Electric Vehicle (EE60082)

Lecture 11: BMS part1: Battery fundamentals

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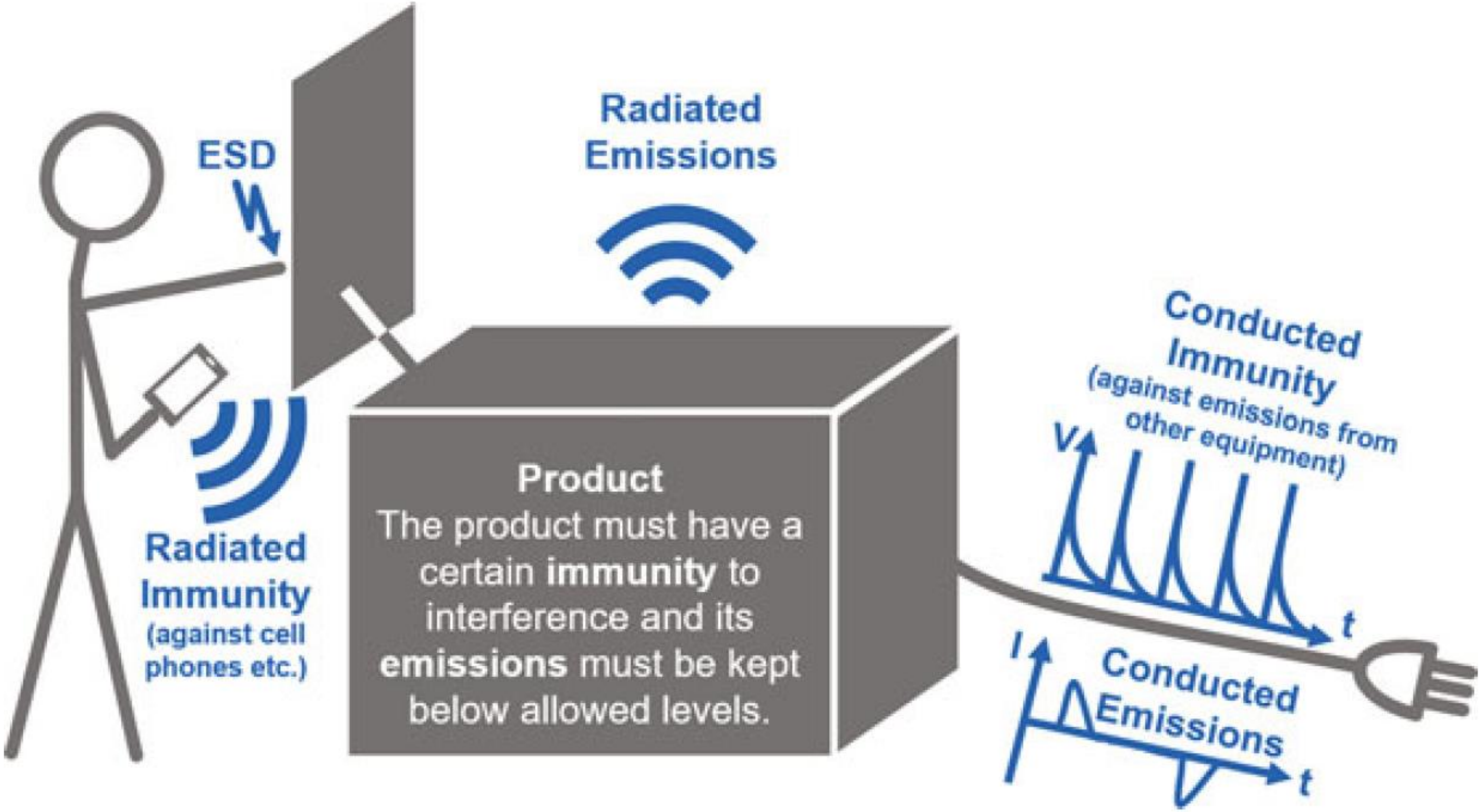
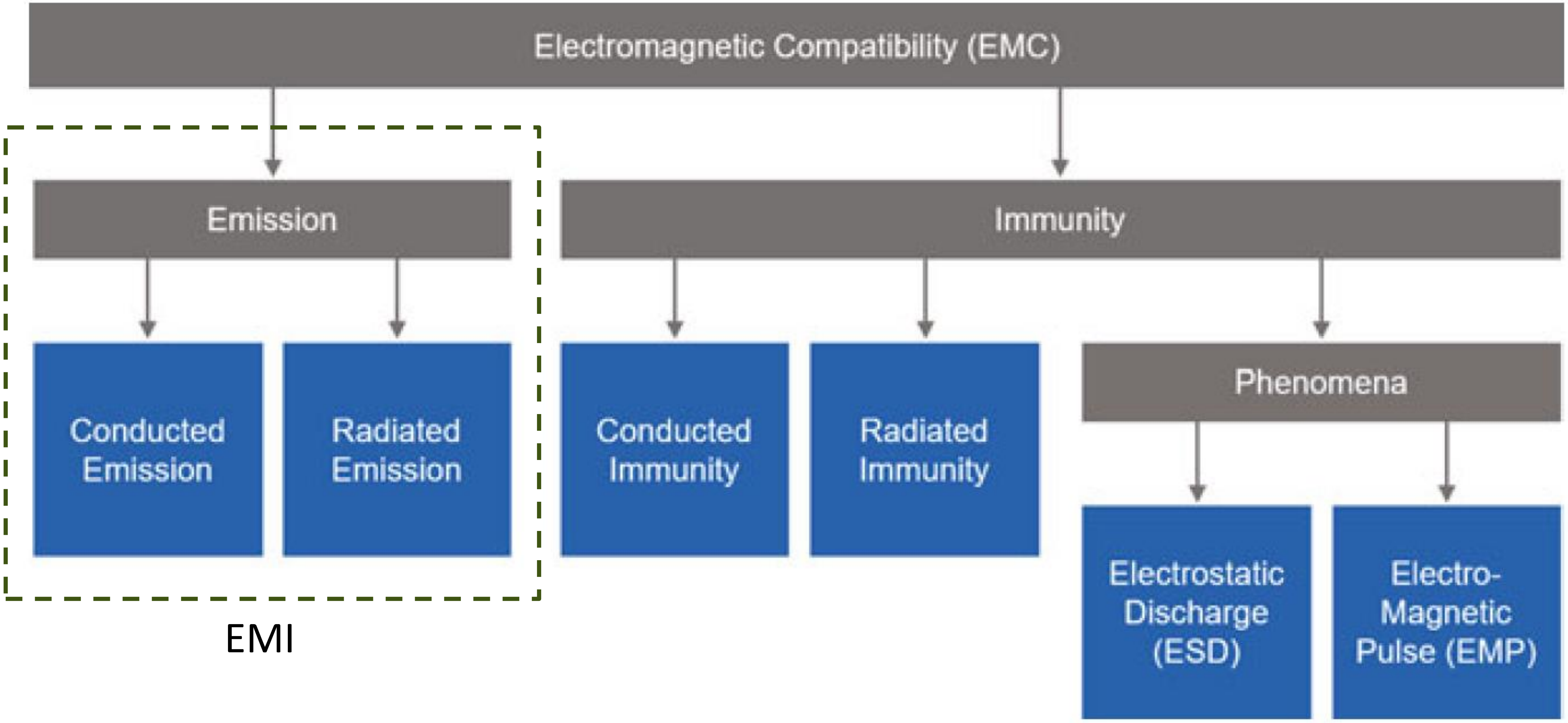
Electromagnetic Interference (recap)



Electromagnetic Compatibility (EMC) (recap)



EMI standards (recap)

- Conducted EMI standards
  - measurement done on the connecting cables
  - Frequency range depends on products and standards to comply
    - 150 kHz to 30MHz (CISPR 32 and FCC 47)

- Radiated EMI standards
  - measured in an anechoic or semi-anechoic chamber or at an open area test site (OATS).
  - frequency range depends on products and standards to comply
    - 30MHz to 6 GHz (CISPR 32)
    - 30MHz up to 40 GHz (FCC 47)

EMC compliance mark (recap)

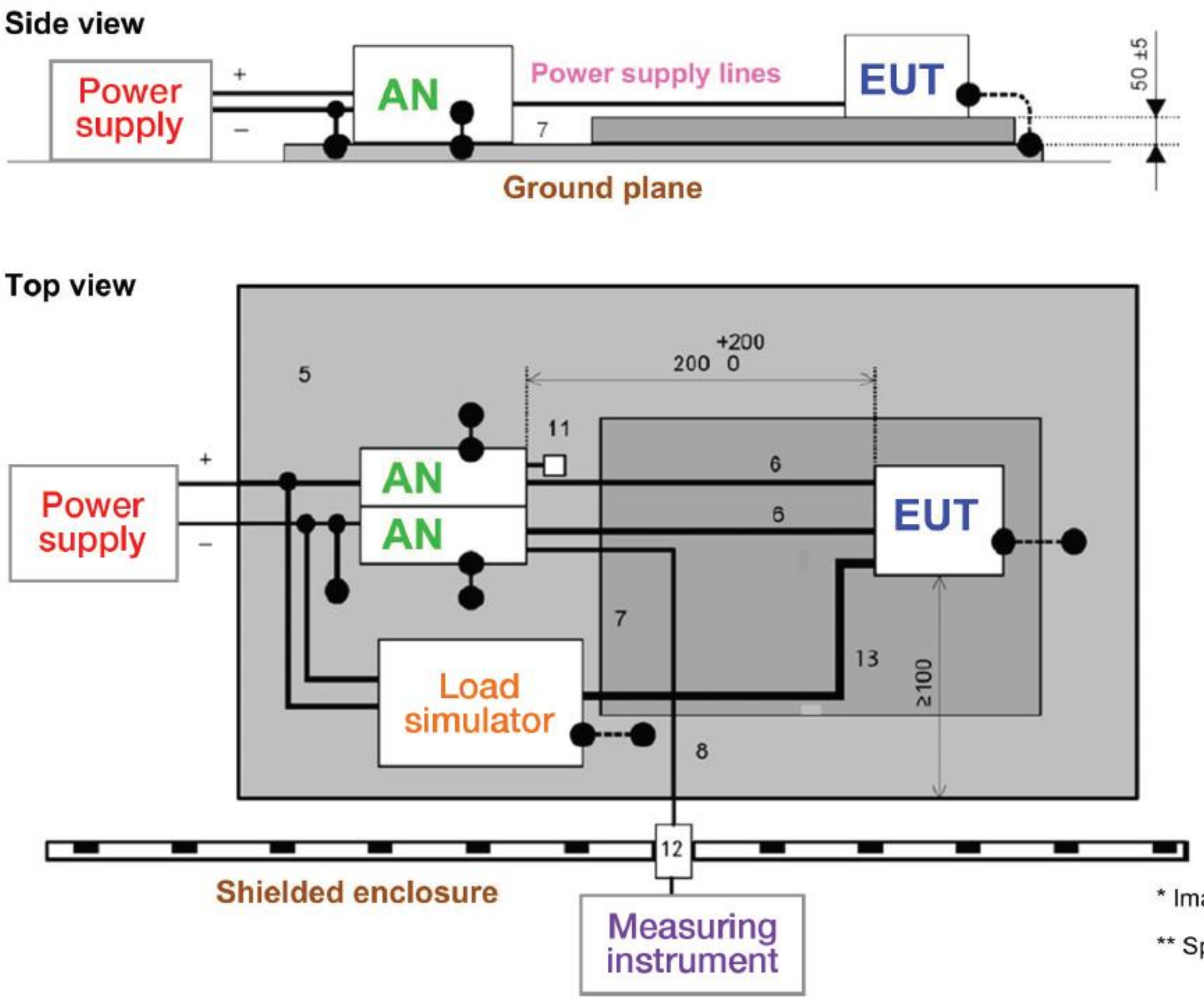
- Bureau of Indian Standards (BIS) mandates Compulsory Registration Scheme (CRS)
  - BIS CRS Mark

IS ------

R-xxxxxxxx

- For imported products, following marks are recognized,
  - CE Mark (Europe)
  - FCC Mark (USA)

CISPR 25 EMI test setup (recap)



5 = Reference ground plane

6 = Power supply lines

7 = Low relative permittivity support, $\varepsilon_R \leq 1.4$

8 = High-quality 50-Ω coaxial cable,

11 = 50 Ω load termination

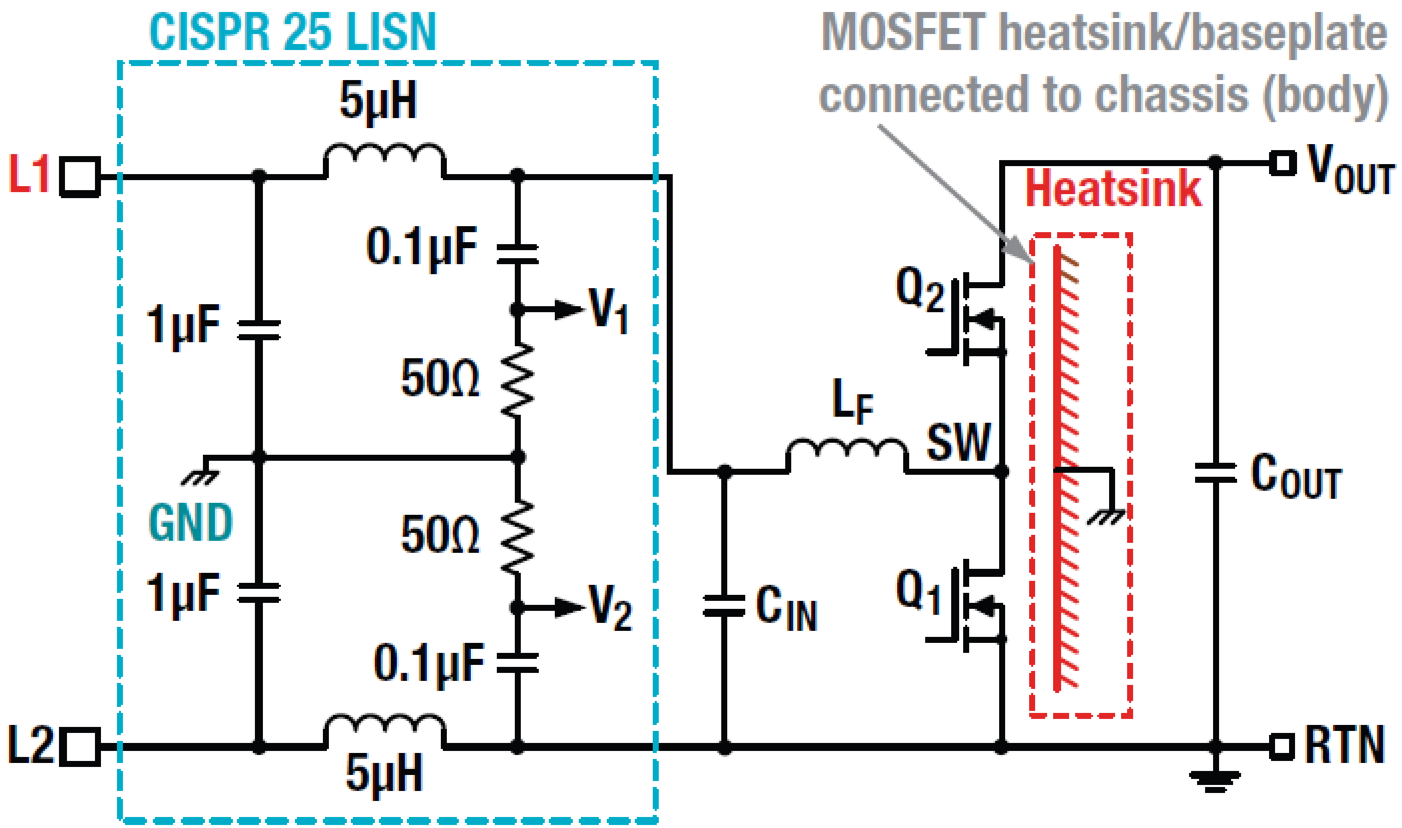
12 = Bulkhead connector

13 = Test harness (excluding power lines)

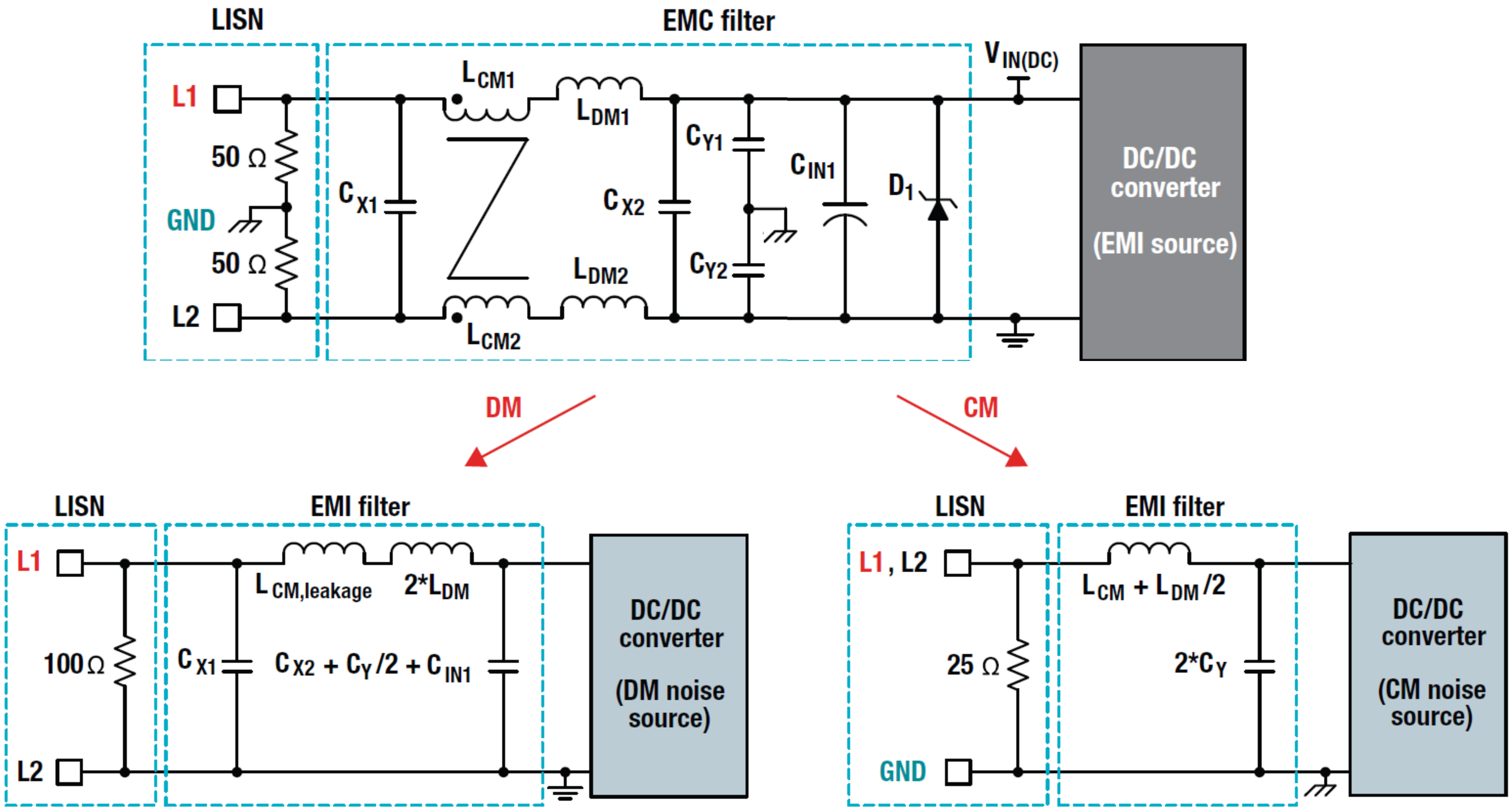
* Image adapted from CISPR 25 ed. 4 specification

** Spatial distances in mm

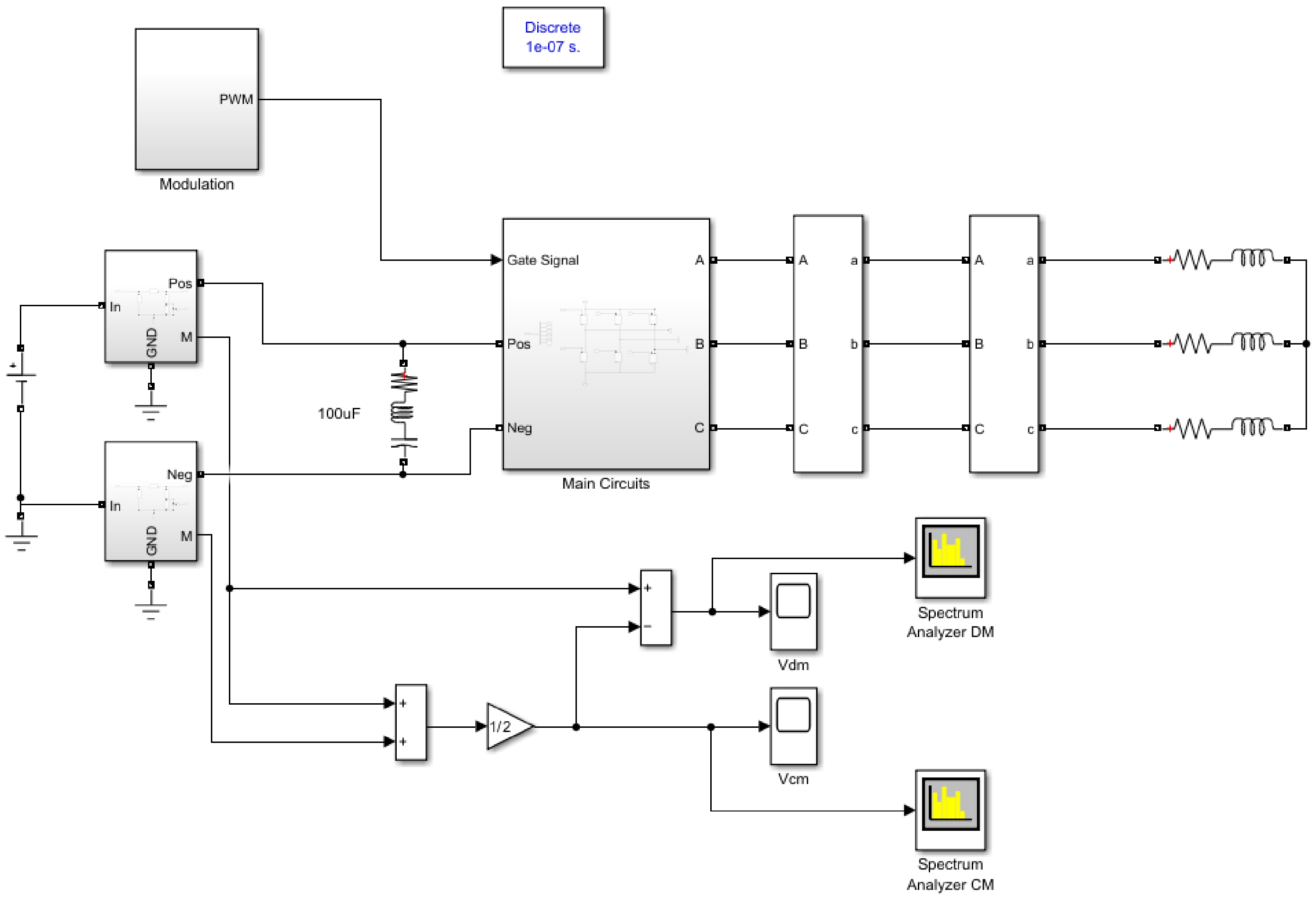
CISPR 25 EMI test example (recap)



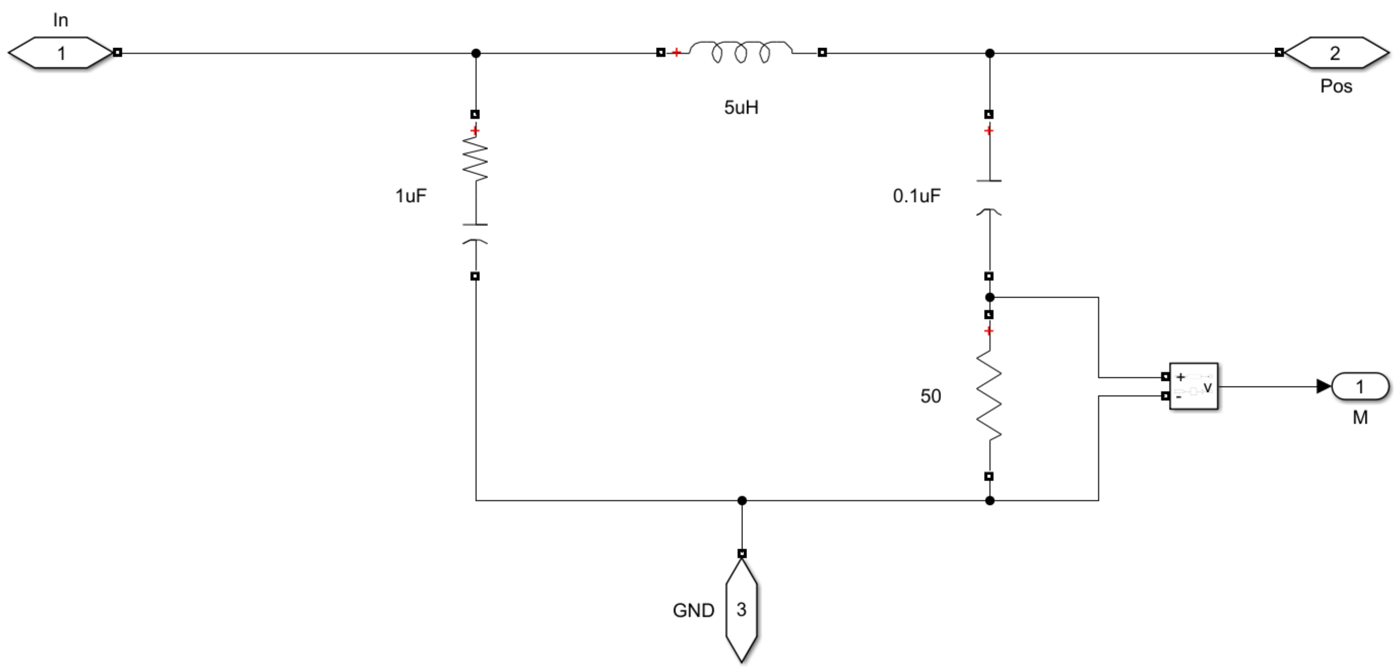
EMI Filter (recap)



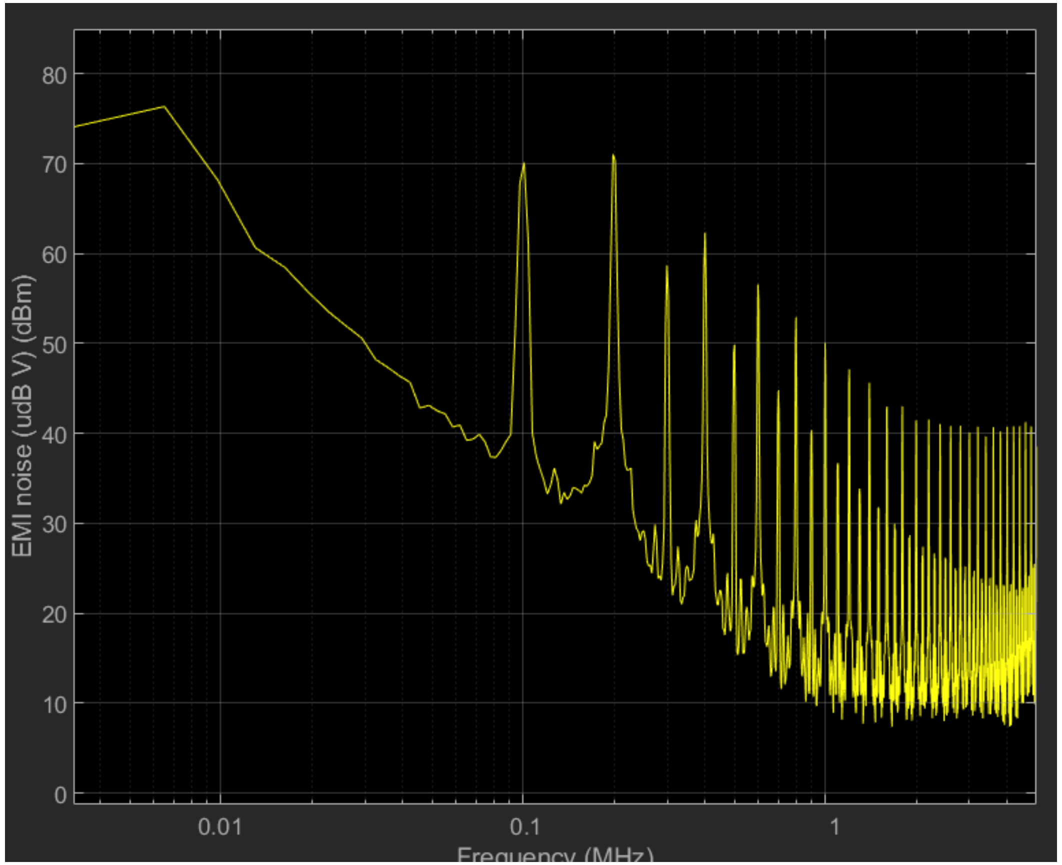
EMI noise simulation (recap)



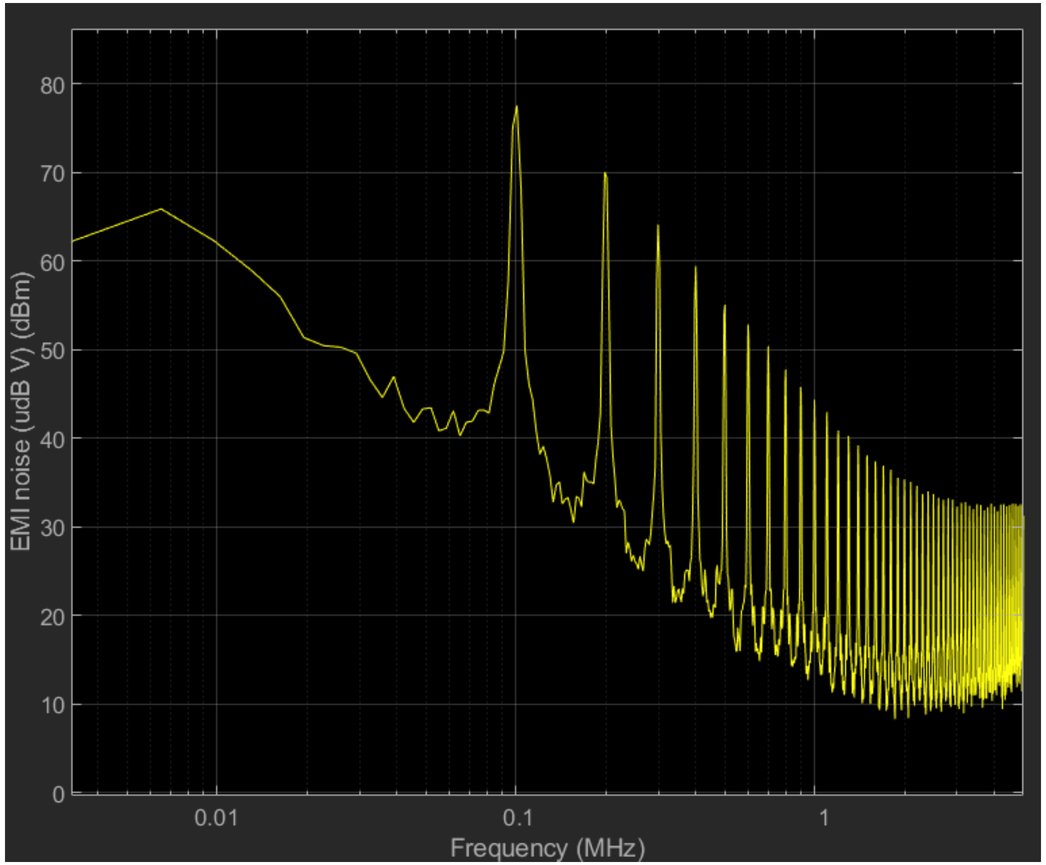
LISN model (recap)



EMI DM noise comparison (recap)



3-ph symmetric SVPWM

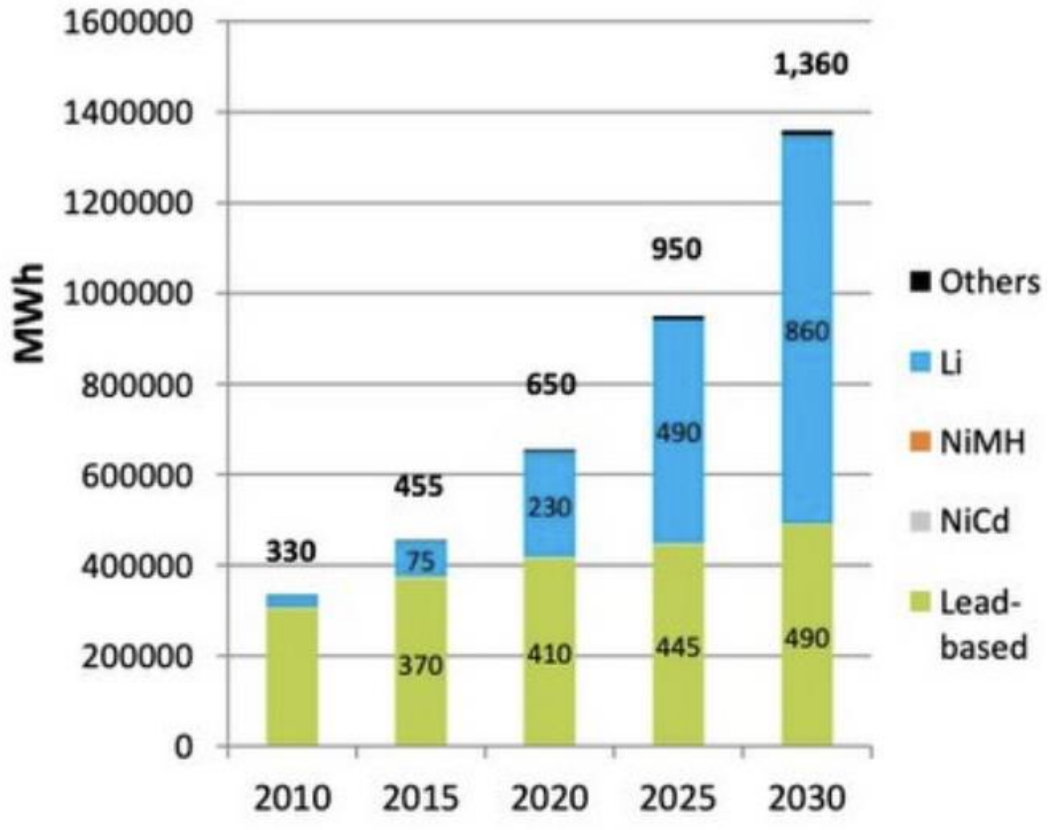


2-ph symmetric SVPWM

Module 3: Battery Management System (BMS)

Battery market

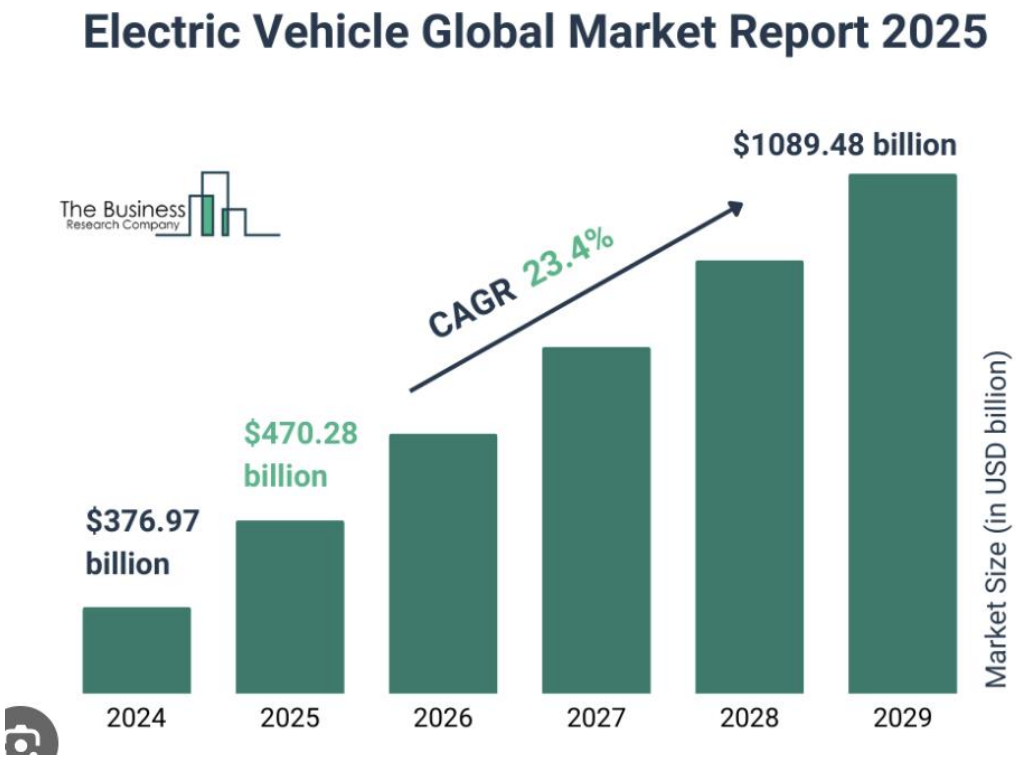
- Most popular battery?



Source: Avicenne Energy

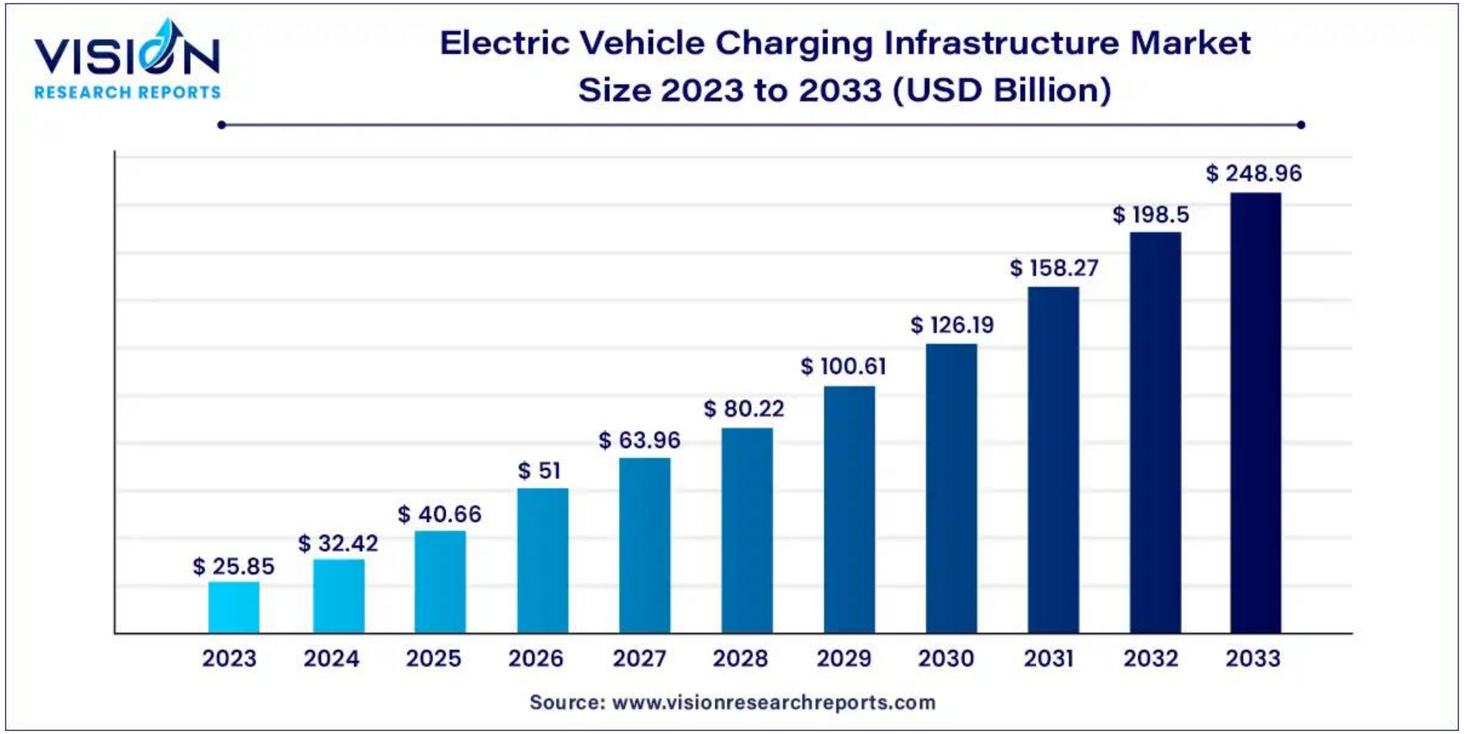
Battery market

- battery market vs. electric vehicle market



Battery market

- battery market vs. charging infrastructure market



Ni-Cd cell → Ni-MH cell → Li-ion cell

Basic terminology

Cell: the most basic element of a battery;

Block: a collection of cells wired directly in parallel;

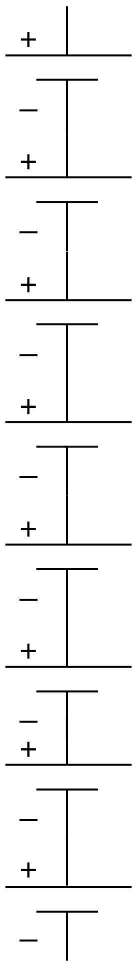
Battery: a collection of cells or blocks wired in series;

Pack: a collection of batteries.

Cell, Battery and Pack

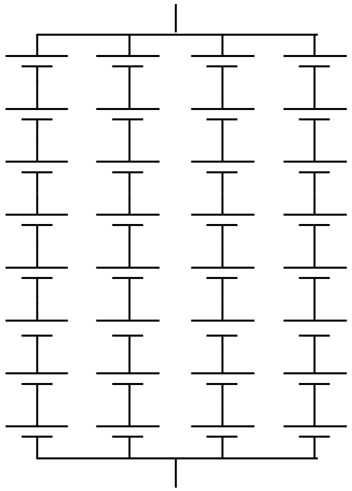
series connection

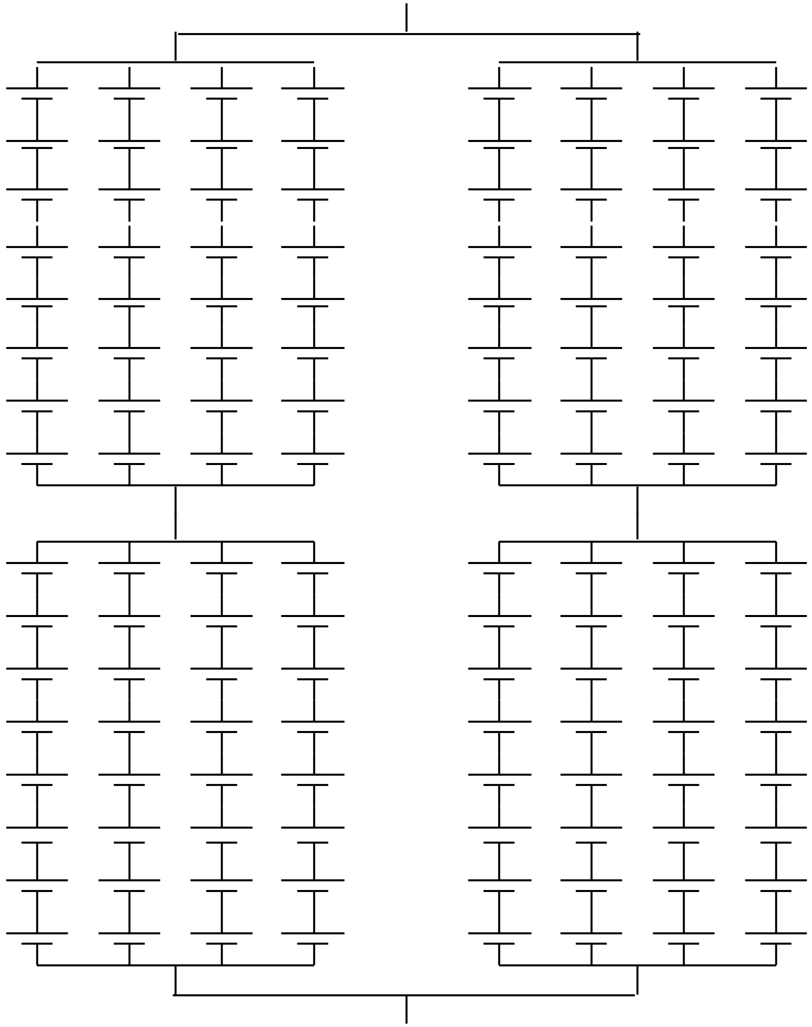
increases voltage



parallel connection

increases current





combinations

increase both

voltage &

current

Battery specs

- **Voltage (Volts - V)**

- Voltage (Electromotive Force - E) is a measure of energy per unit charge.

- **Current – I (Amperes - A)**

- A measure of the transfer of electric charge (coulombs per second).

- **Power (Watts - W)**

- A function of both current and voltage: P (W) = E(V) x I (A)

- **Capacity - C (Ampere-hours – Ah)**

- A measure of total electrical charge(equivalent to coulombs).

- **Energy (Watt-hours – Wh)**

- A function of both capacity and voltage: E (Wh) = E(V) x C (Ah)

Battery Parameters

Specification sheet reference

- Columbic: 3600 Coulombs = Amp-hours [Ah]
- Energy: Watt-hours [Wh]
  - (Amp-hours)·(Volts) = (Watt-hours)

- Examples:
  - 40 Ah Battery @ 5 A discharge.
    - Find time to total discharge:
  - 4.2 V battery with 35 Ah.
    - Find energy capacity:

Charge and Energy Density

Gravimetric Charge Density (Ah/kg)

Volumetric Charge Density (Ah/L)

Gravimetric Energy Density (Wh/kg)

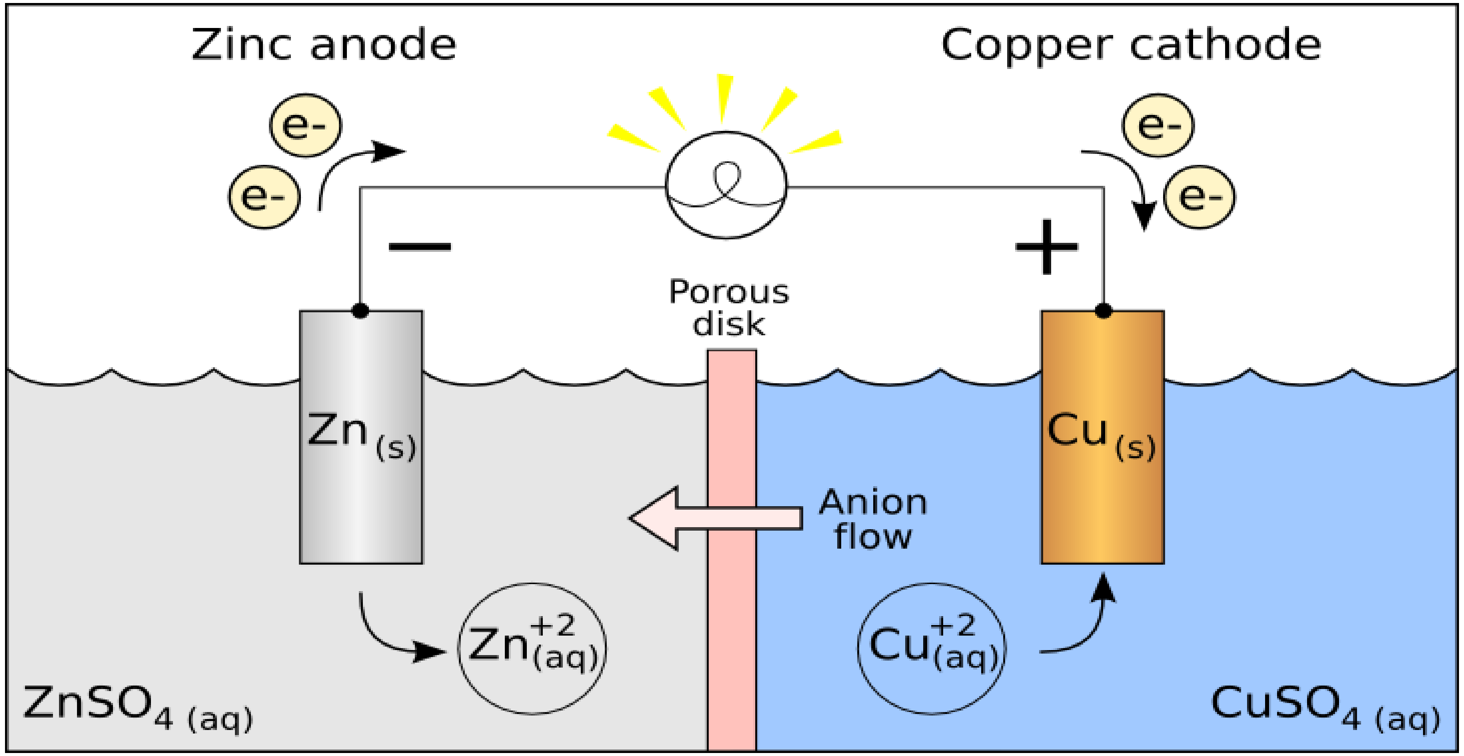
Volumetric Energy Density (Wh/L)

C-rate

- 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



Galvanic cell

Battery Structure

- The primary elements of a cell are the Anode, cathode, separator, current collectors, electrolyte, and enclosure hardware.

- The **anode** (Negative Electrode) is the source of the oxidation reaction (during discharge).
- The **cathode** (Positive Electrode) is the source of the reduction reaction (during discharge).
- Both electrodes contain (together) the active materials for the electrochemical reaction.
- The **separator** is an insulating divider, which physically separates the electrodes (to prevent electrical shorting), and facilitates ion flow from one electrode to the other.
- The **current collectors** reside within each electrode, acting as a physical support for the electrode materials, and conduct electrons to and from the active materials, within the external electrical circuit.
- The **electrolyte** provides the ions necessary to support the electrochemical reaction.
- The **enclosure hardware** contains the electrodes, separator, current collectors and electrolyte, and both protects all components from the external environment, and users from the internal components, and isolates cells.

Charge Density

Can we calculate the gravimetric energy density of the battery?

1. One electron: $-1.602*10^{-19}$C
2. One H-Atom mass: $1.667*10^{-27}$kg

Periodic Table of Elements

Periodic Table of the Elements 2005

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.01																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 15.99	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 25.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.41	31 Ga 69.72	32 Ge 72.64	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (270)	109 Mt (268)	110 Ds (281)	111 Rg (272)							
				58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.97	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
				90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

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Battery Density

$$\text{Li} \quad + \quad \text{MnO}_2 \quad \rightarrow \quad \text{LiMnO}_2 \quad \text{(discharge)}$$

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

Theoretical Open Circuit Voltage :

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

$$Cell\ Voltage = E°_{positive} - E°_{négative}$$

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

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?

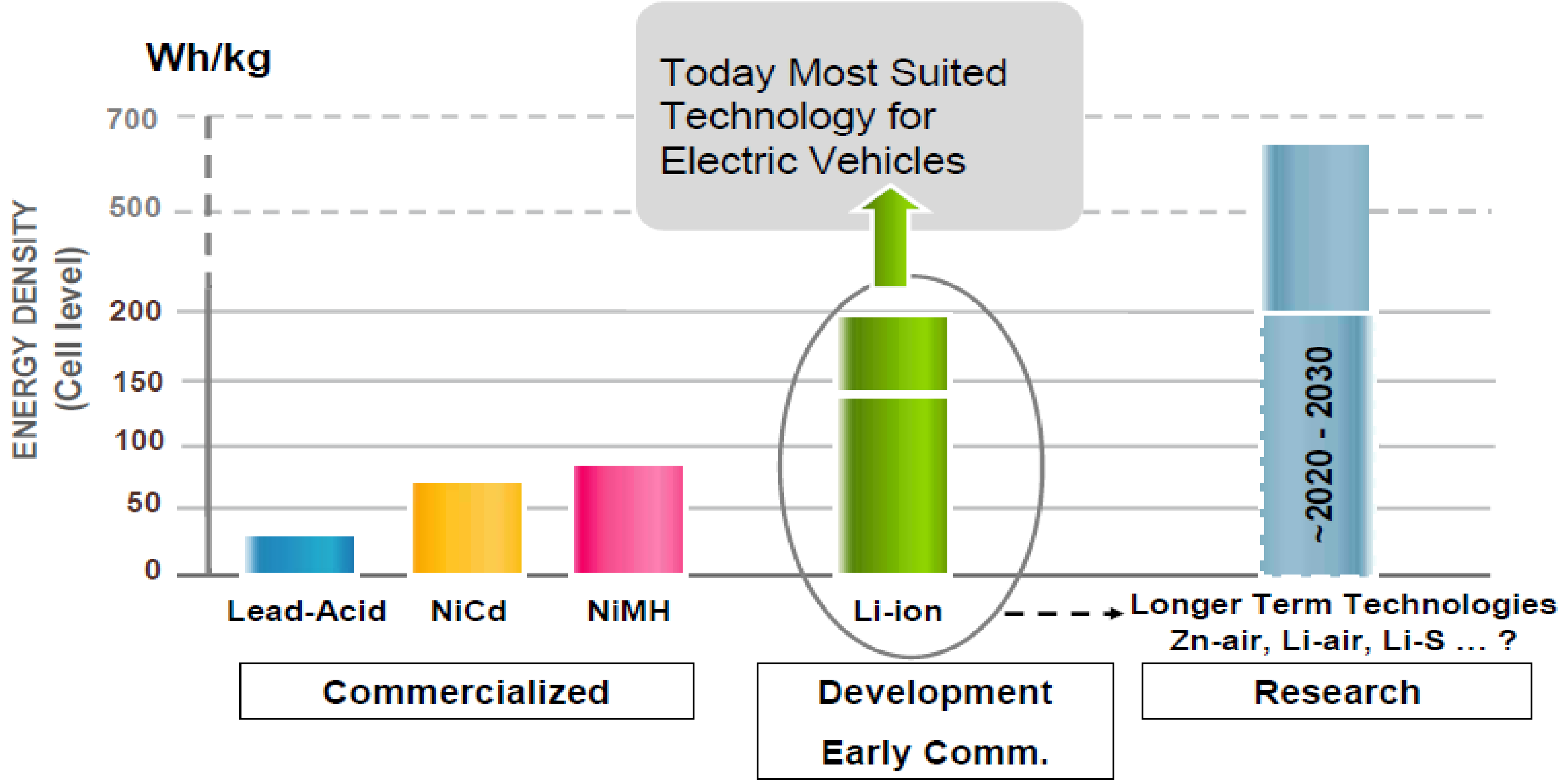
Anode Materials

Material	Theoretical Properties		
	Capacity, Ah/Kg	Voltage vs. H/H$^+$, V	Specific Energy, WH/Kg
Li	3860	3.05	11,800
Mg	2200	2.37	5200
Al	2980	1.67	5000
Zn	820	0.76	620
Metal Hydride	~300	0.85	~260

Cathode Materials

Material	Theoretical Properties			
	Capacity, Ah/Kg	Voltage vs. Zn/Zn^{+2}, V	Voltage vs. Li/Li^{+}, V	Cell Specific Energy, WH/Kg
NiOOH	295	1.74		350
AgO/Ag_2O	430	1.83/1.57		580
O_2	3350	1.65	2.91*	1090 (Zn)/5200 (Li)
S	1670		2.1	2450
TiS_2	240		2.15	490
CoO_2	295		3.7	1010
CF	865		2.6	1840

Battery Evolution



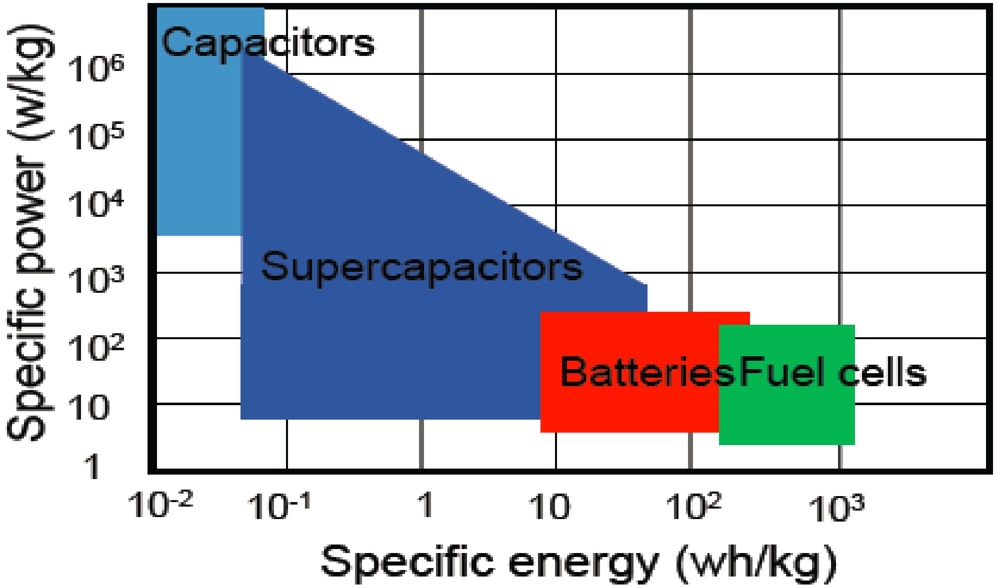
Power density

- 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

	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

Energy Storage Technology



Important parameters:

- Energy density (volume); Specific Energy (weight)
- Power density; Specific power
- Cycle life, calendar life
- Safety
- Cost

Energy density comparison

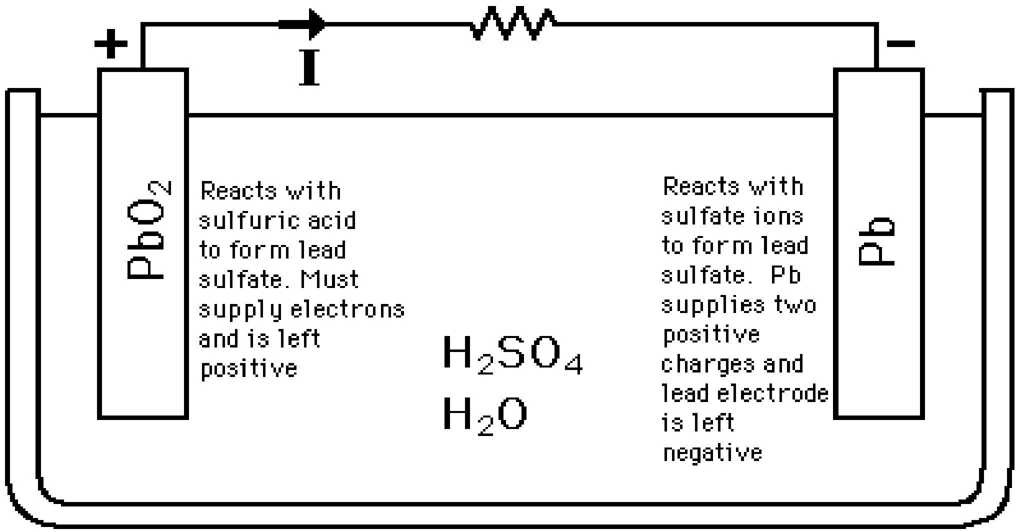
Energy Sources	Energy Density (Wh/kg)
Gasoline	12 500
Natural Gas	9350
Hydrogen	33 000
Coal	8200
NiMH Battery	50
Li-Ion Battery	120
Ultra-cap	3.3

Lead-Acid Battery

Negative electrode: Pb (loses electrons when discharging)

Positive electrode: PbO_2 (gains electrons when discharging)

Electrolyte: H_2SO_4 (Sulfuric Acid)



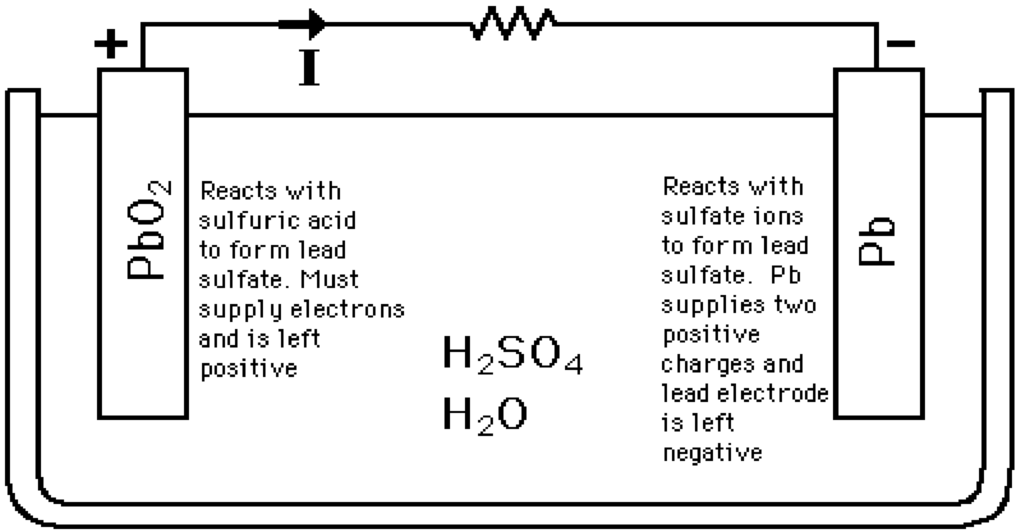
Lead-Acid Battery

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



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Lead-Acid Battery

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 $Q/M/3600=83$Ah/kg

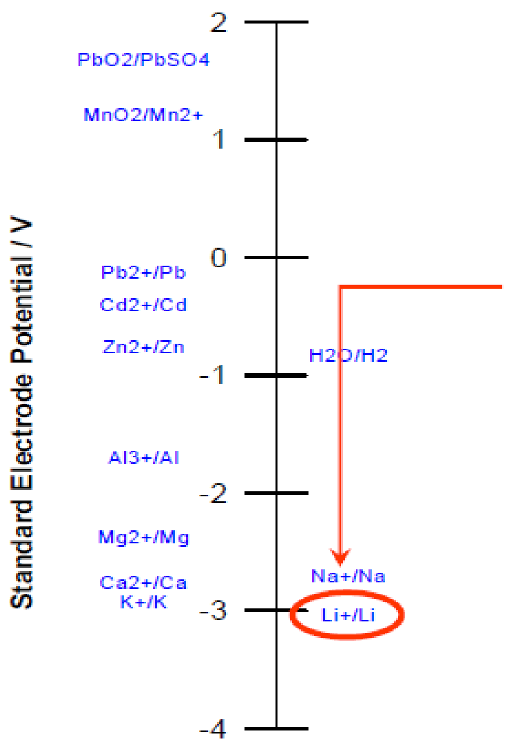
Lead-Acid Battery

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.



Lead-Acid Battery

Question 3: Charging?

Negative Plate (reduction): $PbSO_4 + H^+ + 2e^- \longrightarrow Pb + HSO_4^-$

Positive Plate (oxidation): $PbSO_4 + 2H_2O \longrightarrow PbO_2 + HSO_4^- + 3H^+ + 2e^-$

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

Lead-Acid Battery

PbO_2: Positive Electrode
Pb: Negative Electrode:
H_2SO_4: Concentrated Electrolyte

$$PbO_2 + Pb + 2\,H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2\,PbSO_4 + 2\,H_2O$$

OCV: 2.1V

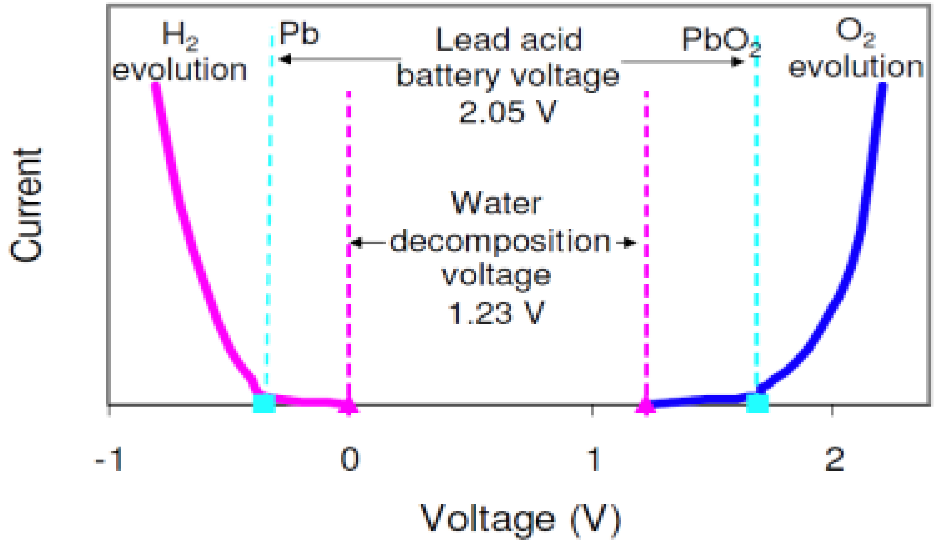
Water hydrolysis during charging

Oxidation reaction at the positive electrode

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

Reduction reaction at negative electrode

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



Gas release in Pb-acid battery

PbA batteries will generate gas when charging.

1. *Gas will accumulate on the electrode surface and obstruct the chemical reactions;*

2. *High gas pressure will damage the electrode, separator and enclosure;*

3. *High gas pressure will need be released, yielding the loss of the water and slowed chemical reactions.*

Thank you!