DC/DC

5V
800mA
5V

3.3V
2.0A

2.85V
2.5A

1.8V
2.5A

1.2V
400mA

0.95V
1A

<=3.3V
<=5V
<=35V

Octavio Salazar
## Energy Storage - industry priorities

<table>
<thead>
<tr>
<th>Cell Chemistries parameters</th>
<th>Portable</th>
<th>Power tools</th>
<th>Transportation</th>
<th>Medical</th>
<th>Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Highest</td>
</tr>
<tr>
<td>Energy Density (Wh/L)</td>
<td>Highest</td>
<td>High</td>
<td>High</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Energy Density (Wh/Kg)</td>
<td>High</td>
<td>High</td>
<td>Highest</td>
<td>high</td>
<td>Medium</td>
</tr>
<tr>
<td>Cycle Life (80% capacity)</td>
<td>&gt;600</td>
<td>Medium</td>
<td>Highest</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Self-Discharge Rate (Month)</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Highest</td>
<td>High</td>
</tr>
<tr>
<td>High Temperature Performance (55+/-2)</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Low Temperature Performance (-20+/-2)</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>High-rate Discharge/Power (10C)</td>
<td>Medium (4G-H)</td>
<td>Highest</td>
<td>Highest</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Safety &amp; Environmental Concern</td>
<td>High</td>
<td>High</td>
<td>Highest</td>
<td>Highest</td>
<td>Highest</td>
</tr>
</tbody>
</table>

(Ref. ARPAe GENI, BEEST, GRIDS programs)
Cathode material - Lithium Ion Batteries

<table>
<thead>
<tr>
<th>Cell Chemistries</th>
<th>LiCoO$_2$</th>
<th>LiFePO$_4$</th>
<th>LiMn$_2$O$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate Voltage</td>
<td>3.7V</td>
<td>3.2V</td>
<td>3.8V</td>
</tr>
<tr>
<td>Charging Voltage</td>
<td>4.2V</td>
<td>3.7V</td>
<td>4.2V</td>
</tr>
<tr>
<td>Discharging end Voltage</td>
<td>3.0V</td>
<td>2.0V</td>
<td>2.5V</td>
</tr>
<tr>
<td>Energy Density (Wh/L)</td>
<td>447</td>
<td>222</td>
<td>253</td>
</tr>
<tr>
<td>Energy Density (Wh/Kg)</td>
<td>140-145</td>
<td>90-110</td>
<td>105-115</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>&gt;700</td>
<td>&gt;1800</td>
<td>&gt;500</td>
</tr>
<tr>
<td>Self-Discharge Rate (Month)</td>
<td>1%</td>
<td>0.05%</td>
<td>5%</td>
</tr>
<tr>
<td>High Temperature Performance (55+/-2°C)</td>
<td>Good</td>
<td>Excellent</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Low Temperature Performance (-20+/-2°C)</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>High-rate Discharge (10C)</td>
<td>Good</td>
<td>Acceptable</td>
<td>Best</td>
</tr>
<tr>
<td>Safety &amp; Environmental Concern</td>
<td>Poor</td>
<td>Excellent</td>
<td>Good</td>
</tr>
</tbody>
</table>
Power conversion - regulation topologies

- Typical regulator topologies used for a single cell system

- Portable System
  - <=3.3V: USB, Memory, I/O, System, Expansion
  - <=1.8V: DSP, MCU, ASIC Cores
  - <=5V: RF, Audio, Data Acquisition, Disk Drive, etc.
  - <=35V: Flash LED, Back light, LED string, Display

V_in - Input Voltage - V
V_o - Output Voltage - V

- Flyback
- Boost or Charge Pump
- Buck-Boost or Charge Pump
- Buck or LDO
Crystal structure – back up slide

Three Major Cathode Materials for Li Battery

**Olivine**
- Single channel diffusion
- Higher cycle life
- Lower discharge rate

**Layered**
- 2D diffusion
- Current used material

**Spinel**
- 3D diffusion
- Higher discharge rate
- Lower capacity

\[
\text{LiCoO}_2 : \approx 160 \text{ mAh/g}
\]

\[
\text{LiFePO}_4 : \approx 160 \text{ mAh/g}
\]

\[
\text{LiMn}_2\text{O}_4 : \approx 100 \text{ mAh/g}
\]
State of Charge (SOC) - Coulomb counting
System power management (architecture)

\[ P_0 = P_i \times \text{eff} \]

\[ P = IV \]

\[ I = \frac{P}{V} \]

**Buck: 3.6 to 3.3V**

\[ 660mA = \frac{2.37W}{3.6V} \]

\[ 3.6V \to 3.3V \]

\[ 3.6V \to 2.75V \]

\[ 4.2V \to 2.75V \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

**Boost: 3.6 to 5V**

\[ 1260mA = \frac{4.55W}{3.6V} \]

\[ 5V \]

\[ 800mA \]

\[ 4W \]

\[ <= 5V \]

RF, Audio, Data Acquisition, Disk Drive, etc.

**Portable System**

\[ 5.9W \]

\[ <= 3.3V \]

I/O, Memory, System, Expansion, USB, sensor SIM/SD card

**LDO’s**

\[ 100mA \]

\[ 0.36W \]

\[ \text{eff} = \frac{1.8}{3.3} \]

\[ 75mA \]

\[ 0.27W \]

\[ \text{eff} = \frac{1.2}{3.3} \]

\[ 1.8V \]

\[ 100mA \]

\[ 0.18W \]

\[ 1.2V \]

\[ 75mA \]

\[ 0.09W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 5V \]

\[ 800mA \]

\[ 4W \]

\[ <= 5V \]

\[ 4.2V \]

\[ \to 2.75V \]

\[ (3.6V) \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]

\[ 6.9W \]

\[ 3.6V \]

\[ 1920mA \]
System power management (architecture)

**Buck: 3.6 to 3.3V**

- V_{IN} = 3.6V
- V_{OUT} = 3.3V
- I_{LOAD} = 660mA
- Power = \frac{2.37W}{3.6V}

**Portable System**

- <=3.3V
  - I/O, Memory, System, Expansion
  - USB, sensor SIM/SD card
- <=1.8V
  - DSP, MCU, ASIC, Cores

**LDO’s**

- \text{eff} = \frac{1.8}{3.3}

**Power Calculations**

- 3.3V
  - 100mA, 0.36W
  - 75mA, 0.27W
- 1.8V
  - 1.8.0V, 100mA, 0.18W
  - 1.2V, 75mA, 0.09W

**Battery Characteristics**

- Charge: 1150mA (1mA / 4.2V (CC-CV) / 2.5h)
- Discharge: 0.2mA, 0.5mA, 1mA (E.V. = 2.75V)
- Temperature: 25 deg. C

Octavio Salazar
Back up slides: Battery basics-lithium-ion batteries

Intercalation process

Lithium Ion batteries take advantage of the structure of graphite to intercalate Li ions without drastically changing its initial structure.
State of Charge (SOC) - Coulomb counting

![Diagram showing the process of charge and discharge in a sodium-sulfur battery system. The diagram includes symbols for sodium (Na), sodium ions (Na⁺), elemental sulfur (S), sodium polysulfide (Na₂Sₓ), and an electron (e⁻). The reaction equation for discharge is given as 2Na + xS → Na₂Sₓ (EMF: 2.08 1.78 V).]