Electric Vehicle (EE60082)

Lecture 13: BMS part3

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Basic terminology (recap)

Cell: the most basic element of a battery;

Block: a collection of cells wired directly in parallel;

Battery: a collection of cells or blocks wired in series;

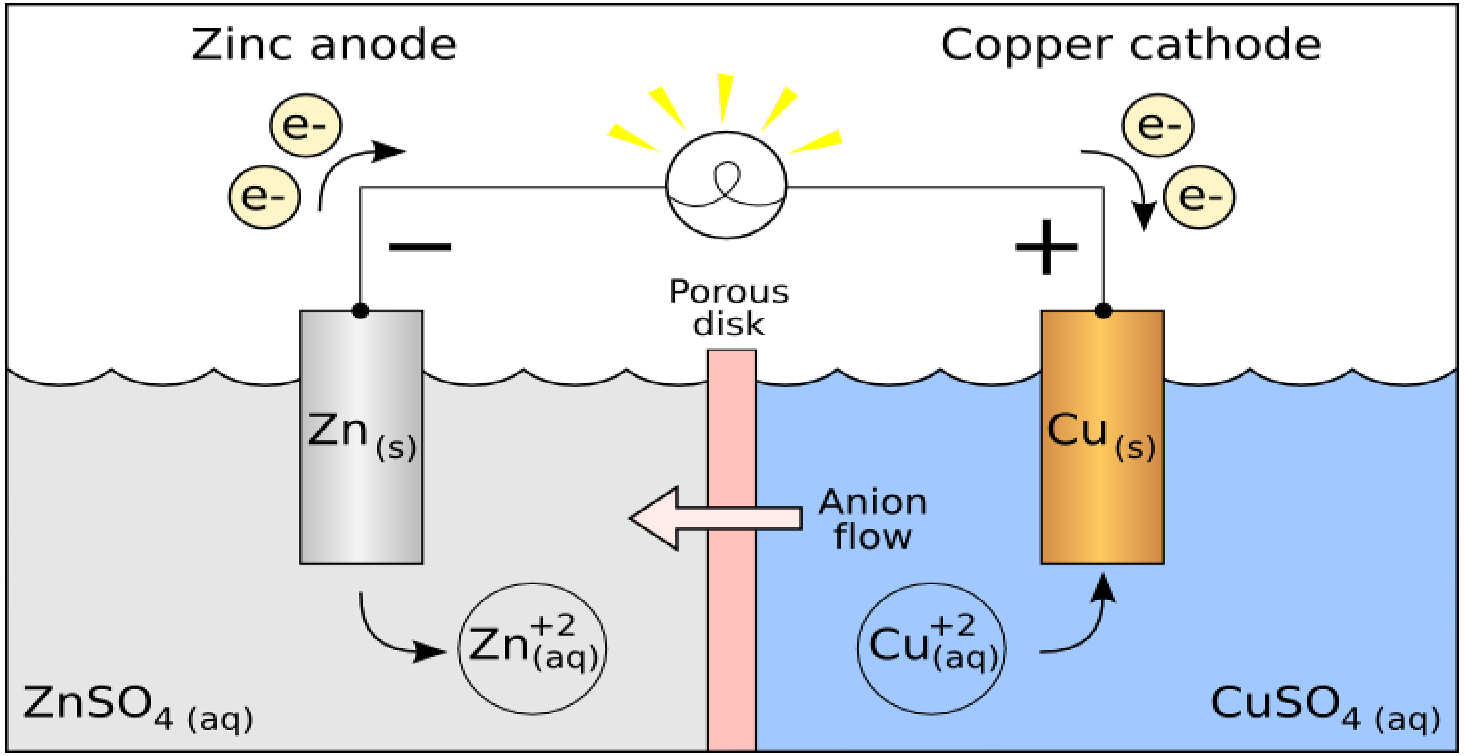
Pack: a collection of batteries.

C-rate(recap)

- C-rate is unit of current (relative to battery charge capacity)
- 1 C-rate = the current needed to discharge the battery fully in 1 hour

- Examples:
  - 40 Ah Battery, 20 A discharge.
    - Find the C-rate of discharge
  - 10 Ah, being discharged at C/2.
    - Find the time to discharge completely

Battery Chemistry (recap)



Galvanic cell

Battery Charge Density (recap)

$$Li \quad + \quad MnO_2 \quad \rightarrow \quad LiMnO_2 \quad \text{(discharge)}$$

6,94 86,9

1. Generated charge Q: one electron ($-1.602*10^{-19}$C)
2. Used mass M: $(6.94+86.9)*1.667*10^{-27}$kg
3. Charge Density: Q/M/3600=284Ah/kg
4. How to calculate energy density?

Battery OCV (recap)

Theoretical Open Circuit Voltage :

- Defined by positive and negative electrode active materials
- Calculated from standard potentials of each electrode

$$\textit{Cell Voltage} = E^\circ_{positive} - E^\circ_{négative}$$

Example : Li + $MnO_2 \rightarrow LiMnO_2$ (discharge reaction – Li primary cell)

Negative Electrode (oxydation) : $Li \rightarrow Li^+ + 1\,e^-$ -3,04V/ENH
Positive Electrode (reduction) : $MnO_2 + Li^+ + e^- \rightarrow LiMnO_2$ 0,25V/ENH

$\Rightarrow$ V^{theo}_{cell} = 0,25 – (-3,04) = 3,29 V

TABLE 18.1 Standard Reduction Potentials at 25°C

Stronger oxidizing agent

Weaker reducing agent

Reduction Half-Reaction		$E°$ (V)
$F_2(g) + 2e^-$	$\longrightarrow 2F\ (aq)$	2.87
$H_2O_2(aq) + 2H^+(aq) + 2e^-$	$\longrightarrow 2H_2O(l)$	1.78
$MnO_4^-(aq) + 8H^+(aq) + 5e^-$	$\longrightarrow Mn^{2+}(aq) + 4H_2O(l)$	1.51
$Cl_2(g) + 2e^-$	$\longrightarrow 2Cl^-(aq)$	1.36
$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^-$	$\longrightarrow 2Cr^{3+}(aq) + 7H_2O(l)$	1.33
$O_2(g) + 4H^+(aq) + 4e^-$	$\longrightarrow 2H_2O(l)$	1.23
$Br_2(l) + 2e^-$	$\longrightarrow 2Br^-(aq)$	1.09
$Ag^+(aq) + e^-$	$\longrightarrow Ag(s)$	0.80
$Fe^{3+}(aq) + e^-$	$\longrightarrow Fe^{2+}(aq)$	0.77
$O_2(g) + 2H^+(aq) + 2e^-$	$\longrightarrow H_2O_2(aq)$	0.70
$I_2(s) + 2e^-$	$\longrightarrow 2I^-(aq)$	0.54
$O_2(g) + 2H_2O(l) + 4e^-$	$\longrightarrow 4OH^-(aq)$	0.40
$Cu^{2+}(aq) + 2e^-$	$\longrightarrow Cu(s)$	0.34
$Sn^{4+}(aq) + 2e^-$	$\longrightarrow Sn^{2+}(aq)$	0.15
$2H^+(aq) + 2e^-$	$\longrightarrow H_2(g)$	0
$Pb^{2+}(aq) + 2e^-$	$\longrightarrow Pb(s)$	−0.13
$Ni^{2+}(aq) + 2e^-$	$\longrightarrow Ni(s)$	−0.26
$Cd^{2+}(aq) + 2e^-$	$\longrightarrow Cd(s)$	−0.40
$Fe^{2+}(aq) + 2e^-$	$\longrightarrow Fe(s)$	−0.45
$Zn^{2+}(aq) + 2e^-$	$\longrightarrow Zn(s)$	−0.76
$2H_2O(l) + 2e^-$	$\longrightarrow H_2(g) + 2OH^-(aq)$	−0.83
$Al^{3+}(aq) + 3e^-$	$\longrightarrow Al(s)$	−1.66
$Mg^{2+}(aq) + 2e^-$	$\longrightarrow Mg(s)$	−2.37
$Na^+(aq) + e^-$	$\longrightarrow Na(s)$	−2.71
$Li^+(aq) + e^-$	$\longrightarrow Li(s)$	−3.04

Weaker oxidizing agent

Stronger reducing agent

Lithium-Fluoride battery?

Power density (recap)

- Battery power = battery terminal voltage x discharge current
- Power density = Maximum power per unit volume or weight
- Unit of power density = W/kg or W/l
- Power density depends on
  - loss inside the battery
  - Maximum permissible temperature in battery
  - Thermal management of battery pack

Battery Evolution (recap)

	Lead-Acid		Nickel-Metal Hydride		Lithium-Ion	
	SLI	Advanced	HEV	BEV	HEV	PHEV-BEV
V	2.0	2.0	1.2	1.2	3.3-3.8	3.3-3.8
Wh/l	60	75	100	250	150	200-400
Wh/kg	25	40	50	100	90	120-200
W/l	1200	600	2000 - 2500	500-800	3500-9000	800-2200
W/kg	500	250	1000-1300	200-400	2000-4000	500-1200

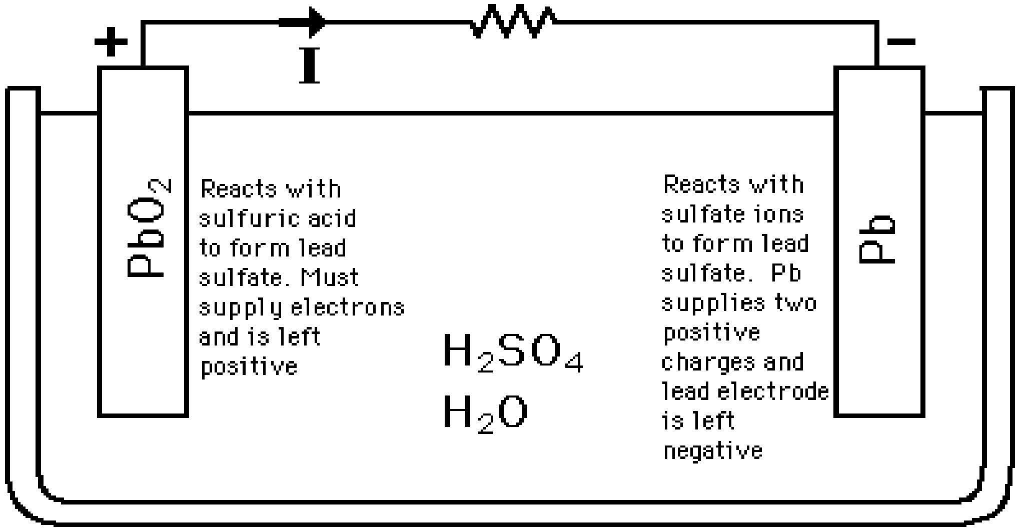
Lead-Acid Battery (recap)

Discharging

Negative Plate: $Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e^-$

Positive Plate: $PbO_2 + HSO_4^- + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$

Overall: $PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$



Lead-Acid Battery (recap)

Question 1: What's the theoretical gravimetric charge density (Ah/kg)

Overall:	$\mathbf{PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O}$
Charge	2e-
Mass	239 207 196

Relative mass:
Pb: 207
O:16
S: 32

Other info:

1. One electron: $-1.602*10^{-19}$C
2. One hydrogen atom: $1.667*10^{-27}$kg

To transfer $Q=2*1.602*10^{-19}$C charge, we need the mass $M=(239+207+196)*1.667*10^{-27}$kg, yielding Q/M/3600=83Ah/kg

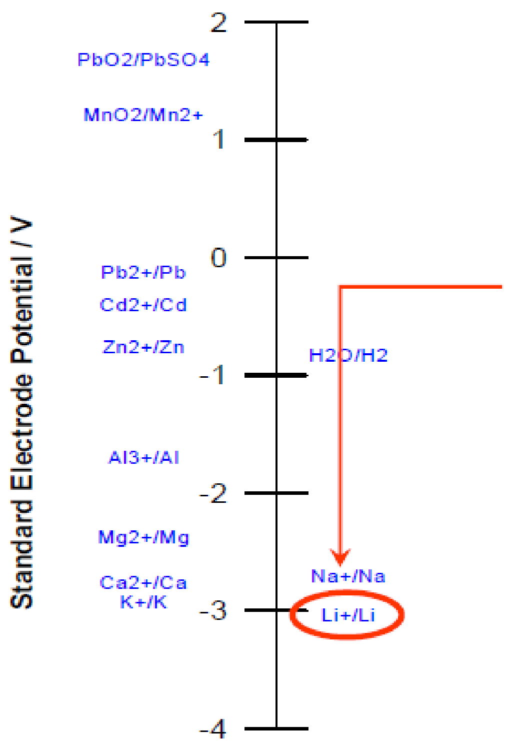
Lead-Acid Battery (recap)

Question 2: What's the theoretical gravimetric energy density (Wh/kg)

Charge density of lead-acid battery is 83Ah/kg;

Energy density of lead-acid battery is 2.1V*83Ah/kg=174Wh/kg

Not competitive in terms of the terminal voltage.



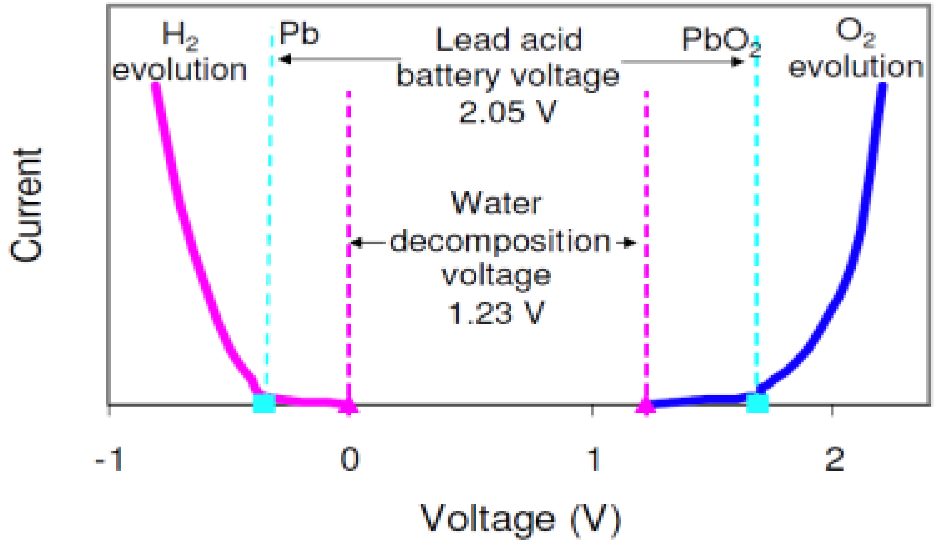
Water hydrolysis during charging (recap)

Oxidation reaction at the positive electrode

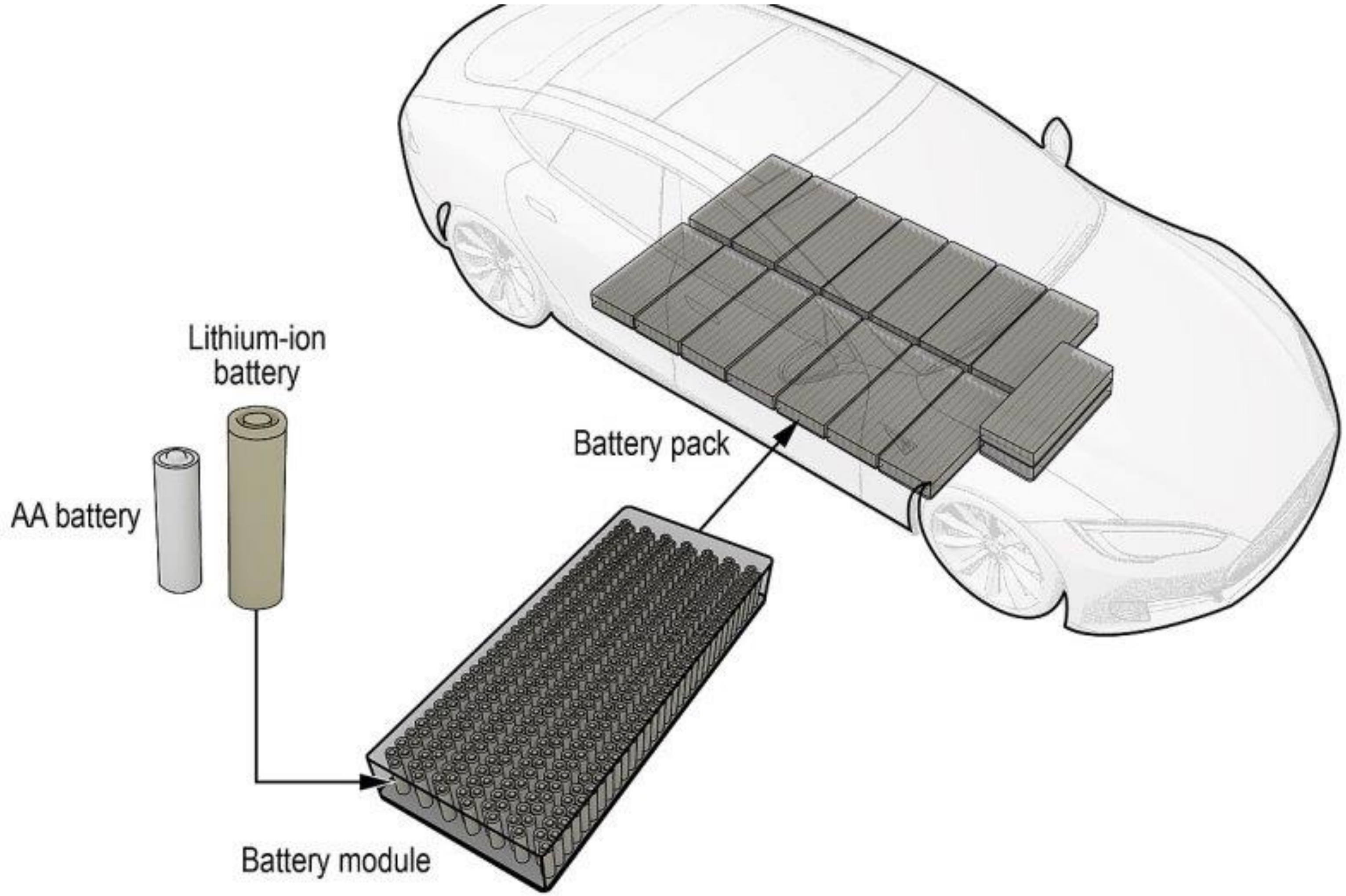
$2H_2O <=> O_2 + 4H^+ + 4e^-$

Reduction reaction at negative electrode

$H^+ + e^- <=> \frac{1}{2} H_2$



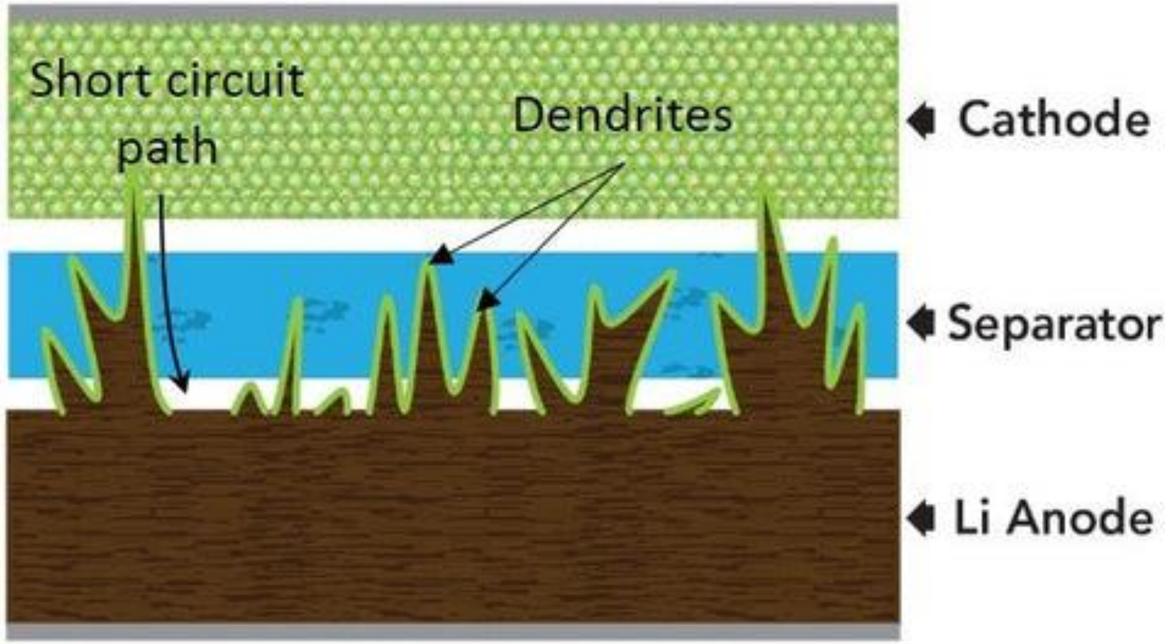
Li-ion cells (recap)



Li-metal battery (recap)

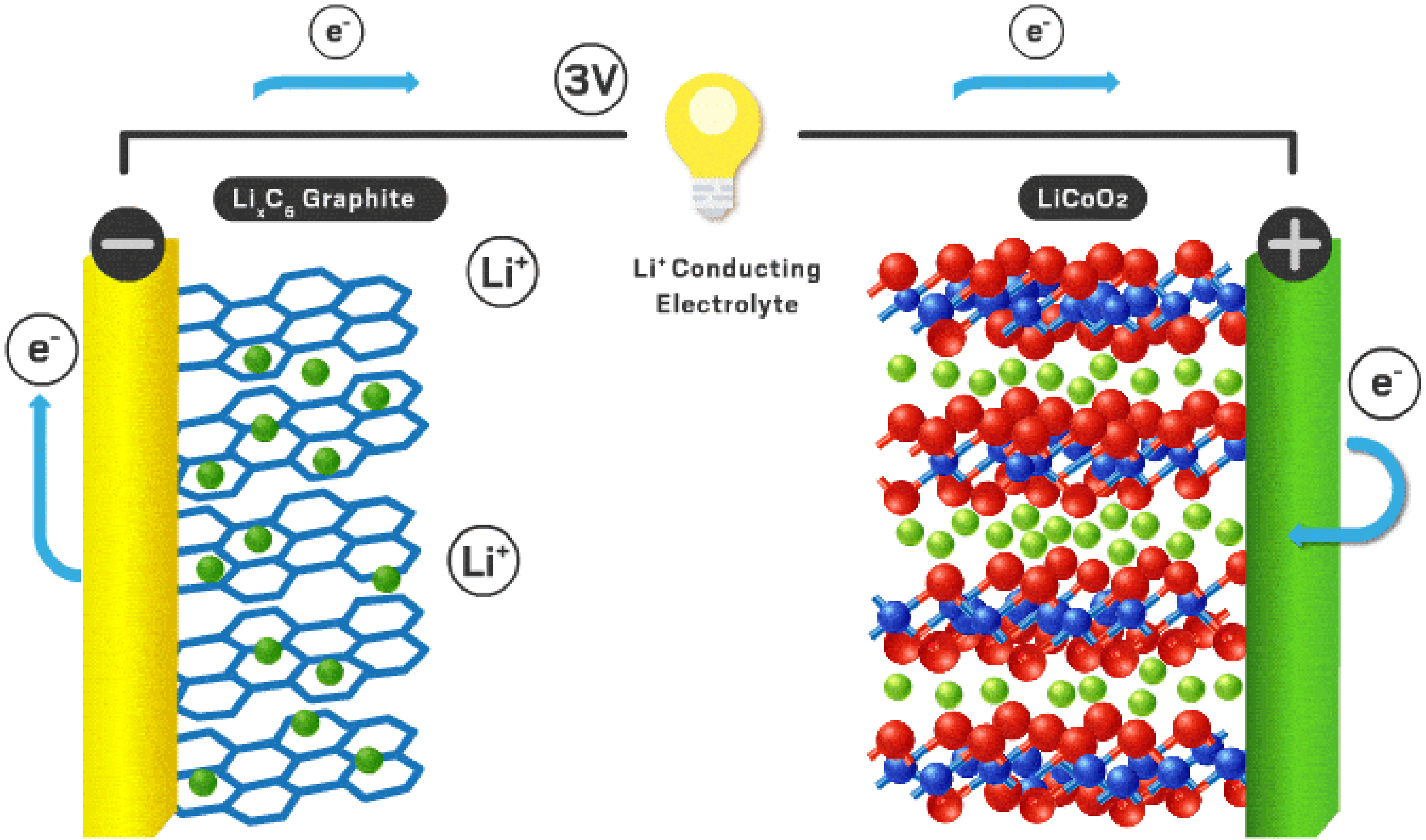
Ex: Li-Sulfur battery $2Li + S \rightarrow Li_2S$

- High energy density
- Dendrite formation



- Dendrite formation, leading to short-circuit and thermal runaway
- Shorter life-span

Intercalation electrode (recap)

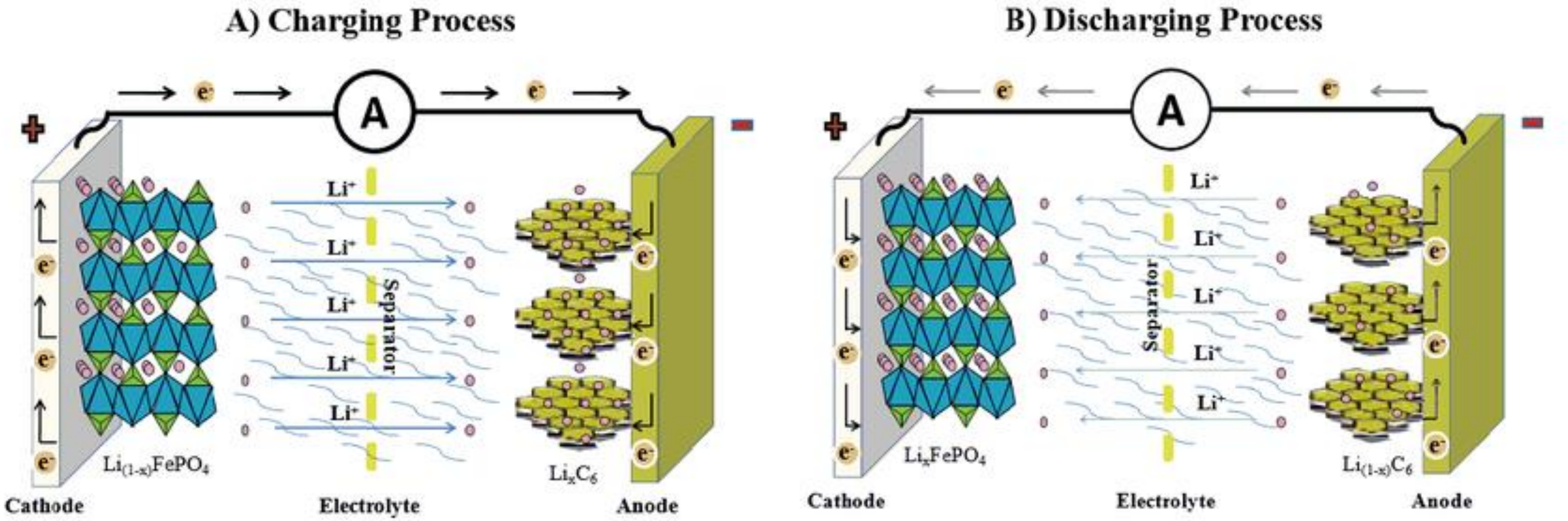


Li-Ion Battery (recap)

Many Li-Ion chemistries are available. They are usually named according to the composition of the *cathode (positive electrode).*

- $LiCoO_2$: Standard lithium-cobalt-oxide;
- LiMnNiCo: Lithium-manganese-nickel-cobalt;
- $LiFePO_4$: lithium-iron-phosphate;
- $LiMnO_2$: Lithium-manganese-oxide;
- $Li_4Ti_5O_{12}$: Lithium-titanate;
- $LiMn_2O_4$: Lithium-manganese-oxide;
- $LiNiO_2$: Lithium-nickel-oxide.

$LiFePO_4$ cell reactions (recap)



Example – LiCoO2 cells (recap)

CoO_2 + LiC_6 → $LiCoO_2$ + 6C

Relative mass   59+16*2   6.9+12*6

To generate Q=1.602*10^{-19}C, we need M=169.9*1.667*10^{-27}kg. Therefore the gravimetric charge density is Q/M/3600=157Ah/kg.

The energy density is 3.4V*151Ah/kg=534Wh/kg

What are those parameters of the Pb-Acid Battery?

83Ah/kg
174Wh/kg

Battery chemistry	Energy density (Wh/kg)	
	Theoretical	Practical
Pb-acid	174	60-75
Li-ion	534	120-200

Example – $LiFePO_4$ cells (recap)

$$FePO_4 \quad + \quad LiC_6 \quad \rightarrow \quad LiFePO_4 \quad + \quad 6C$$

Relative mass 55.9+31+16*4 6.9+12*6

To generate $Q=1.602*10^{-19}C$, we need $M=229.8*1.667*10^{-27}kg$. Therefore the gravimetric charge density is Q/M/3600=116Ah/kg.

The energy density is 3.2V*116Ah/kg=372Wh/kg

How do those parameters compare with LiCoO2 chemistry?

Battery chemistry	Charge density (Ah/kg)	Energy density (Wh/kg)
LiCoO2	157	534
LiFePO4	116	372

Use of $LiFePO_4$ cells (recap)

Advantages of $LiFePO_4$ cells

- Longer life (3000-5000 cycles vs. 500-1500 cycles in case of other Li-ion chemistries)
- Thermally stable: do not catch fire like other Li-ion cells
- Wider temperature range (-20^0C to 60^0C)
- Lower self-discharge rate
- Eco-friendly and non-toxic

Tesla Model 3 Standard Range LFP battery pack

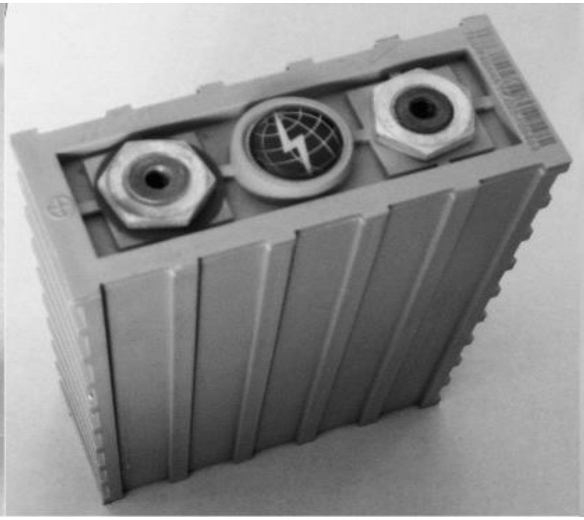
Comparison of Li-ion chemistries (recap)

Key Active Material	Lithium-Iron Phosphate	Lithium Nickel Manganese Cobalt Oxide	Lithium Manganese Oxide	Lithium Nickel Cobalt Aluminum	Lithium Titanate
Technology Short Name	LFP	NMC	LMO	NCA	LTO
Cathode	$LiFePO_4$	$LiNi_xMn_yCo_{1-x-y}O_2$	$LiMn_2O_4$ (spinel)	$LiNiCoAlO_2$	variable
Anode	C (graphite)	C (graphite)	C (graphite)	C (graphite)	$Li_4Ti_5O_{12}$
Safety					
Power Density					
Energy Density					
Cell Costs Advantage					
Lifetime					
BESS Performance					

Source: International Renewable Energy Agency (IRENA), 2017

Li-Ion Cell Packages (recap)

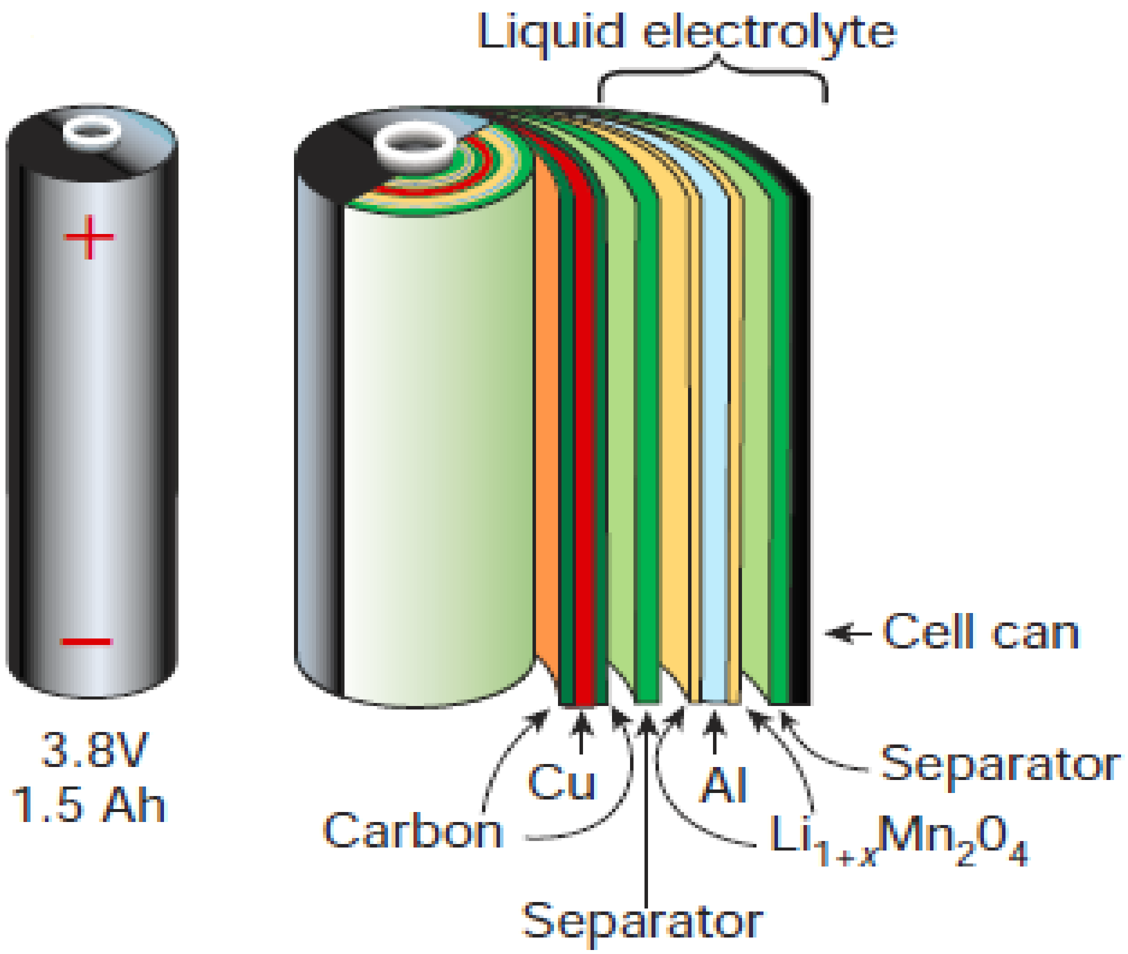
Cylindrical



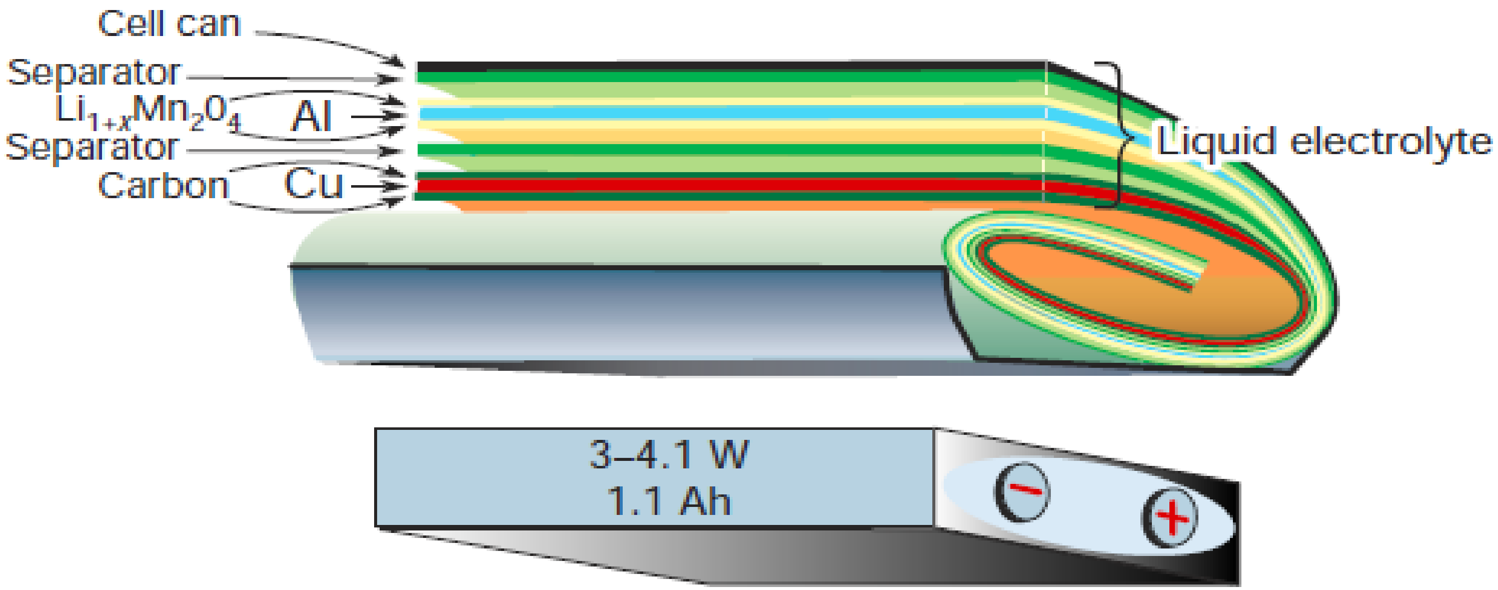
Prismatic (convenient)

Pouch

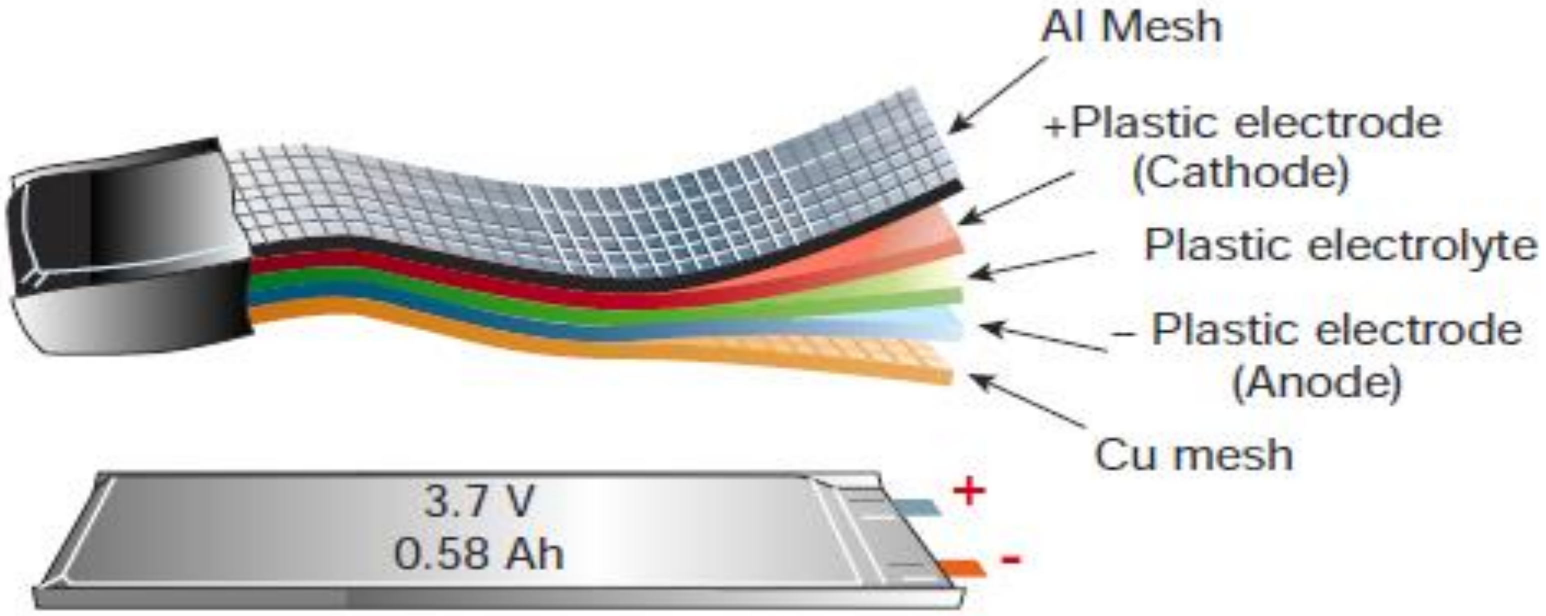
Cylindrical (Hard Can) (recap)



Prismatic (Hard Can) (recap)



Pouch (recap)



Al Mesh
+Plastic electrode
(Cathode)
Plastic electrolyte
– Plastic electrode
(Anode)
Cu mesh
3.7 V
0.58 Ah
+
-

Li-polymer cells (recap)

Li-polymer cells use gel-like or solid polymer electrolyte (in flexible pouch packaging)

- Advantages:
  - Slim & Lightweight Design
  - Better Safety & Stability
  - Customizable Shapes
  - Improved Fast Charging
- Limitations:
  - Lower Energy Density
  - Shorter Lifespan (about half)
  - Higher Cost

Battery parameters and characteristics

Agenda

- SOC & DOD;
- SOH.

Cell specs

-SAMSUNG SDI Confidential Proprietary –

SAMSUNG SDI

Spec. No.	ICR18650-26F	Version No.	0.0

SPECIFICATION OF PRODUCT

for Lithium-ion Rechargeable Cell

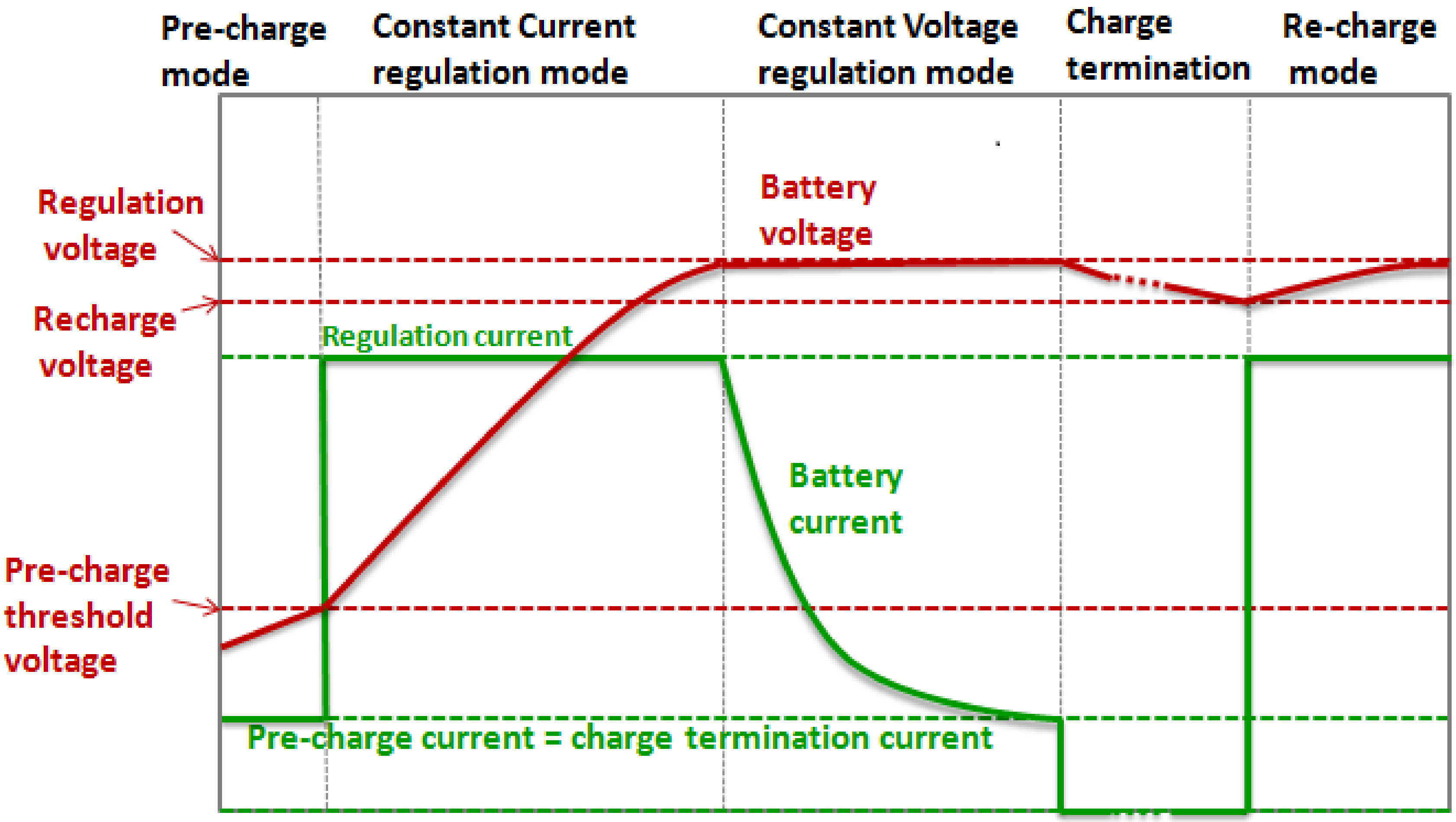
Model : ICR18650-26F

Cell specs

3. Nominal Specifications

Item	Specification
3.1 Nominal Capacity	2600mAh (0.2C, 2.75V discharge)
3.2 Minimum Capacity	2550mAh(0.2C, 2.75V discharge)
3.3 Charging Voltage	4.2 ±0.05 V
3.4 Nominal Voltage	3.7V
3.5 Charging Method	CC-CV (constant voltage with limited current)
3.6 Charging Current	Standard charge: 1300mA Rapid charge : 2600mA
3.7 Charging Time	Standard charge : 3hours Rapid charge : 2.5hours
3.8 Max. Charge Current	2600mA(ambient temperature 25℃)
3.9 Max. Discharge Current	5200mA(ambient temperature 25℃)
3.10 Discharge Cut-off Voltage	2.75V

CC-CV charging



Cell specs

7.6 Charge Rate Capabilities

Discharge capacity is measured with constant current 520mA and 2.75V cut-off after the cell is charged with 4.2V as follows.

	Charge Condition			
Current	0.2C (520mA)	0.5C (1300mA)	1.0C (2600mA)	2.0C (5200mA)
Cut-off	7h or 0.05C	2.5h or 0.05C	2.5h or 0.05C	2.5h or 0.05C
Relative Capacity	100%	95%	90%	80%

Note: Percentage as an index of the capacity at 25℃(=2550mAh) is 100%.

7.7 Discharge Rate Capabilities

Discharge capacity is measured with the various currents in under table and 2.75V cut-off after the standard charge.

	Discharge Condition			
Current	0.2C (520mA)	0.5C (1300mA)	1.0C (2600mA)	2.0C (5200mA)
Relative Capacity	100%	95%	90%	80%

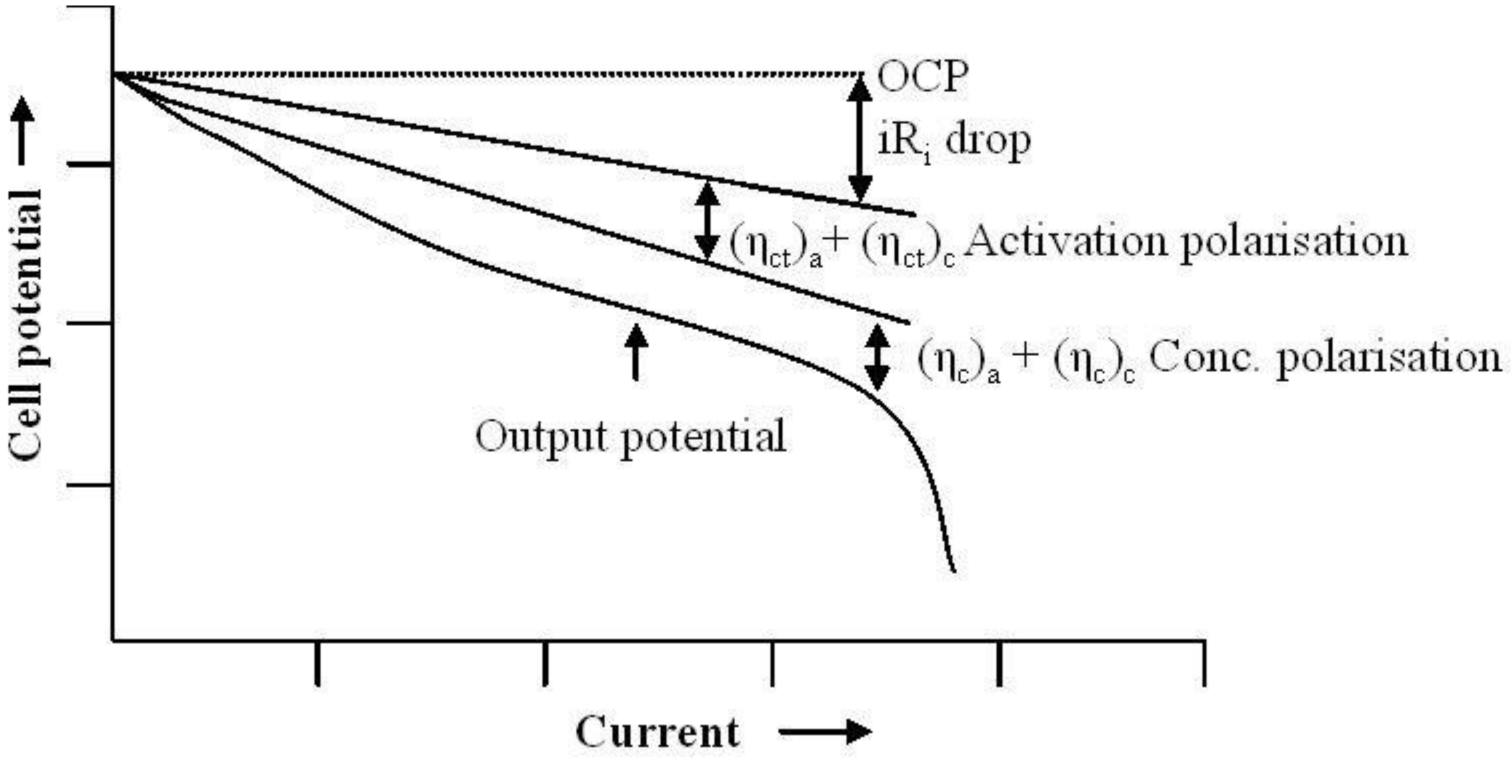
Note: Percentage as an index of the capacity at 25℃(=2550mAh) is 100%.

Cell voltage characteristics

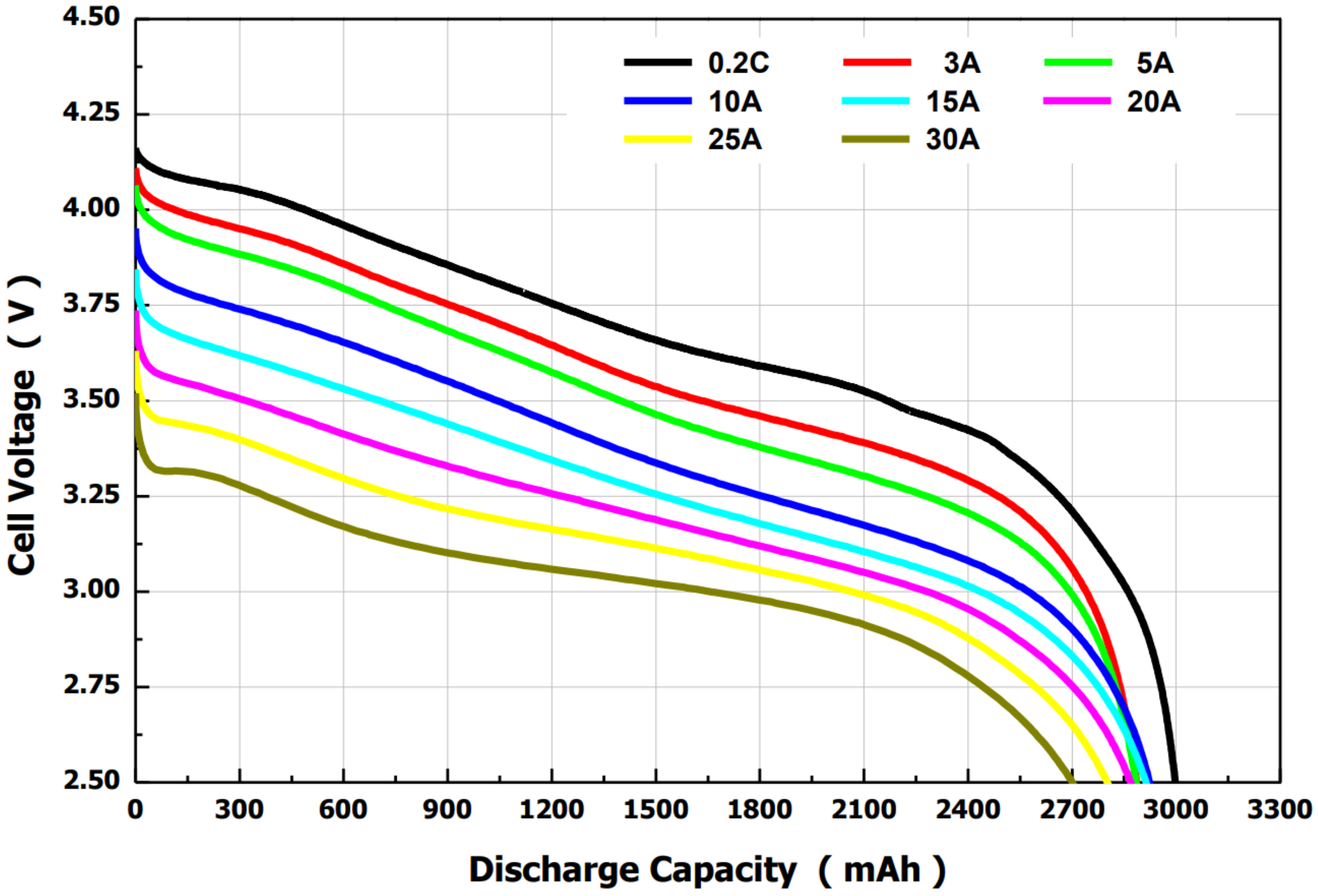
- Whenever current flows in a cell, voltage drop is observed at the terminals

- Voltage drop is due to
  - Ohmic drop
  - Activation polarization
  - Concentration polarization

- Voltage drop increases with current
  - Not a linear relation



Cell discharge characteristics



Cell specs

Charge Temperature	Discharge temperature			
25℃	-10℃	0℃	25℃	40℃
Relative Capacity	50%	80%	100%	80%

Note: If charge temperature and discharge temperature is not the same,

7.5 Temperature Dependence of Charge Capacity

Capacity comparison at each temperature, measured with discharge constant current 520mA and 2.75V cut-off after the standard charge is as follows.

	Charge temperature			Discharge temperature
	0℃	25℃	45℃	25℃
Relative Capacity	80%	100%	80%	

Note: If charge temperature and discharge temperature is not the same,
the interval for temperature change is 3 hours.
Percentage as an index of the capacity at 25℃ (=2550mAh) is 100%.

State of Charge (SOC)

SOC: a proportion of the charge available at that point compared to the total charge available when it is fully charged. Full:100%. Empty: 0%;

In EV, **SOC** evaluation is also known as *fuel gauge* due to its analogy to a gas car's fuel gauge.

Attention: Cell SOC ≠ Battery SOC

Example 1

- A battery was rated as 100Ah. In the beginning its SOC=92%. After discharging at 50A for 1hr, what is SOC?

- (92%*100Ah-50A*1h)/100Ah=42%

- Now it gets charged with 2A for 3 hours. What’s the left SOC?

- (42%*100Ah+2A*3h)/100Ah=48%

Example 2

Three cells are series connected. Their SOCs are 90%, 80% and 70%, respectively. What is the overall SOC of the whole battery pack?

Depth of Discharge

DOD: a measure of the charge removed from the battery or cell. DOD could be expressed either in Ah or %.

In most cases: DOD(%) = 1-SOC. This description is not always true.

Example 3:

A battery with 100Ah rated volume could be further discharged even when its SOC is already 0 (not recommended though). This battery could discharged 105Ah, meaning over discharged. Using DOD(%) = 1-SOC, its SOC = 0% and its DOD is 100%, however although it actually released 105Ah charge.

Therefore for DOD, we prefer to using Ah instead of %.

Depth of Discharge

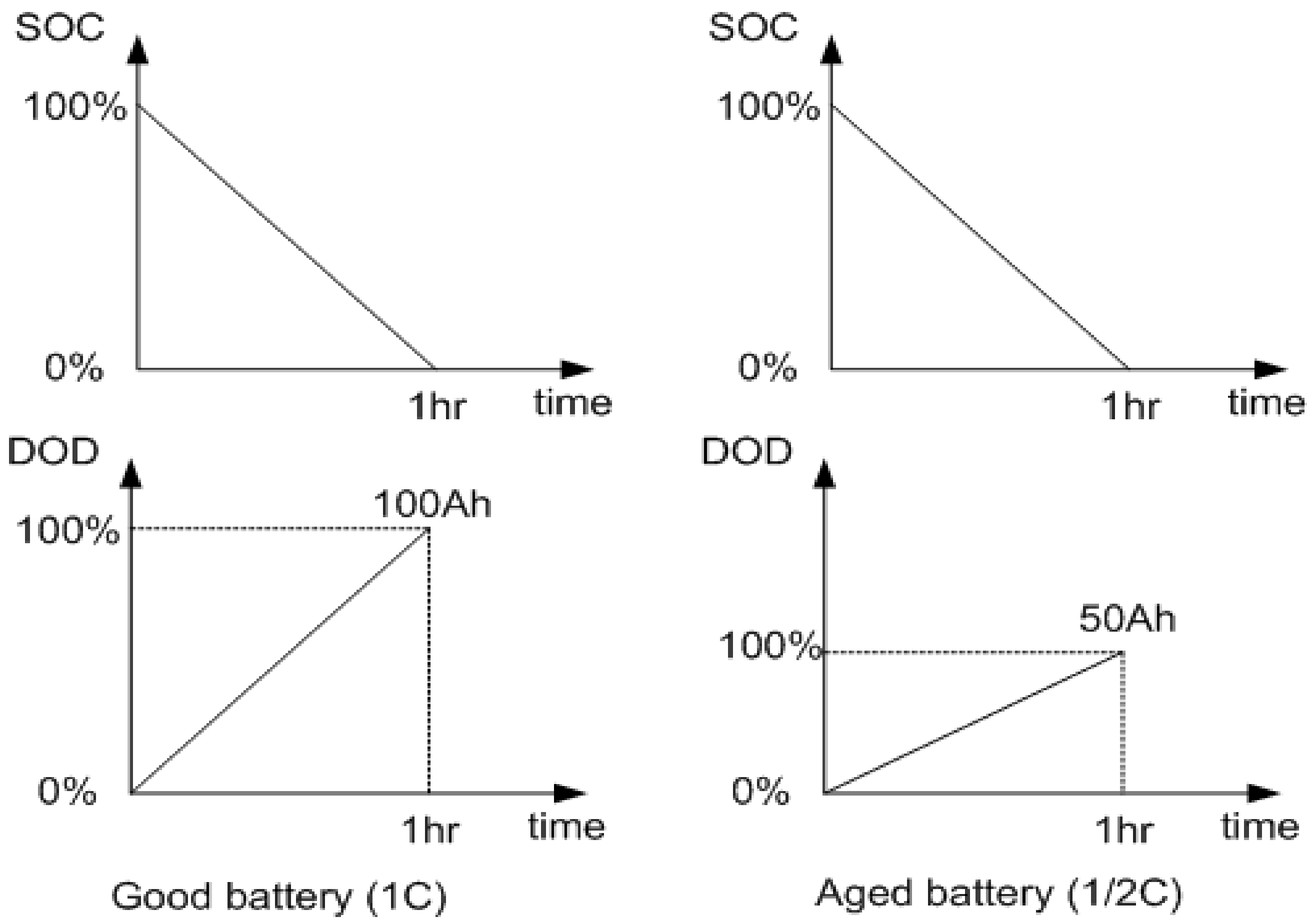
Example 4: A battery was labelled as 100Ah. But after several years it's aged to only 50Ah.

So with 50A discharging for 1hr,

SOC: 0%;

DOD: 100% (which however does not mean 100Ah)

SOC vs DOD


SOC
100%
0%
1hr
time
DOD
100Ah
100%
0%
1hr
time
Good battery (1C)
SOC
100%
0%
1hr
time
DOD
50Ah
100%
0%
1hr
time
Aged battery (1/2C)

State of Health (SOH)

Charge capacity: amount of charge in battery when it is fully charged.

SOH is defined to capture the impact of battery aging

- SOH is defined as,

$$SOC = \frac{Charge\ capacity\ now}{Charge\ capacity\ at\ the\ beginning\ of\ life}$$

- SOH is required for accurate estimation of available charge
  - Reduce range anxiety

End of life (EOL)

- End of life (EOL) definition:
  - SOH is below 80% or,
  - Cell resistance increases more than 50%

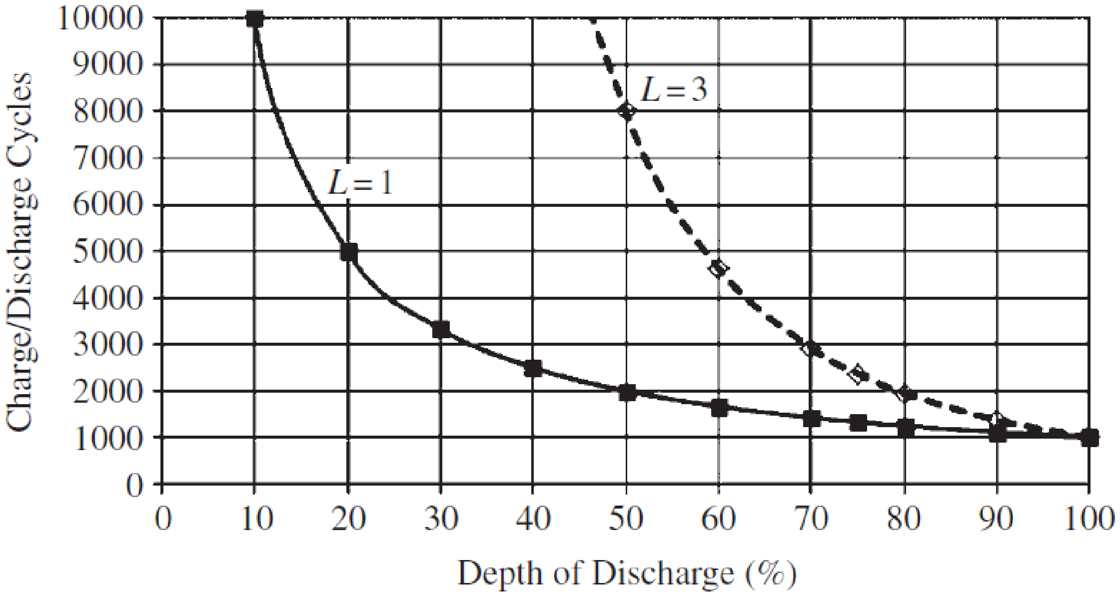
- For low power applications EOL criteria can be relaxed
  - example: energy storage applications, where energy and power density are not critical
  - Discarded EV battery pack can be reused
  - Called second life of battery

Cycle life of battery

Cycle life: Number of charge-discharge cycles before EOL is reached

Cycle life for a given DOD,

$$N = N_{100\%}\left(\frac{100\%}{DOD}\right)^{L} \quad \text{or} \quad DOD = \left(\frac{N_{100\%}}{N}\right)^{1/L} \times 100\%$$



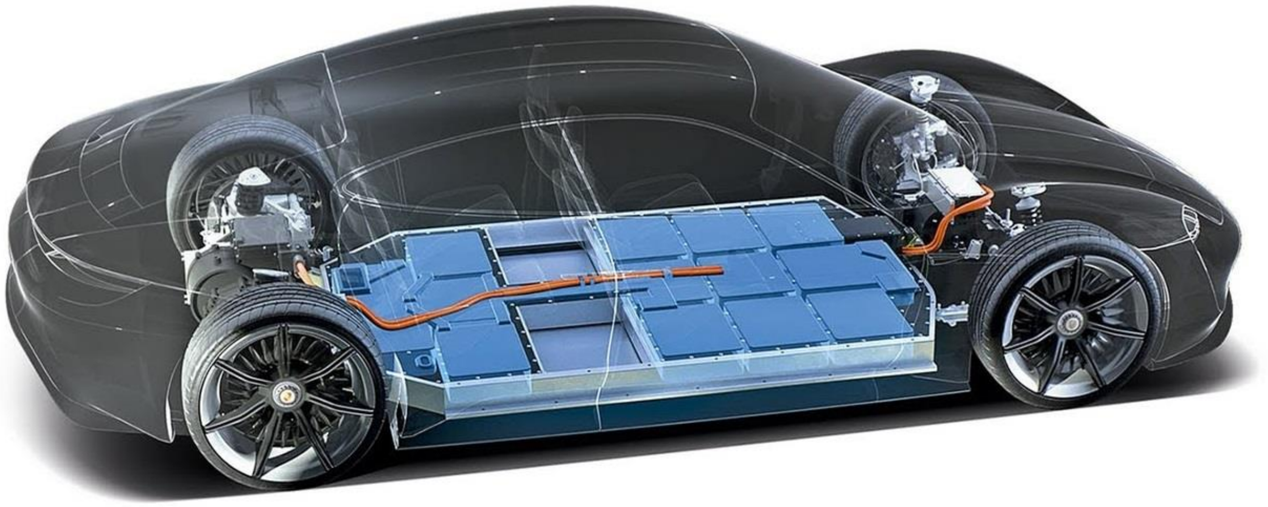
L is the cycle life index, depends on cell chemistry, design, and operating conditions

$N_{100\%}$ is the cycle life with 100% DOD

Sizing of battery pack

- How large should the battery pack be?

- Depends on several performance requirements
  - Energy requirement by the EV before it can recharge
  - Peak power requirement of the EV
  - Aging characteristics of the battery
  - Environmental impact



Battery pack sizing example

A BEV battery pack has the following requirements:

- eight years of operation, an average of S_{day}=48 km of driving per day
- daily charging
- an average battery output energy E_{km} = 180 Wh/km.
- Cycle limit index L = 1 and expected life $N_{100\%}$ = 1000.

Determine the beginning-of-life (BOL) kilowatt-hour storage required.

What are the vehicle ranges at BOL and EOL?

Battery pack sizing example (cont.)

- The total number of cycles, N = 8 years × 365 = 2920 cycles
- Maximum allowable DOD, $DOD = \left(\frac{N_{100\%}}{N}\right)^{1/L} x100\% = 34.25\%$
- Average daily energy output, $E_{day} = S_{day}E_{km} = 8.64\ kWh$
- EOL energy storage, $E_{EOL} = \frac{E_{day}}{DOD} = 25.23\ kWh$
- BOL energy storage, $E_{BOL} = \frac{E_{EOL}}{0.8} = 31.54\ kWh$

Battery pack sizing example (cont.)

- Range at BOL, $R_{BOL} = \frac{E_{BOL}}{E_{km}} = 175.2\ km$

- Range at EOL, $R_{EOL} = \frac{E_{EOL}}{E_{km}} = 140.2\ km$

Battery pack sizing example (cont.)

How to construct the required battery pack?

- cell specs: 3.7V nominal, 25Ah

- Pack specs: 350V nominal voltage

Battery pack sizing example (cont.)

- number of cells in series $\geq 350/3.7 = 95$
- Ah requirement for the pack = 31.54 kWh/350V = 90.1 Ah
- Number of cells in parallel $\geq 90.1/25 = 4$

Thank you!