Spring Semester, 2011
Energy Engineering
에너지공학

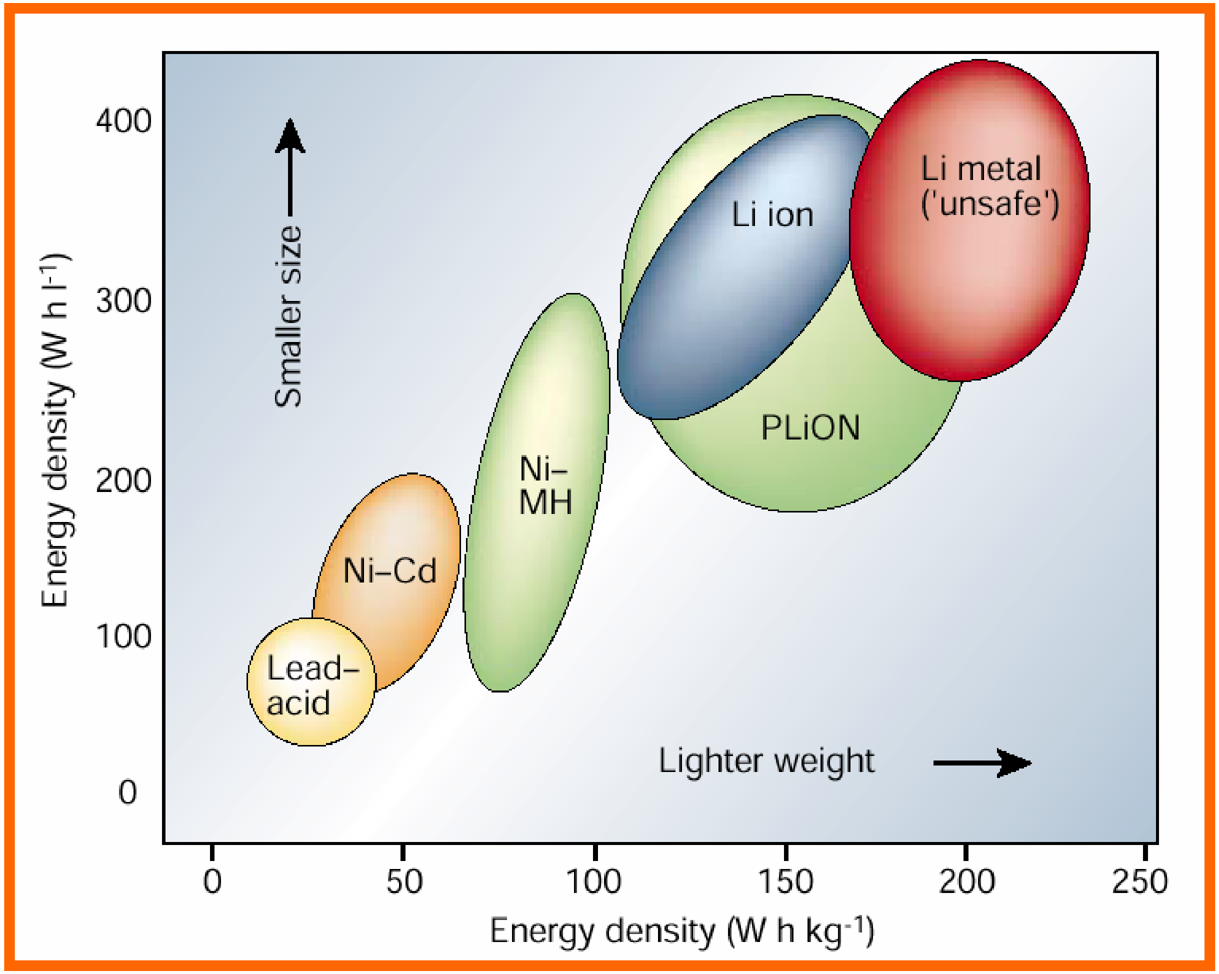
Rechargeable Battery

History of Secondary Batteries

Date	Type	Chemistry
1860	Lead-acid	$PbO_2/H_2SO_4/Pb$
1900	Edison cell	Ni/2NiOOH/Fe
	Ni-Cd cell	Ni/2NiOOH/Cd
1965	Beta cell	Na/β-Al_2O_3/S
1970	Zinc-chlorine	$Zn/ZnCl_2/Cl_2$
1980–90	Li/SSE	Li/PC-Li_2ClO_4/MX_2
	Polymeric cells	Li/PEO-$LiClO_4/TiS_2$
	Glassy cells	Li/Li^+-glass/TiS_2
1991	Li microbatteries	Li/Li^+-glass/TiS_2
1992	Rocking-chair cells	$LiMn_2O_4$/elect./carbon
		$LiCoO_2$/elect./carbon
		$LiNiO_2$/elect./carbon

From Julien, C. and Nazri, G.A., *Solid State Batteries: Materials Design and Optimization*, Kluwer, Boston, 1994. With permission.

Secondary(or Rechargeable) Batteries



Comparison of Rechargeable Batteries

System	Anode	Cathode	electrolyte	Working voltage	Energy density
Lead-acid	Pb	PbO_2	H_2SO_4 (aqueous solution)	1.9 V	70
Ni-Cd	Cd	NiOOH	KOH (aqueous solution)	1.2 V	90
Ni-MH	MH	NiOOH	KOH (aqueous solution)	1.2 V	200
Li-ion	C	$LiMO_2$	Li-salt	3.6 V	300

Principles of Rechargeable Batteries

Nickel-cadmium electrode reactions

Cathode: $NiOOH + H_2O + e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} Ni(OH)_2 + OH^-$

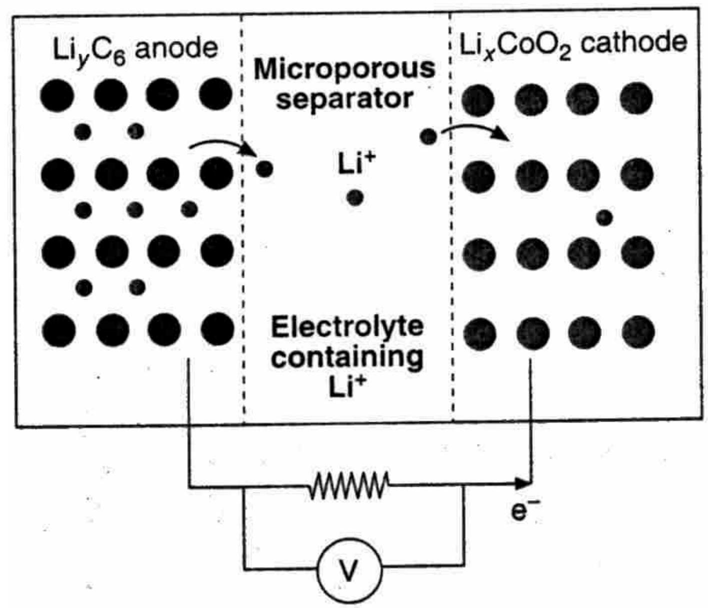
Anode: $Cd + 2\,OH^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} Cd(OH)_2 + 2\,e^-$

Ni-metal hydride electrode reactions

Cathode: $NiOOH + H_2O + e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} Ni(OH)_2 + OH^-$

Anode: $MH + OH^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} M + H_2O + e^-$

Lithium-ion cells discharge by shuttling Li^+ from anode to cathode through separator



$$Li_yC_6 \longrightarrow C_6 + yLi^+ + ye^-$$

$$Li_xCoO_2 + yLi^+ + ye^- \longrightarrow Li_{x+y}CoO_2$$

discharge

Electrode Reaction of Li Rechargeable Battery

Cathode

-Oxide ($LiMn_2O_4$, V_2O_5, $LiCoO_2$, $LiNiO_2$)

$$Li_{1-x}CoO_2 + xLi^+ + xe \xleftrightarrow{\text{discharge}} LiCoO_2$$

-Chalcogenides (MoS_2, TiS_2 layered structure)

$$TiS_2 + xLi^+ + xe \xleftrightarrow{\text{discharge}} Li_xTiS_2$$

Anode

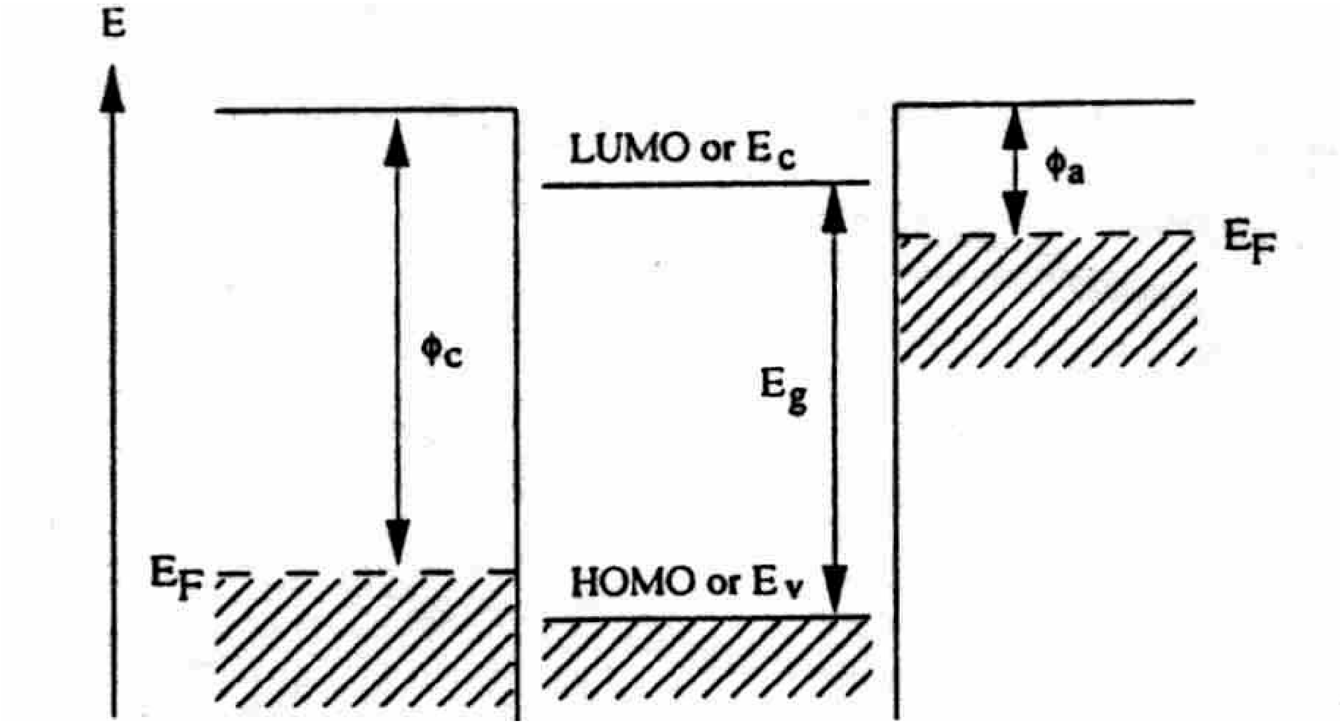
-Lithium (alloy)

$$Li(Al) \xleftrightarrow{\text{discharge}} Li^+ + (Al) + e$$

-Carbon compounds

$$Li_xC_n \xleftrightarrow{\text{discharge}} Li^+ + C_n + xe$$

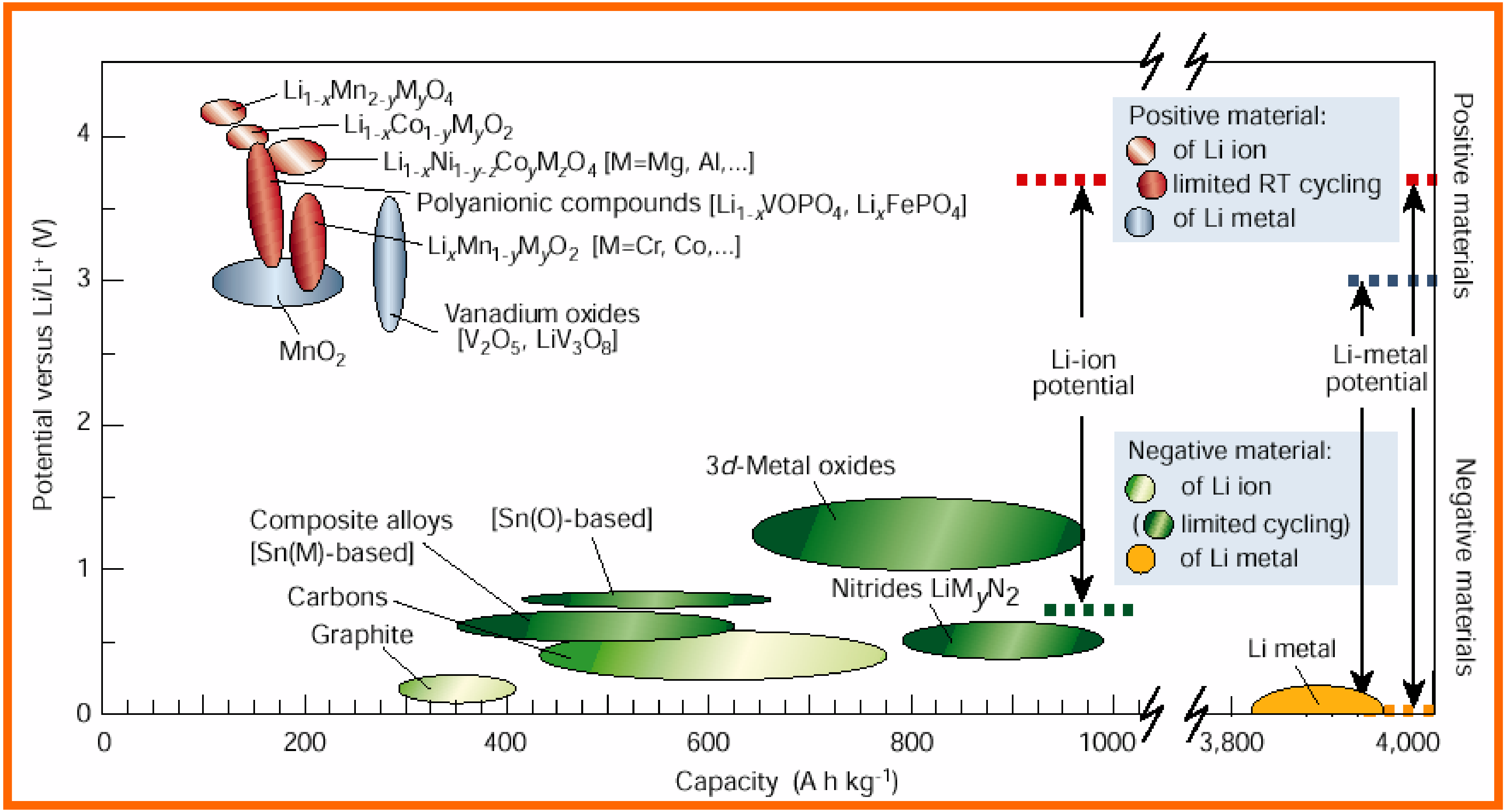
Energy Diagram of Li Rechargeable Battery



Cathode   Electrolyte/separator   Anode

Chemical stability:
no reduction at
anode side &
no oxidation at
cathode side

Battery Materials



Li 이차전지 종류

i) Li metal battery (LMB): Li metal anode

ii) Li ion battery (LIB): carbon anode

iii) Li ion polymer battery (LIPB): carbon anode, liq. Electrolyte + polymer (gel type)

iv) Li polymer battery (LPB): Li metal anode, solid polymer electrolyte

Energetics of batteries

Three major characteristics of an energy storage device;

(1) the operating voltage,

(2) the current that can be drawn at a usable voltage,

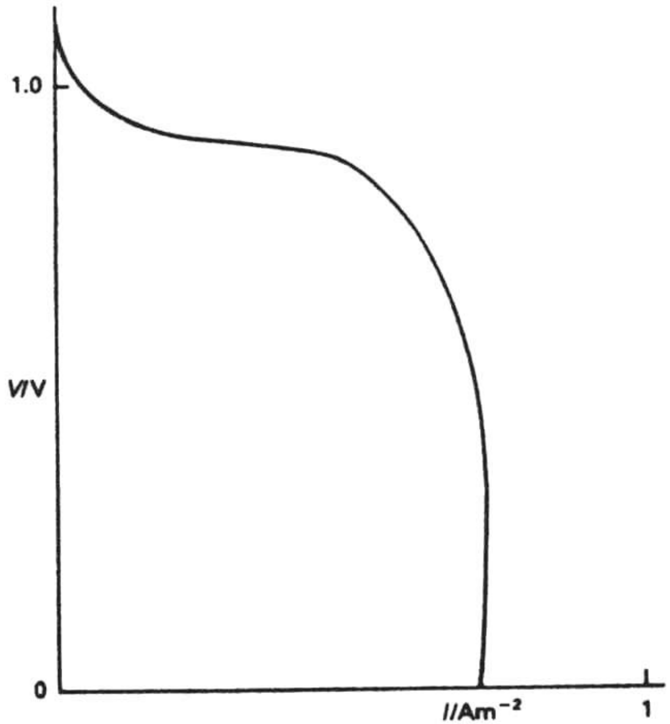
(3) how long it will last

Reaction $\rightarrow \Delta G^0 = -nFE^0$, F; 96500 C or 26.8 Ah

Cell voltage

Actual voltage < $\Delta G/-nF$; overpotential associated with the reaction, resistance losses in the cell, the concentration of the electroactive species in the electrolyte, the way that the cell is discharged $\rightarrow$ ΔG gives the maximum possible potential

Voltage starts at the equilibrium value, then falls, eventually reaching zero at some maximum current



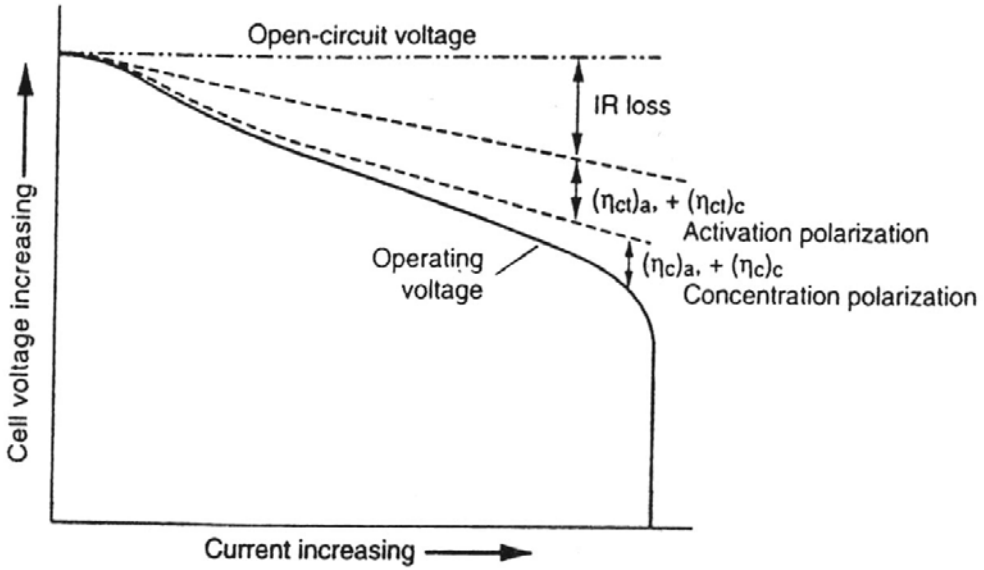


FIGURE 2.1 Cell polarization as a function of operating current.

Battery Evaluations

용량 (Capacity , C or Ah)
- the capacity is the amount of charge that may be delivered by a battery
- theoretical capacity

$$C = nF(W/MW)$$

W: weight of active electrode material, MW: molecular weight of material
F; 96500 C or 26.8 Ah

전극소재별 이론용량
1 mol : 96500 C/mol

e.g.
Li: MW 6.941g $\rightarrow$ 26.8 Ah/6.941 g = 3.861 Ah/g
$LiCoO_2$: MW 97.871g $\rightarrow$ 26.8 Ah/97.871 g = 273.7 mAh/g

TABLE 1.1 Characteristics of Electrode Materials*

Material	Atomic or molecular weight, g	Standard reduction potential at 25°C, V	Valence change	Melting point, °C	Density, g/cm^3	Electrochemical equivalents		
						Ah/g	g/Ah	Ah/cm^3‡
				Anode materials				
H_2	2.01	0	2	—	—	26.59	0.037	
Li	6.94	−3.01	1	180	0.54	3.86	0.259	2.06
Na	23.0	−2.71	1	98	0.97	1.16	0.858	1.14
Mg	24.3	−2.38 −2.69†	2	650	1.74	2.20	0.454	3.8
Al	26.9	−1.66	3	659	2.69	2.98	0.335	8.1
Ca	40.1	−2.84 −2.35†	2	851	1.54	1.34	0.748	2.06
Fe	55.8	−0.44	2	1528	7.85	0.96	1.04	7.5
Zn	65.4	−0.76 −1.25†	2	419	7.14	0.82	1.22	5.8
Cd	112.4	−0.40	2	321	8.65	0.48	2.10	4.1
Pb	207.2	−0.13	2	327	11.34	0.26	3.87	2.9
				Cathode materials				
O_2	32.0	1.23	4	—	—	3.35	0.30	
Cl_2	71.0	1.36	2	—	—	0.756	1.32	
SO_2	64.0	—	1	—	—	0.419	2.38	
MnO_2	86.9	1.23‡	1	—	5.0	0.308	3.24	1.54
NiOOH	91.7	0.49†	1	—	7.4	0.292	3.42	2.16
CuCl	99.0	0.14	1	—	3.5	0.270	3.69	0.95
FeS_2	119.9	—	4	—	—	0.89	1.12	4.35
AgO	123.8	0.57†	2	—	7.4	0.432	2.31	3.20
Br_2	159.8	1.07	2	—	—	0.385	2.95	
HgO	216.6	0.10†	2	—	11.1	0.247	4.05	2.74
Ag_2O	231.7	0.35†	2	—	7.1	0.231	4.33	1.64
PbO_2	239.2	1.69	2	—	9.4	0.224	4.45	2.11

Energy Density

Battery: portable, electric car → size & weight go together!

Energy density of Active Materials (Whkg^{-1} or Whdm^{-3})

- energy from battery: nFE
- energy density: voltage x storage density (Wh = V x Ah)
- few tens Whkg^{-1} of lead-lead acid battery to hundreds for sodium-sulphur

e.g. 1, Zn/Cl_2 cell

$Zn + Cl_2 \rightarrow ZnCl_2$

0.82 Ah/g 0.76 Ah/g

1.22 g/Ah 1.32g/Ah = 2.54 g/Ah or **0.394 Ah/g**

$E^0 = 2.12$ V

Wh/g capacity = 2.12 V x 0.395 Ah/g = **0.838Wh/g**

TABLE 1.2 Theoretical Voltage and Capacity of Major Battery Systems*

Battery	Anode	Cathode	Reaction mechanism	V	Capacity† g/Ah	Capacity† Ah/kg
			Primary			
Leclanché	Zn	MnO_2	$Zn + 2MnO_2 \rightarrow ZnO \cdot Mn_2O_3$	1.6	4.46	224
Magnesium	Mg	MnO_2	$Mg + 2MnO_2 + H_2O \rightarrow Mn_2O_3 + Mg(OH)_2$	2.8	3.69	271
Alkaline MnO_2	Zn	MnO_2	$Zn + 2MnO_2 \rightarrow ZnO + Mn_2O_3$	1.5	4.46	224
Mercury	Zn	HgO	$Zn + HgO \rightarrow ZnO + Hg$	1.34	5.27	190
Mercad	Cd	HgO	$Cd + HgO + H_2O \rightarrow Cd(OH)_2 + Hg$	0.91	6.15	163
Silver oxide	Zn	Ag_2O	$Zn + Ag_2O + H_2O \rightarrow Zn(OH)_2 + 2Ag$	1.6	5.55	180
Zinc/air	Zn	O_2 (air)	$Zn + \frac{1}{2}O_2 \rightarrow ZnO$	1.65	1.55	658
Li/SO_2	Li	SO_2	$2Li + 2SO_2 \rightarrow Li_2S_2O_4$	3.1	2.64	379
Li/MnO_2	Li	MnO_2	$Li + Mn^{IV}O_2 \rightarrow Mn^{IV}O_2(Li^+)$	3.5	3.50	286
			Reserve			
Cuprous chloride	Mg	CuCl	$Mg + Cu_2Cl_2 \rightarrow MgCl_2 + 2Cu$	1.6	4.14	241
Zinc/silver oxide	Zn	AgO	$Zn + AgO + H_2O \rightarrow Zn(OH)_2 + Ag$	1.81	3.53	283

			Secondary			
Lead-acid	Pb	PbO_2	$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$	2.1	8.32	120
Edison	Fe	Ni oxide	$Fe + 2NiOOH + 2H_2O \rightarrow 2Ni(OH)_2 + Fe(OH)_2$	1.4	4.46	224
Nickel-cadmium	Cd	Ni oxide	$Cd + 2NiOOH + 2H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2$	1.35	5.52	181
Silver-zinc	Zn	AgO	$Zn + AgO + H_2O \rightarrow Zn(OH)_2 + Ag$	1.85	3.53	283
Nickel-zinc	Zn	Ni oxide	$Zn + 2NiOOH + 2H_2O \rightarrow 2Ni(OH)_2 + Zn(OH)_2$	1.73	4.64	215
Nickel-hydrogen	H_2	Ni oxide	$H_2 + 2NiOOH \rightarrow 2Ni(OH)_2$	1.5	3.46	289
Nickel-metal hydride	MH‡	Ni oxide	$MH + NiOOH \rightarrow M + Ni(OH)_2$	1.35	6.50	206§
Silver-cadmium	Cd	AgO	$Cd + O + H_2O \rightarrow Cd(OH)_2 + Ag$	1.4	4.41	227
Zinc/chlorine	Zn	Cl_2	$Zn + Cl_2 \rightarrow ZnCl_2$	2.12	2.54	394
Zinc/bromine	Zn	Br_2	$Zn + Br_2 \rightarrow ZnBr_2$	1.85	4.17	239
Lithium/manganese dioxide	Li	MnO_2	$Li + Mn^{IV}O_2 \rightarrow Mn^{IV}O_2(Li^+)$	3.5	3.50	286
Lithium/iron disulfide	Li(Al)	FeS_2	$2Li(Al) + FeS_2 \rightarrow Li_2FeS_2 + 2Al$	1.73	3.50	285
Lithium/iron monosulfide	Li(Al)	FeS	$2Li(Al) + FeS \rightarrow Li_2S + Fe + 2Al$	1.33	2.99	345
Sodium/sulfur	Na	S	$2Na + 3S \rightarrow Na_2S_3$	2.1	2.65	377
Sodium/nickel chloride	Na	$NiCl_2$	$2Na + NiCl_2 \rightarrow 2NaCl + Ni$	2.58	3.28	305
			Fuel cell			
H_2/O_2	H_2	O_2 (or air)	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	1.23	0.336	2975

*See Table 6.2 in Chap. 6 for practical values.

† Based on active anode and cathode materials only, including O_2 (electrolyte not included).

‡ MH = metal hydride.

§ Based on 1.2% hydrogen storage (by weight).

Energy density of Practical Batteries

e.g. C/$LiCoO_2$ Li 2차전지 (최대방전 용량 1400 mAh, 평균작동전압 3,7 V, 중량 43 g, 부피 15.154 cm^3)

i)중량당 에너지 밀도: 얼마나 가벼운 전지를 만들 수 있는가?

(1.4 Ah x 3.7 V) / 0.043 kg = 125.6 Wh/kg

ii) 최적당 에너지밀도: 얼마나 작은 전지를 만들 수 있는가?

(1.4 Ah x 3.7 V) / 15.154 cm^3 (= 0.015154 /) = 356 Wh//

TABLE 6.2 Characteristics of Major Battery Systems[a]

Battery system	Anode	Cathode	Practical battery: Nominal voltage, V	Energy density† Wh/kg	Energy density† Wh/L
Primary					
Leclanché	Zn	MnO_2	1.5	85	165
Magnesium	Mg	MnO_2	1.7	100	195
Alkaline-MnO_2	Zn	MnO_2	1.5	125	330
Mercury	Zn	HgO	1.3	100[c]	470[c]
Mercad	Cd	HgO	0.9	55[c]	230[c]
Silver oxide	Zn	Ag_2O	1.6	120[c]	500[c]
Zinc/air	Zn	O_2(air)	1.5	340[c]	1050[c]
Li/SO_2	Li	SO_2	3.0	260	415
Li/$SOCl_2$	Li	$SOCl_2$	3.6	320	700
Li/MnO_2	Li	MnO_2	3.0	230	550
Li$(CF)_n$	Li	$(CF)_n$	3.0	220	410
Li/FeS_2	Li	FeS_2	1.6	240	500
Solid electrolyte	Li	I_2(P2VP)	2.8	200–300	700–970
Reserve					
Cuprous chloride	Mg	CuCl	1.3	60	80[d]
Zinc/silver oxide	Zn	AgO	1.5	30	75[e]
Thermal	Li	FeS_2	2.0	40[f]	100[f]
Secondary (rechargeable)					
Lead-acid	Pb	PbO_2	2.0	35	70
Edison	Fe	Ni oxide	1.2	30	55
Nickel-cadmium	Cd	Ni oxide	1.2	35	80
Nickel-metal hydride	(MH)	Ni oxide	1.2	50	175
Silver-zinc	Zn	AgO	1.5	90	180
Nickel-zinc	Zn	Ni oxide	1.6	60	120
Nickel-hydrogen	H_2	Ni oxide	1.2	55	60
Silver-cadmium	Cd	AgO	1.1	55	100
Zinc-air	Zn	O_2(air)	1.5	150	160
Zinc/bromine	Zn	Br_2	1.6	70	60
Lithium-ion	C	Li_xCoO_2	4.0	90	200
Lithium-organic	Li	MnO_2	3.0	120	265
Lithium-polymer	Li	V_6O_{13}	3.0	200	350
High temperature	Li(Al)	FeS_2	1.7	180	350
High temperature	Na	S	2.0	170	250

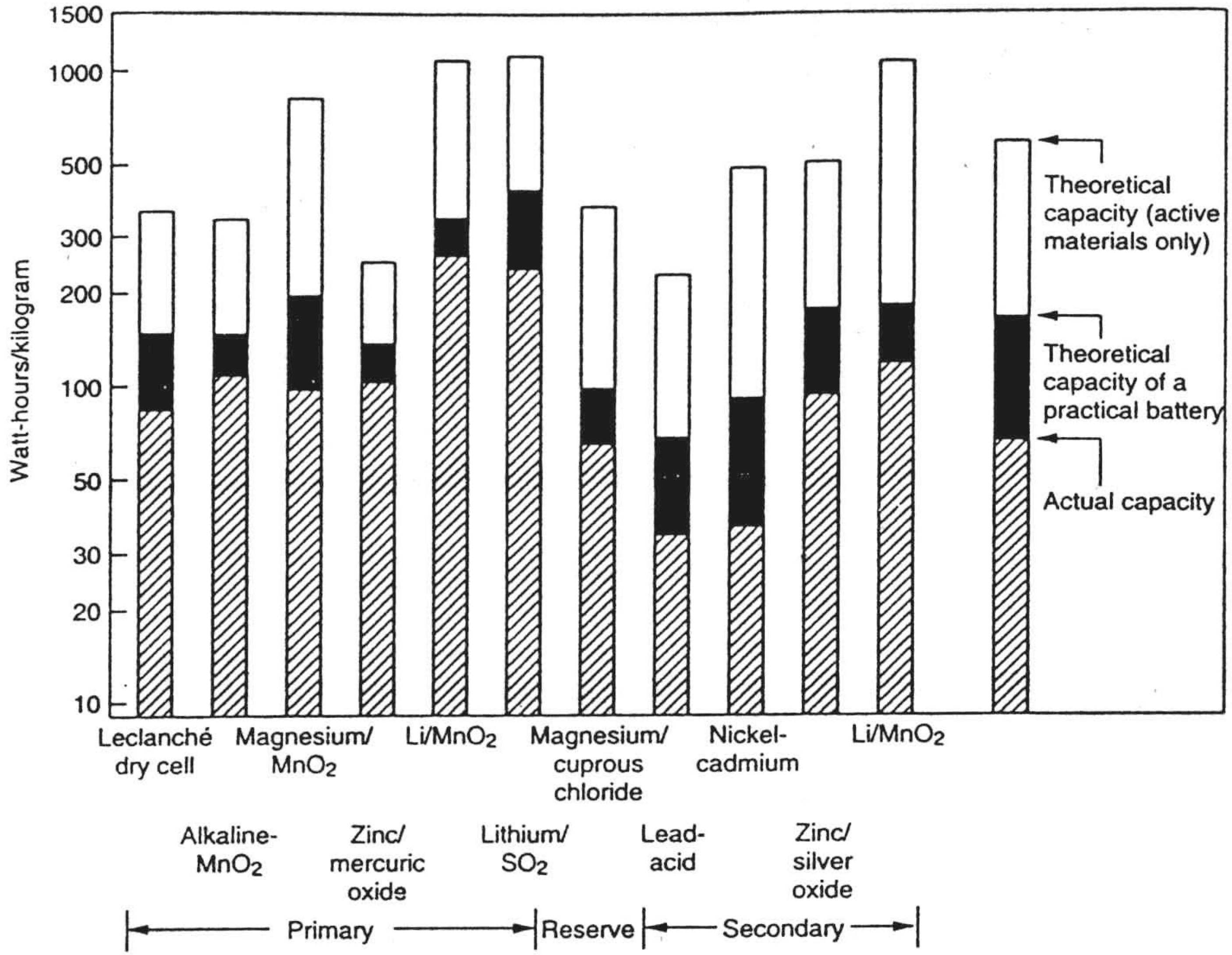


FIGURE 3.3 Theoretical and actual capacity of battery systems.

2차전지 효율

i) Coulometric efficiency

$$q_{Ah} = Q_{discharge}/Q_{charge}$$

For LIB: 95-100%

ii) Energy efficiency (percent)

- the difference between the energy required to charge a secondary battery and the energy delivered by the battery in use ($q_{wh} = q_{Ah} \times V_{discharge}/V_{charge}$)

iii) current efficiency (percent)

- the ratio between the quantity of electricity obtained from a battery and that used to charge it

Cycle life

- a rechargeable battery should be able to be discharged partially or completely, then be recharged, and this should be feasible an infinite number of times → practically not: not the same electrode, electrolyte, separator after charge-discharge cycles, irreversibility in the electrochemial reaction
- **보통 초기용량의** 60-80% **수준까지의 충방전 회수**. **초기용량의 일정** % **시점과 그때의 용량값 명시**. DOD (Depth of Discharge)

Rate Performance

-discharge rate: the discharge rate is, as is current, a measure of the rate at which charge is drawn from the cell. It is normally quoted as the "C/n or n-hour rate, which is the current to discharge the nominal capacity C of the battery in n hours.

e.g., 300 mAh capacity battery: 300 mA in 1 h "C-rate"

C/5-rate, 5 h discharge

-Rate performance**가 좋으면 상업화 가능성이 더 크다**. (**예**: C-rate**에서** 95% **방전** > 60% **방전**)

Economics of batteries

i) Shelf life: self-discharge
ii) reliability; e.g., pacemaker
iii) overcharge
iv) economic & environmental factors

Hydrogen Production/Storage

Hydrogen Storage

On weight basis: hydrogen has 3 times energy content vs. gasoline

(120 MJ/kg H_2 vs. 44 MJ/kg gasoline)

On volume basis: 8 MJ/liter H_2 vs. 32 MJ/liter gasoline

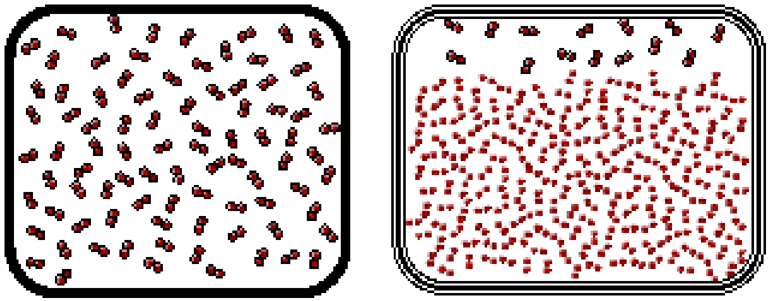
Comparison of storage weight

Storage system	Fuel vol(*l*)	Fuel wt(kg)	Tank weight(kg)	Total weight(kg)
Gasoline	30	22	5	27
Compressed H_2	670	8.2	755	763
Liquid H_2	115	8.2	65	73
Metal hybrid	-	8.2	764	772

Hydrogen can be Stored in Different Forms

From DOE

In tanks . . .

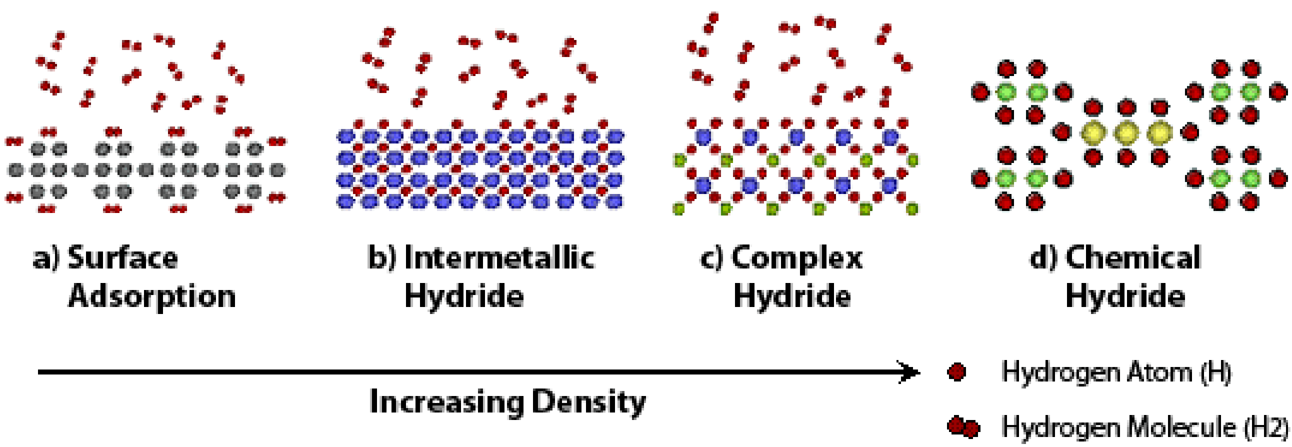


Compressed Gas

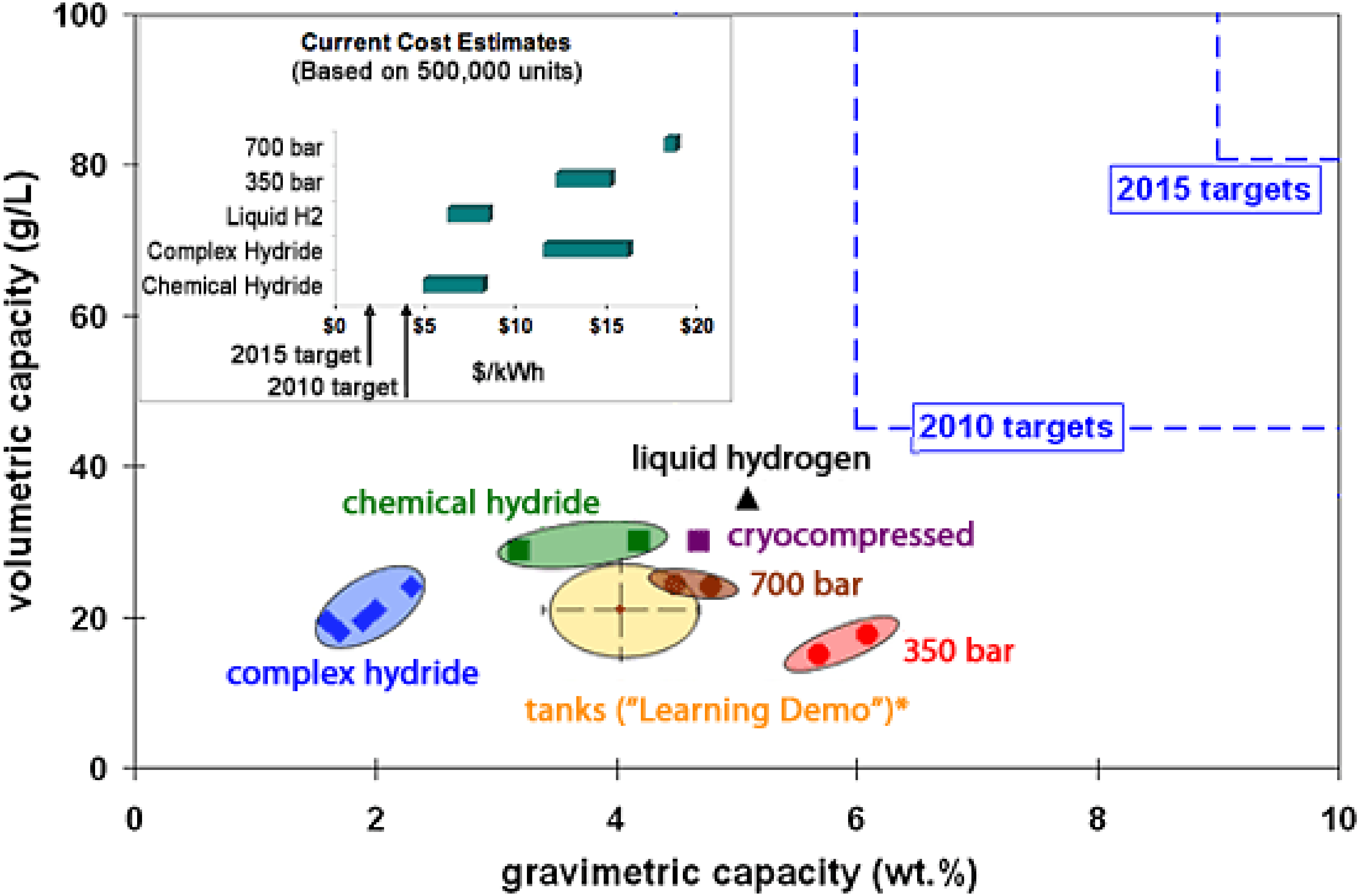
Cryogenic Liquid

and in materials . . .

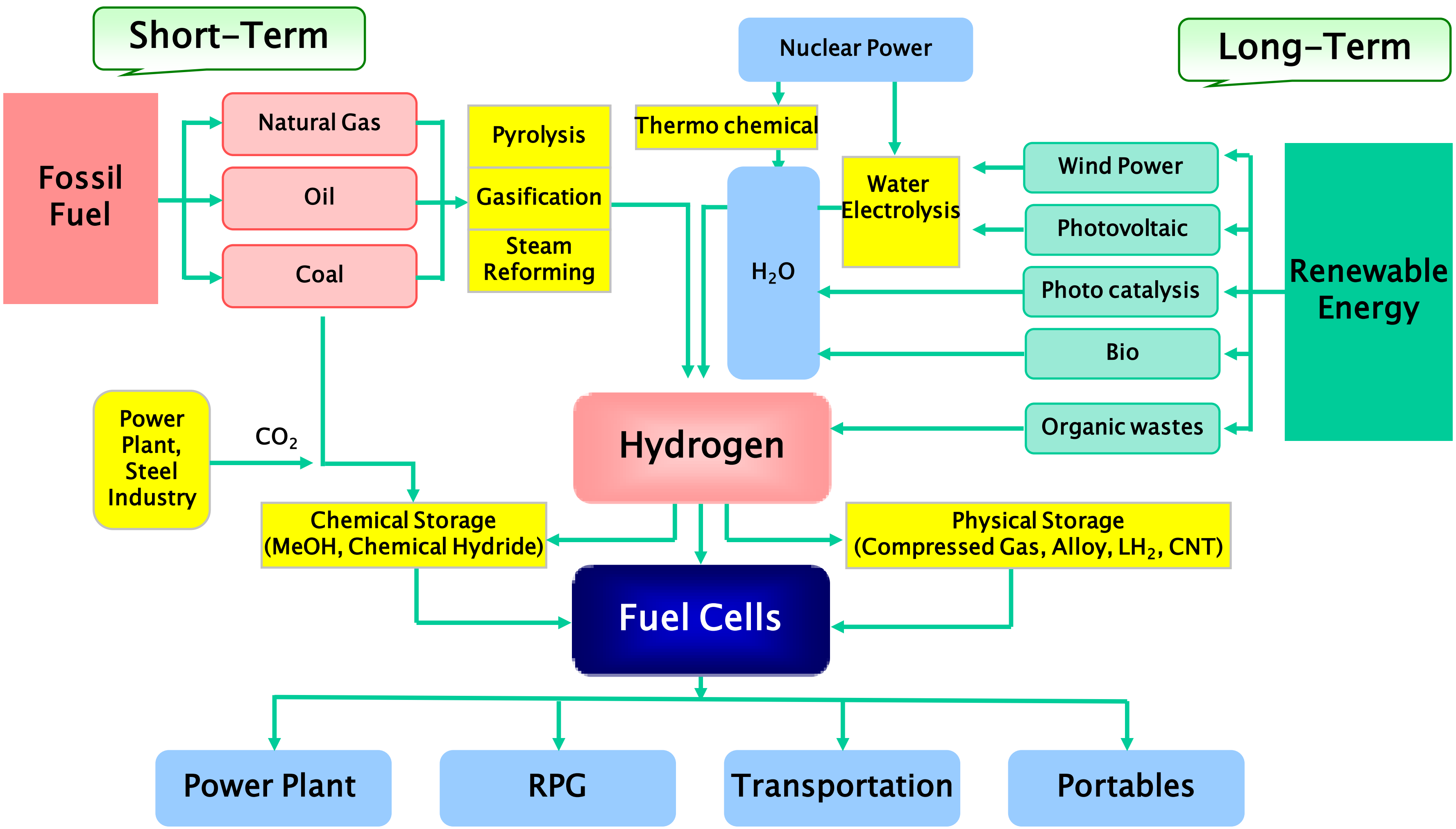
Hydrogen can be stored on the surfaces of solids by adsorption or within solids by absorption. In adsorption (a) hydrogen attaches to the surface of a material either as hydrogen molecules (H2) or hydrogen atoms (H). In absorption (b), hydrogen molecules dissociate into hydrogen atoms that are incorporated into the solid lattice framework—this method may make it possible to store larger quantities of hydrogen in smaller volumes at low pressure and temperatures close to room temperature. Finally, hydrogen can be strongly bound within molecular structures, as chemical compounds containing hydrogen atoms (c).



From DOE


Current Cost Estimates
(Based on 500,000 units)
700 bar
350 bar
Liquid H2
Complex Hydride
Chemical Hydride
$0
$5
$10
$15
$20
2015 target
2010 target
$/kWh
2015 targets
2010 targets
liquid hydrogen
chemical hydride
cryocompressed
700 bar
350 bar
complex hydride
tanks ("Learning Demo")*
volumetric capacity (g/L)
gravimetric capacity (wt.%)
0
20
40
60
80
100
0
2
4
6
8
10

Hydrogen Economy

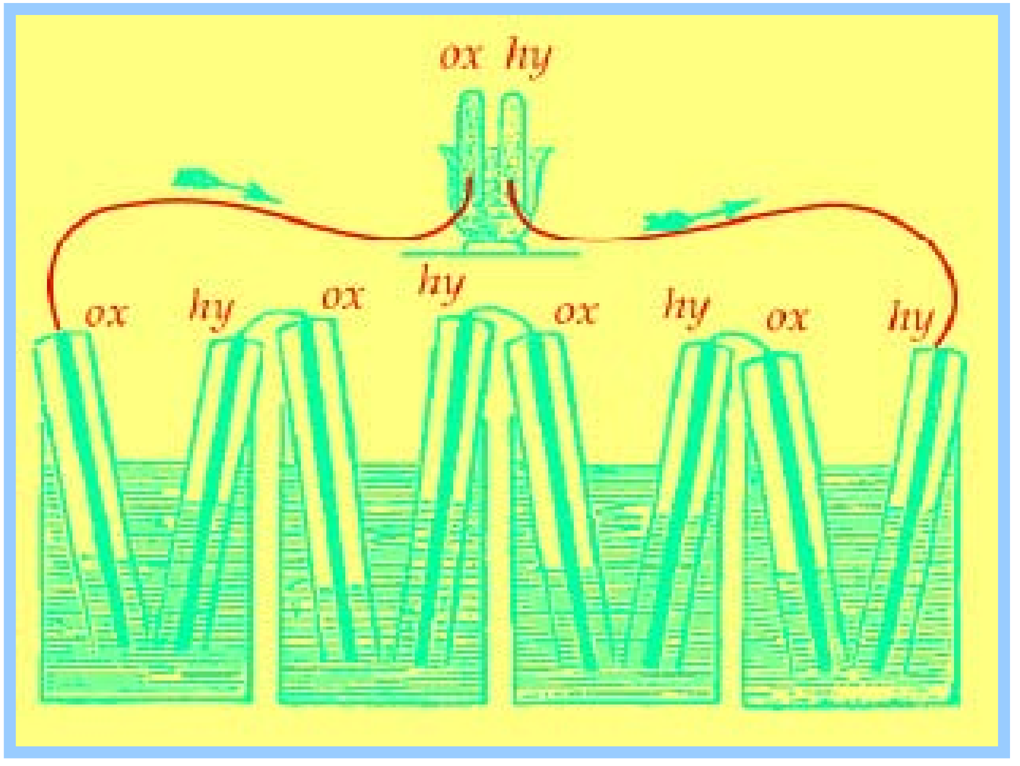


from H_2FC

Fuel Cells

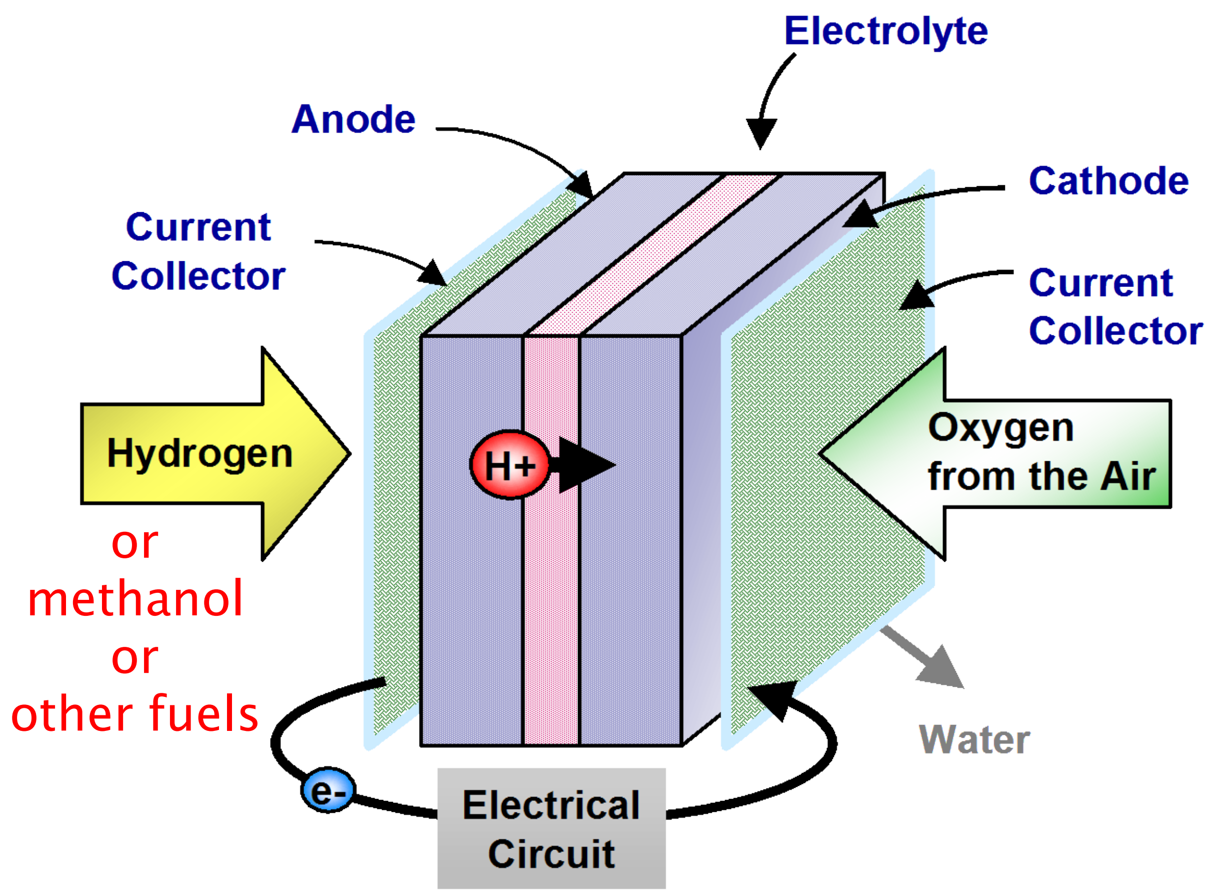
Brief History

- 1839 Discovery of fuel cell, William Grove
- 1960s Success as power during space flight, NASA
- 1984 Transportation technologies, U.S. Depart. of Energy
- 2000s Portable power sources, Electric company



Fuel Cells

an electrochemical cell which can continuously convert the chemical energy of a fuel and an oxidant to electrical energy



H_2-O_2 Fuel Cell reaction

-In <u>acidic electrolyte</u>

anode: $H_2 \rightarrow 2H^+ + 2e^-$ $E_0 = 0.000$ V
cathode: $1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$ $E_0 = 1.229$ V
Total: $H_2 + 1/2O_2 \rightarrow H_2O$ $E_0 = 1.229$ V

-In <u>alkaline electrolyte</u>

anode: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ $E_0 = -0.828$ V
cathode: $1/2O_2 + H_2O + 2e^- \rightarrow 2OH^-$ $E_0 = 0.401$ V
Total: $H_2 + 1/2O_2 \rightarrow H_2O$ $E_0 = 1.229$ V

수소-산소 반응의 열역학 및 Kinetics

- Thermodynamics

$$\Delta G = \Delta H - T\Delta S, \quad \Delta G^0 = -RTlnK$$

K; equilibrium constant, $\Delta G < 0 \rightarrow$ a reaction can occur

$$\Delta G = -nFE$$

- Kinetics

- overvoltage or polarization: activation, ohmic, concentration

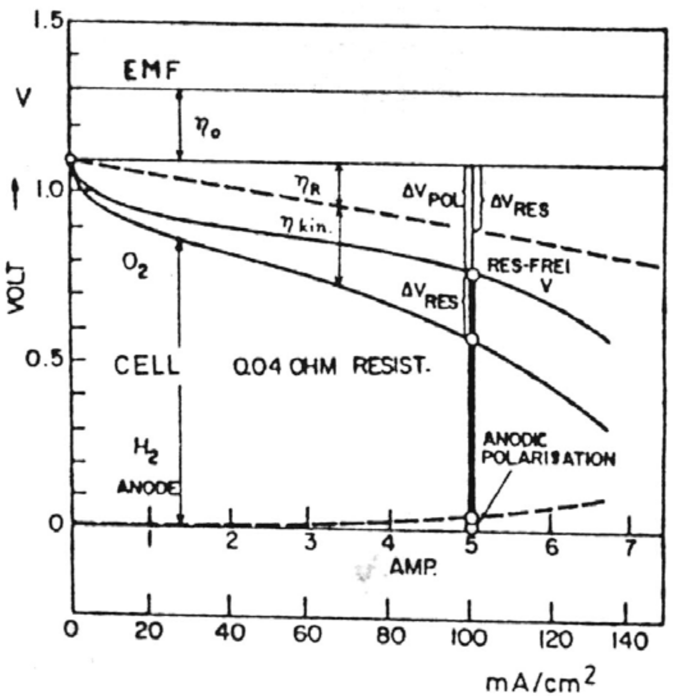
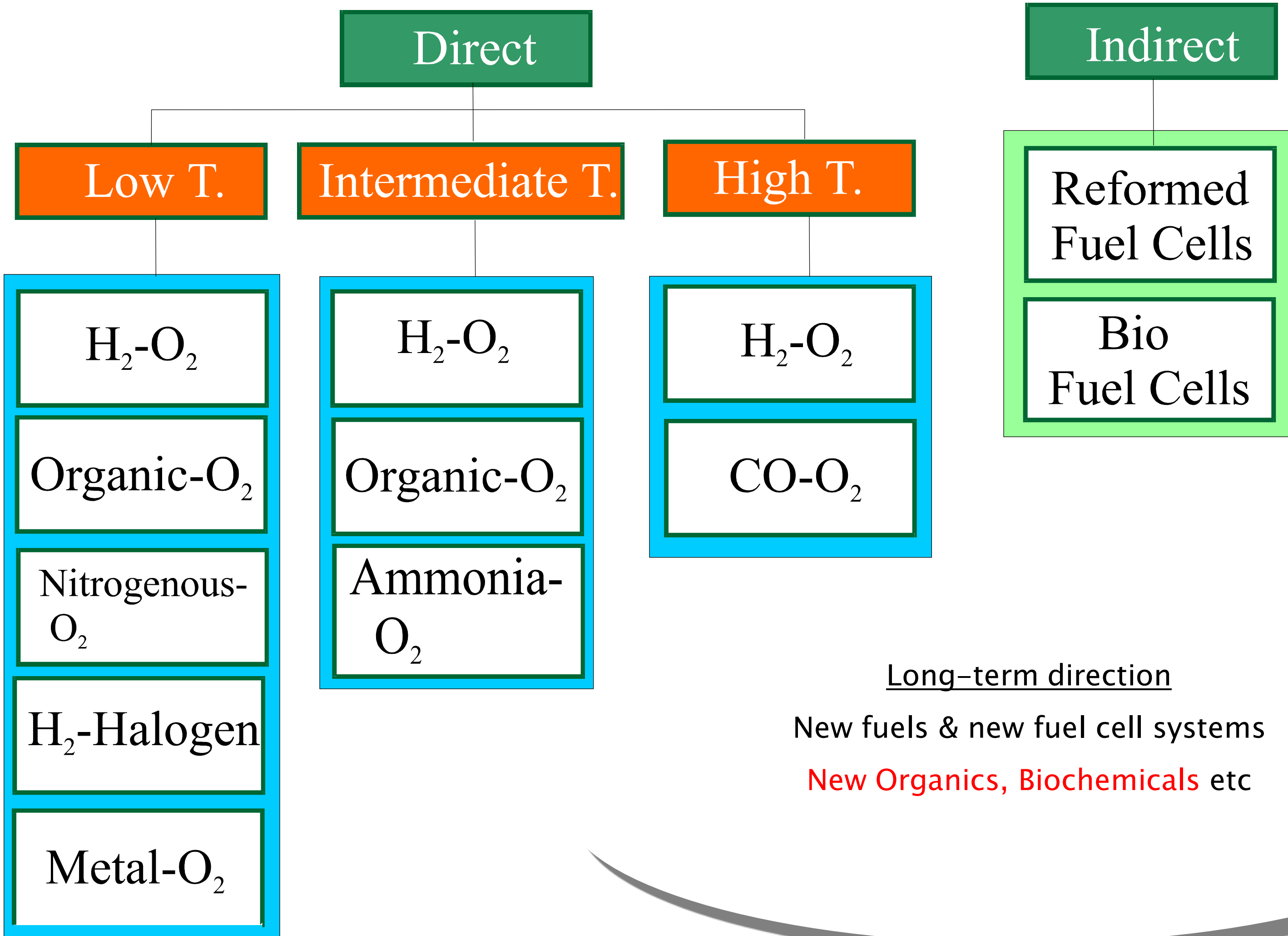


Figure 3-1. Polarization curves of a H_2-O_2 cell illustrating the components of the cell voltage [4].

Fuel Cells



<u>Long-term direction</u>

New fuels & new fuel cell systems

New Organics, Biochemicals etc

Fuel cell efficiency

- thermodynamic efficiency

$$\eta_{th} = \Delta G/\Delta H = 1 - T\Delta S/\Delta H$$

- typically ~90% ($H_2 + 1/2O_2 \rightarrow H_2O$, 83%) to over 100% if the entropy of the products is greater than the entropy of the reactants ($C + 1/2O_2 \rightarrow CO$, 124%)

- effect of T; $\Delta H<0$, $\Delta S<0$ (gas $\rightarrow$liq) $\rightarrow$ thermodynamic efficiency $\downarrow$ as T$\uparrow$
cf) high temp; no expensive electrocatalysts needed

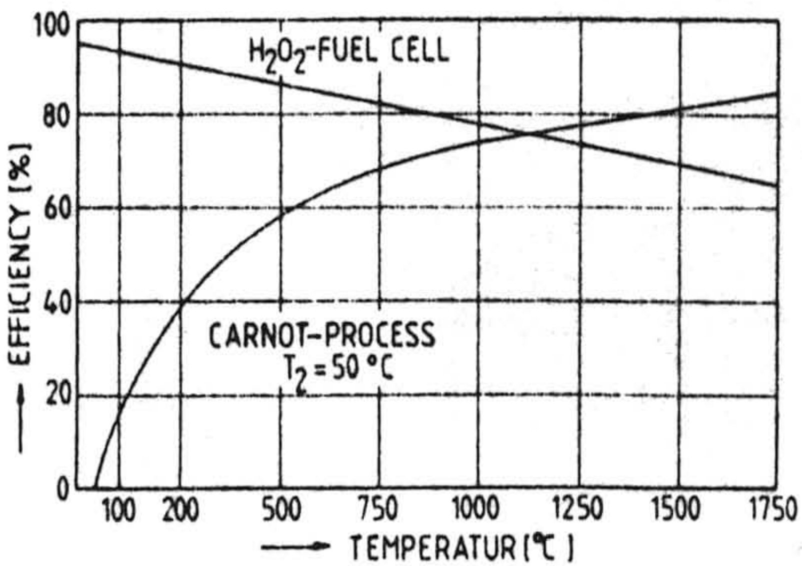


Figure 3-13. Comparison between the Carnot and the Thermodynamic Efficiency of a Fuel Cell

Table 3-1. Thermodynamic Data for some Candidate Fuel-Cell Reactions Under Standard Conditions at 25 °C.

Fuel	Reaction	n	$-\Delta H^0$ [kJ/mol]	$-\Delta G^0$ [kJ/mol]	E^0 rev. [V]	%
Hydrogen	$H_2 + 0.5\ O_2 \longrightarrow H_2O_{(l)}$	2	286.0	237.3	1.229	83.0
	$H_2 + Cl_2 \longrightarrow 2\ HCl_{(aq)}$	2	335.5	262.5	1.359	78.3
	$H_2 + Br_2 \longrightarrow 2\ HBr$	2	242.0	205.7	1.066	85.0
Methane	$CH_4 + 2\ O_2 \longrightarrow CO_2 + 2\ H_2O_{(l)}$	8	890.8	818.4	1.060	91.9
Propane	$C_3H_8 + 5\ O_2 \longrightarrow 3\ CO_2 + 4\ H_2O_{(l)}$	20	2221.1	2109.9	1.093	95.0
Decane	$C_{10}H_{22} + 15.5\ O_2 \longrightarrow 10\ CO_2 + 11\ H_2O_{(l)}$	66	6832.9	6590.5	1.102	96.5
Carbon monoxide	$CO + 1.5\ O_2 \longrightarrow CO_2$	2	283.1	257.2	1.066	90.9
Carbon	$C + 0.5\ O_2 \longrightarrow CO$	2	110.6	137.3	0.712	124.2
	$C + O_2 \longrightarrow CO_2$	4	393.7	394.6	1.020	100.2
Methanol	$CH_3OH + 1.5\ O_2 \longrightarrow CO_2 + 2\ H_2O_{(l)}$	6	726.6	702.5	1.214	96.7
Formaldehyde	$CH_2O_{(g)} + O_2 \longrightarrow CO_2 + 2\ H_2O_{(l)}$	4	561.3	522.0	1.350	93.0
Formic-acid	$HCOOH + 0.5\ O_2 \longrightarrow CO_2 + H_2O_{(l)}$	2	270.3	285.5	1.480	105.6
Ammonia	$NH_3 + 0.75\ O_2 \longrightarrow 0.5\ N_2 + 1.5\ H_2O$	3	382.8	338.2	1.170	88.4
Hydrazine	$N_2H_4 + O_2 \longrightarrow N_2 + 2\ H_2O_{(l)}$	4	622.4	602.4	1.560	96.8

- Practical efficiency

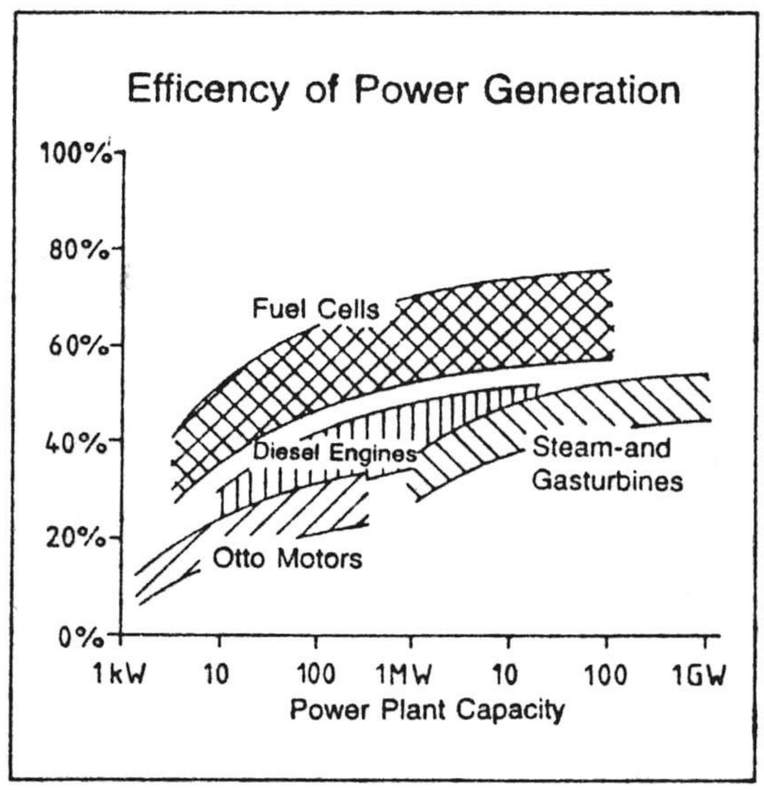
$$\eta_p = = -nFE_K/\Delta H$$

$E_K < E_0$: polarizations

- Faradaic efficiency

$$\eta_f = = I/I_m$$

- Total efficiency



Fuel cell Systems

- classifications; T, P, fuels, electrolytes
- H_2-O_2 fuel cell types

Fuel Cell System	Temperature (C)	Efficiency (cell)	Electrolyte	Anode	Cathode	Charge carrier	Fuel
Alkaline Fuel Cell (AFC)	60-90	50-60 %	35-50% KOH	Pt base	Pt base	H^+	수소
Phosphoric Acid Fuel Cell (PAFC)	160-220	55 %	Phosphoric acid	Pt base	Pt base	H^+	수소
Molten Carbonate Fuel Cell MCFC)	620-660	60-65 %	Molten Salts	Ni	NiO	CO_3^{2-}	수소
Solid Oxide Fuel Cell (SOFC)	700-1000	55-65 %	Ceramic	ZrO_2	Perovskite	O^{2-}	수소
Polymer Electrolyte Fuel Cell (PEMFC)	50-80	50-60 %	Polymer Membrane	Pt base	Pt base	H^+	수소
Direct Methanol Fuel Cell (DMFC)	2 -80	50-60 %	Ion Exchane Membrane	Pt base	Pt base	H^+	메탄올

연료전지 제품 종류

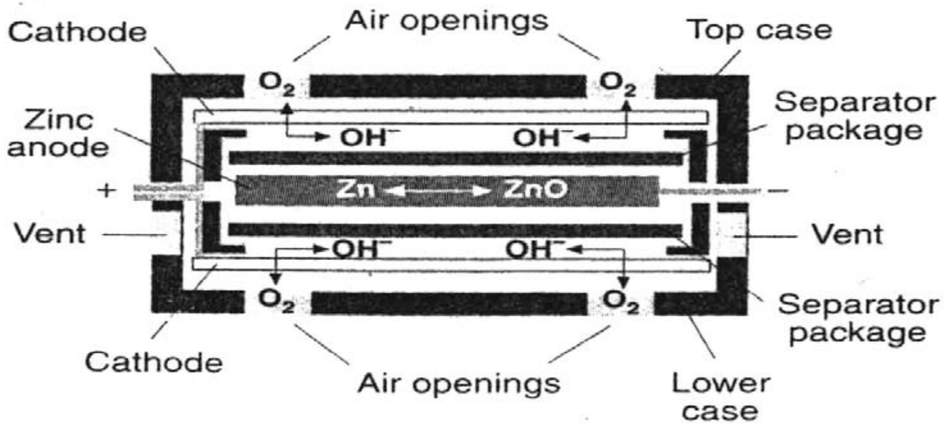
구분	제품종류 (용량)	연료전지					비고
		PAFC	MCFC	SOFC	PEMFC	DMFC	
대형 발전	지역분산 및 집중 발전 (수십MW 이상)	○	●	●	○	○	
분산 발전	산업용 (수백kW~수십MW)	○	●	●	●	○	
	상업용 (수kW~수백kW)	●	●	●	●	○	
	주거용 (수백W~수kW)	○	○	●	●	○	
수송용	주동력용 (선박용)	○	●	●	●	○	
	주동력용 (승용, 버스)	○	○	●	●	○	
	보조전원용 (수MW~수십MW)	○	●	●	●	○	
	보조전원용 (수kW~수백kW)	○	○	●	●	○	
휴대용	이동전원 (수백W~수kW)	○	○	●	●	●	
	노트북용 (20~수백W)	○	○	○	●	●	
	휴대기기 (5~10W)	○	○	○	○	●	

● : 적용 중 ◑ : 고려 중 ○ : 가능성 적음

Hybrid cells

- intermediate between the galvanic cells & fuel cells; advantage of both battery & fuel cells
- metal-air batteries

Zinc-air cells draw O_2 from air to fuel electrochemical reaction



Cathode: $\frac{1}{2} O_2 + H_2O + 2e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2\,OH^-$

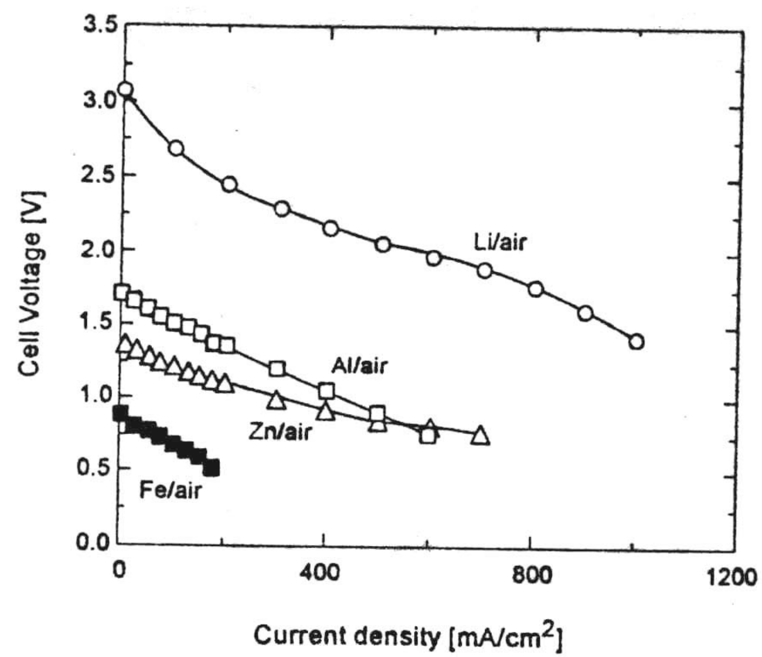
Anode: $Zn + 2\,OH^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} ZnO + H_2O + 2e^-$

Part battery and part fuel cell, a rechargeable Zn-air cell's cathode catalytically converts ambient O_2 to OH^- during discharge while a zinc anode is converted to ZnO. When recharging, the reverse reaction occurs.

Table 4-16. Comparison of Metal/Air Batteries

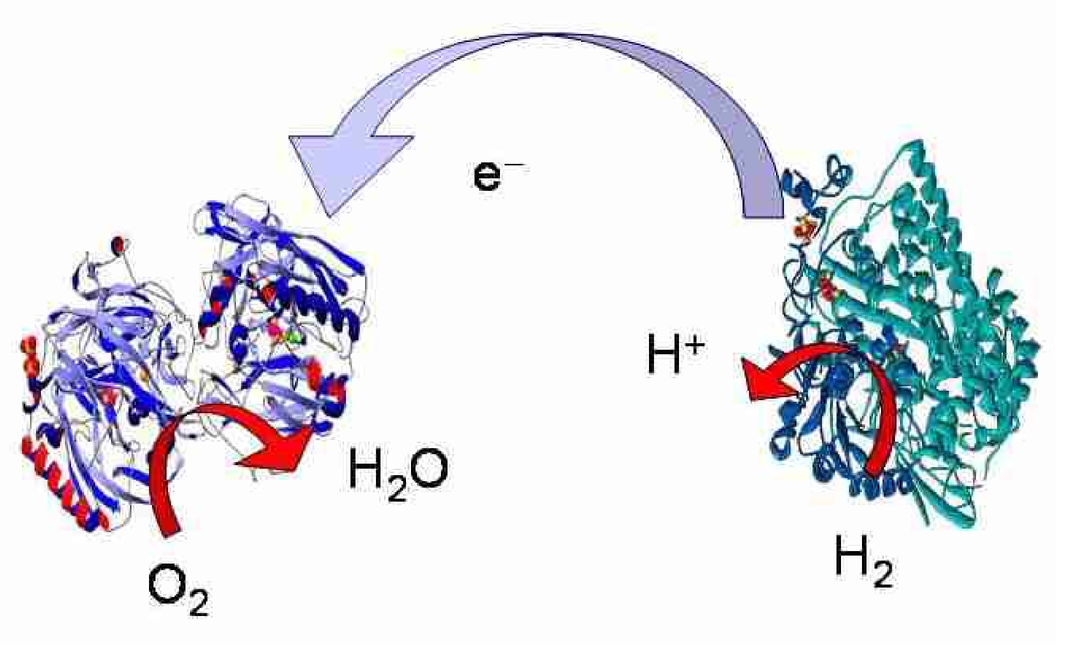
Metal Anode	Electrochemical Equivalent of Metal [Ah/g]	Theoretical Cell Voltage* [V]	Valence Change	Theoretical Specific Energy (of Metals) [Wh/g]	Practical Operating Voltage [V]
Li	3.86	3.4	1	13	2.4
Ca	1.34	3.4	2	4.6	2.0
Mg	2.20	3.1	2	6.8	1.4
Al	2.98	2.7	3	8.1	1.6
Zn	0.82	1.6	2	1.3	1.2
Fe**	0.96	1.3	2	1.2	1.0

* Cell voltage with oxygen cathode
** Fe^{2+} (1.8 Wh/g for Fe^{3+})



Bio-fuel Cell

"An electro-chemical device in which energy derived from chemical reactions maintained by a continuous supply of chemical reactants is converted to electrical energy by means of the catalytic activity of **living cells and/or their enzymes**."



전극: enzyme, bacteria…