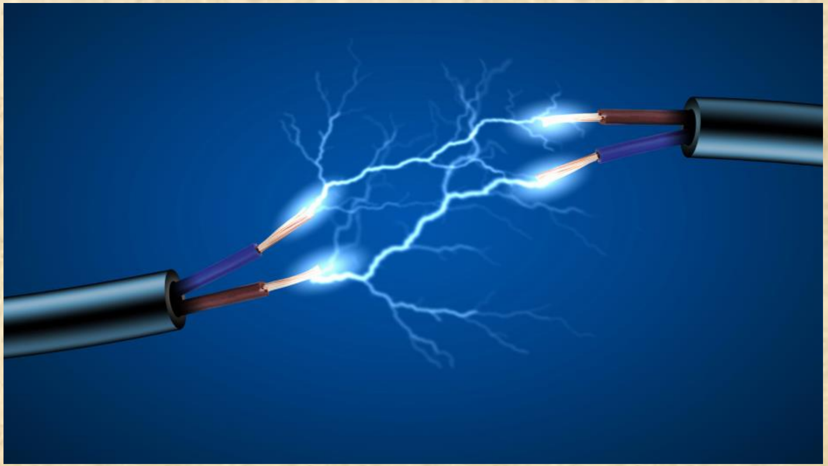
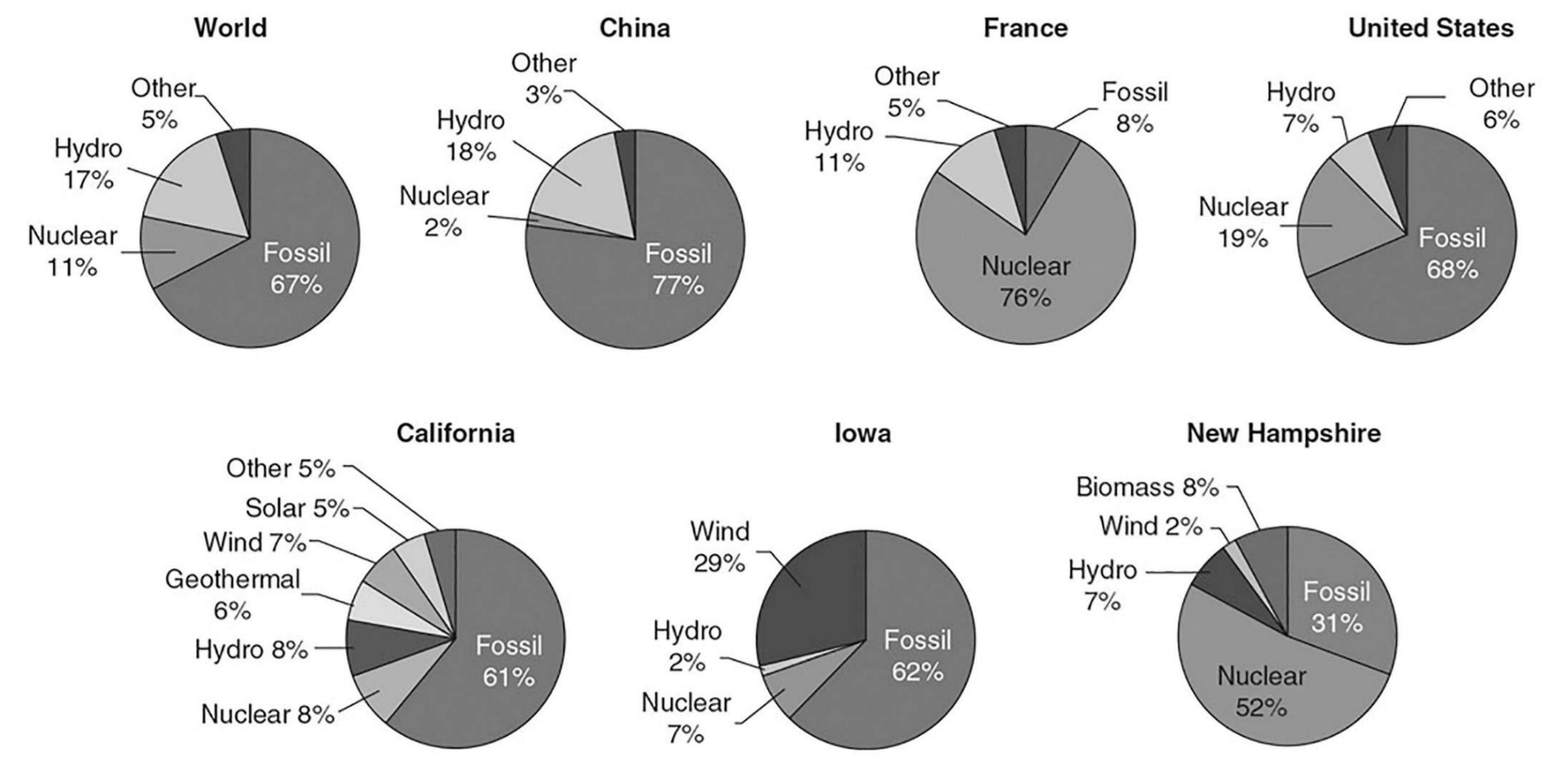
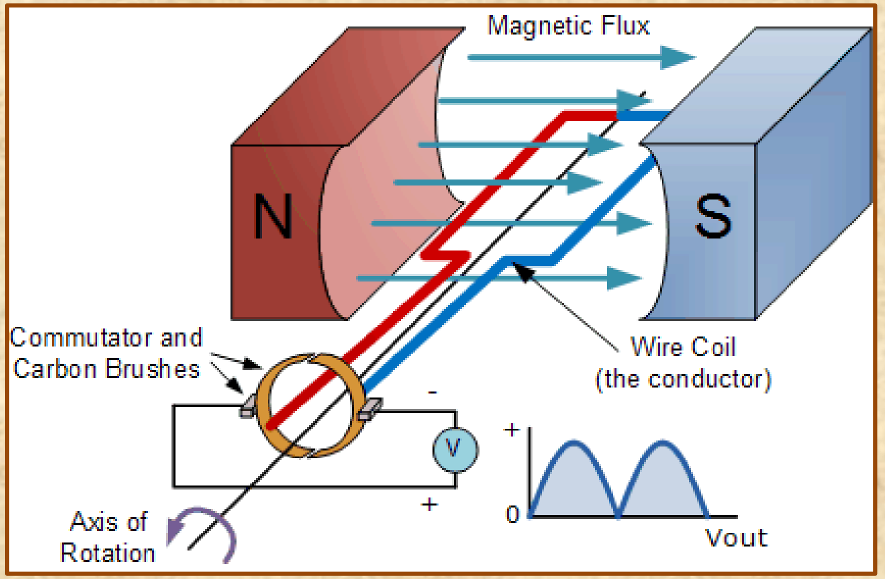
Electrical Energy Generation, Transmission, and Storage



Sources of Energy for Electric Power



Electricity generators and motors



Wire moving in a magnetic field has a restraining force F = IBL.

- I = current (ampere)
- B = magnetic field strength (tesla)
- L = length of wire (meter)

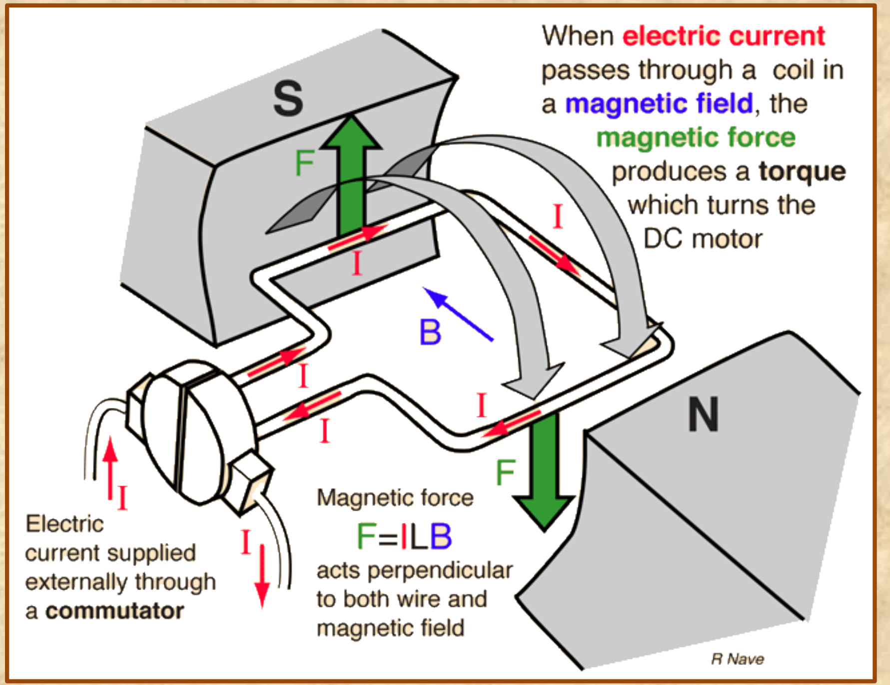
Also, wire moving at velocity (V) experiences an electric field (E) in the opposite direction.
E = VB where E is in volts/meter

Combining these equations yields
P = FV = IBLV = IEL (P is in J/s)

The bottom line re the calculations in the lower left is that mechanical power input (FV) for an ideal generator is equal to the electrical power output (IEL).

If we reverse the process, i.e. electrical power in = mechanical power out we have an electric motor.

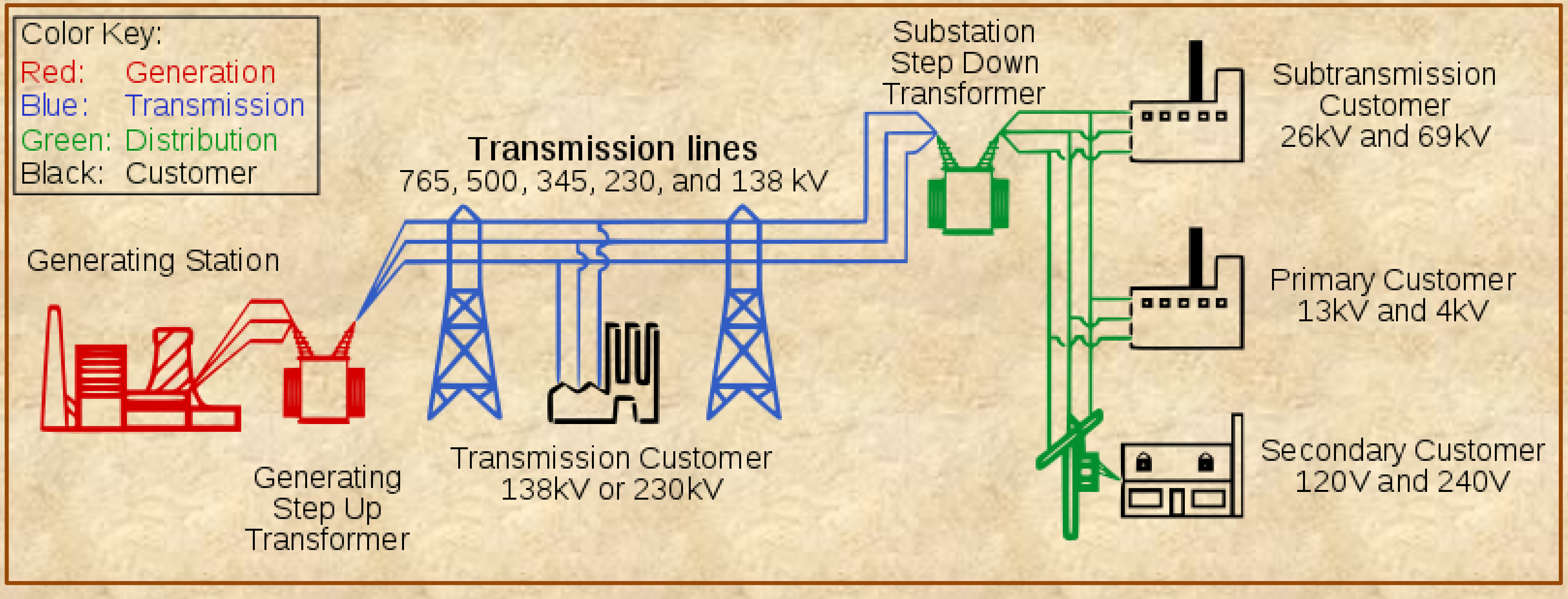
By changing the wiring we can produce (use) either AC or DC current.



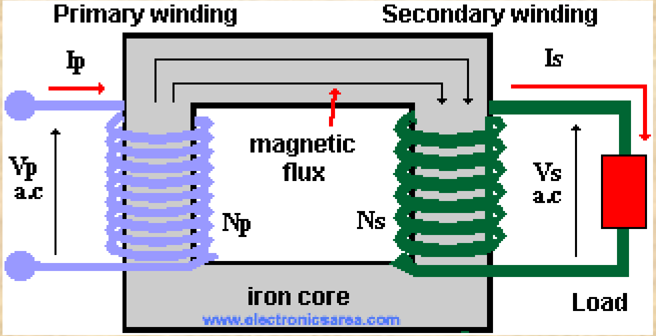
When **electric current** passes through a coil in a **magnetic field**, the **magnetic force** produces a **torque** which turns the DC motor

Electric current supplied externally through a **commutator**

Magnetic force
F=ILB
acts perpendicular to both wire and magnetic field



Transformers



$$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s}$$

N = number of windings on coil

Power (W) = Voltage (V) x Current (I) = J/s

Power Loss = I^2R

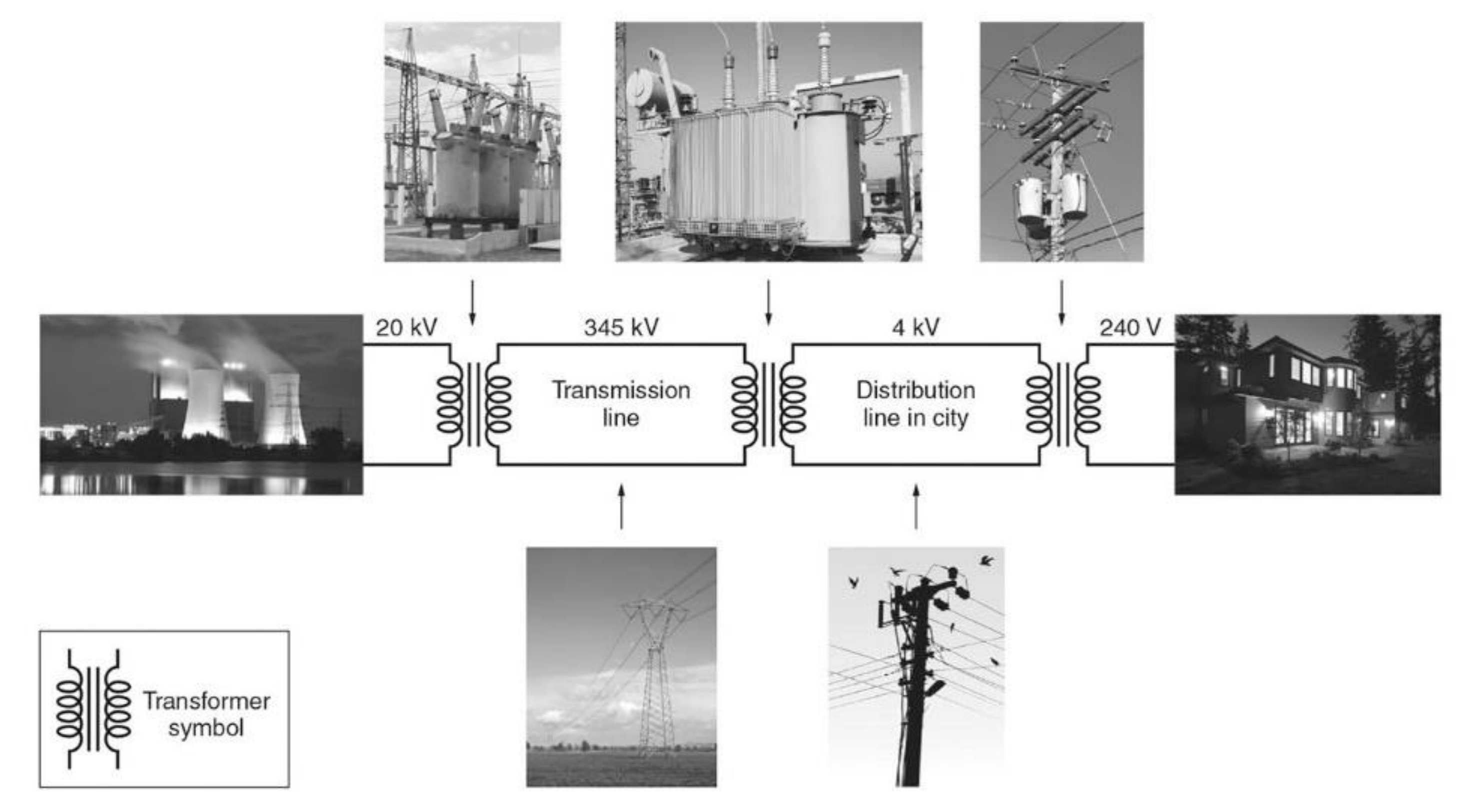
R = Resistance in ohms
I = current in amps
V = voltage in volts

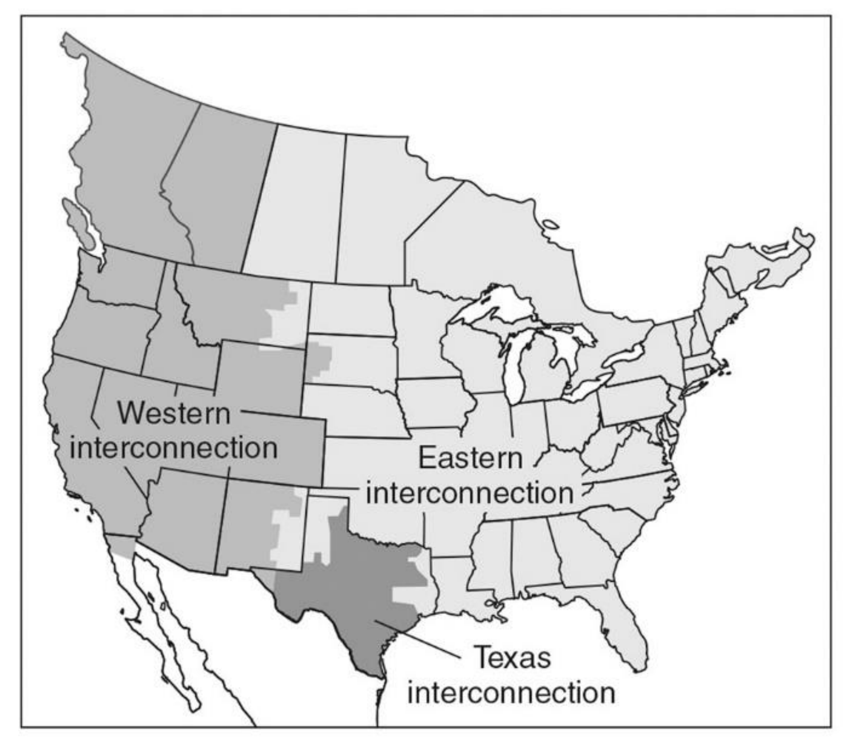
R = resistivity x length/cross sectional area of wire

For Al resistivity = 2.65E-8 ohm·m

For a 500 kV 25mm diameter Al wire transmitting electricity over 500 km –
R = (2.65E-8)(500)(1000)/(4.9E-4) = 27 ohm

For a transmission line carrying 1000 MW the loss is 10.8%

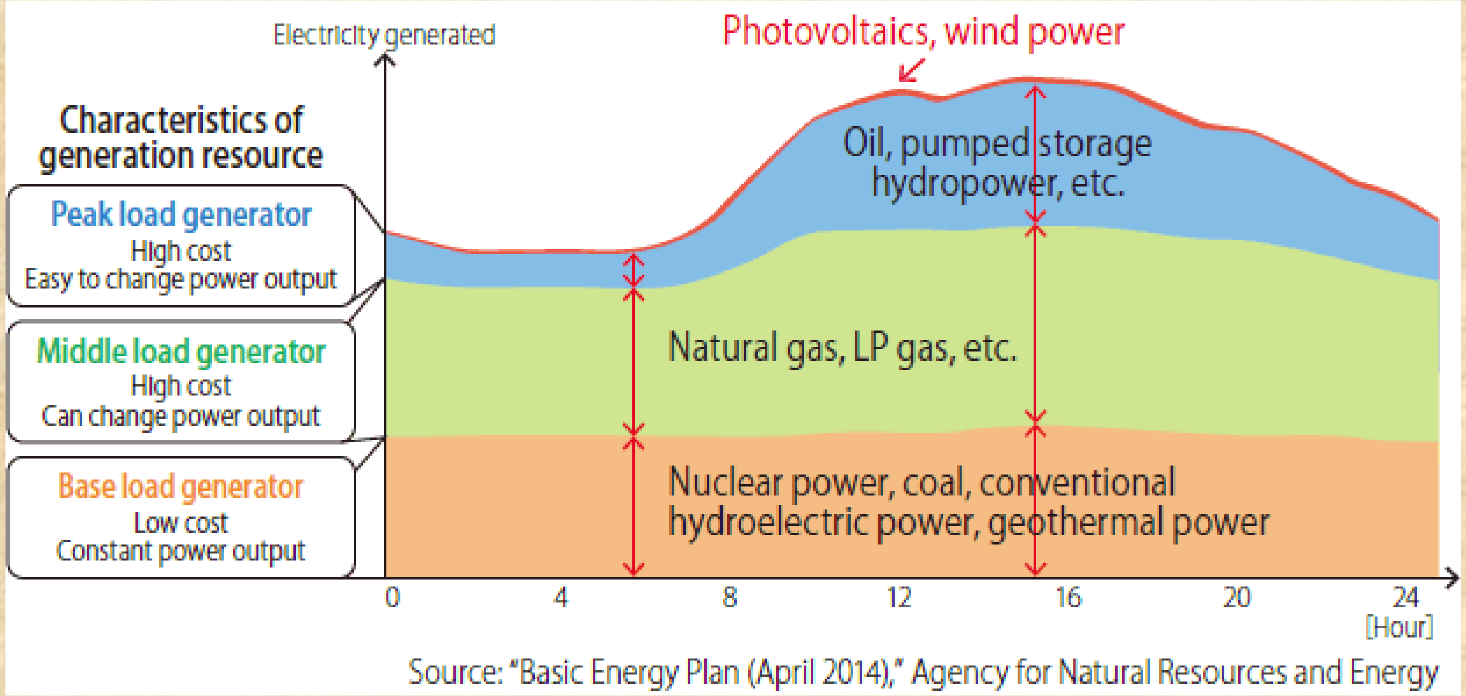




Left: Typical transmission pathway. Ignores three wire system used in NA for AC current

Right: Interconnected grids. There are 3 for the US. Increase reliability. For each grid the AC current must be synchronized. In order to send energy between grids DC is used. Current is synchronized when its converted back to AC. Some renewable energy sources, for example solar cells, generate DC which must be converted to AC before it is added to the grid.

Diurnal variations in electricity demand



Source: "Basic Energy Plan (April 2014)," Agency for Natural Resources and Energy

Base load – daily minimum electricity demand. Supplied by conventional power plants (coal-fired and nuclear power) and renewables such as hydro. For maximum efficiency the output from these plants is maintained at a constant level.

Middle and peak loads – additional electricity to meet immediate demands. Require systems that are easily brought on and off line.

The requirement to purchase electricity from nonconventional sources places a stress on electricity management.

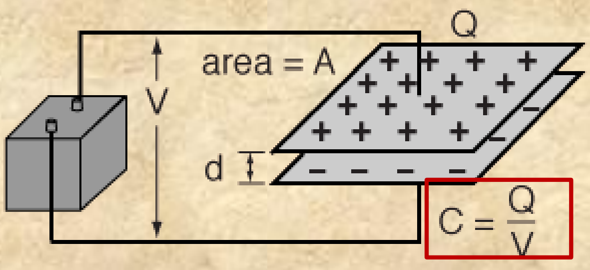
How do utilities manage the variations in supply and demand for electricity?


P-66
PDCI
COI
Path 26
Path 15
10:40:39
-0.880
60.029
27430

How do we store energy to meet peak demands

- Electrostatic energy storage using a capacitor
- Magnetic energy storage
- Electrochemical energy storage, i.e. batteries (lead-acid and lithium-ion)
- Mechanical energy storage (pumped hydropower and flywheel)

Type	Energy/volume (J/m^3)	Energy/mass (J/kg)	Cost ($/MJ)	Efficiency (%)
Capacitor	4E7	4E4		95
Inductor	1E7	2E3	50	95
Pb-acid battery	3E7	2E5	15	75
Pumped hydro	1E3	1	25	70
Flywheel	2E8	2E5		80

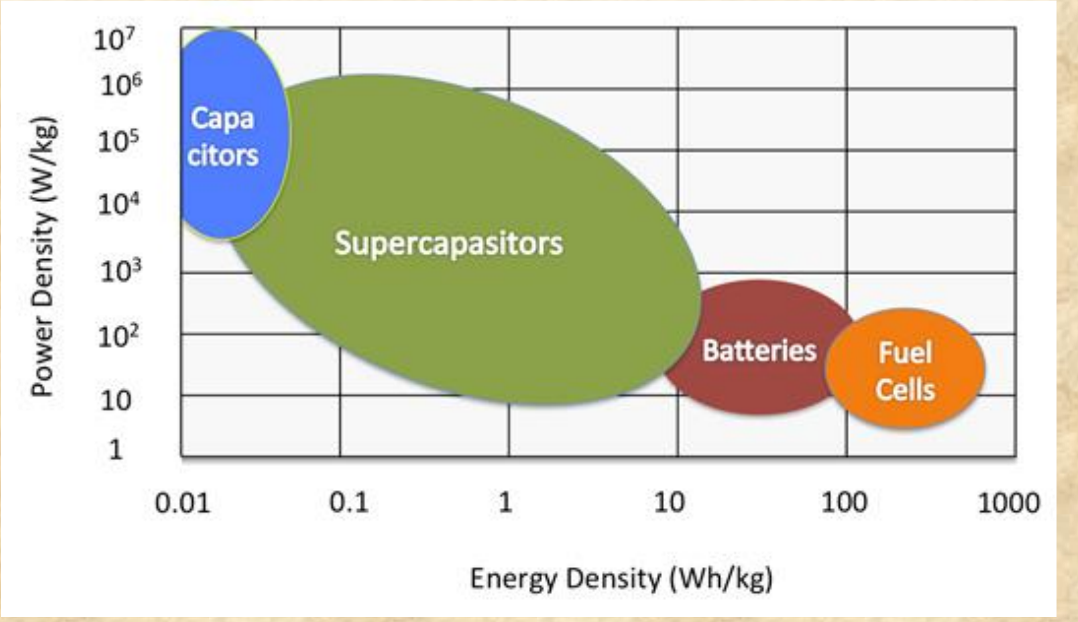


$$C = \frac{\varepsilon_o A}{d}$$

C= capacitance (farads)
ε_o = permitivity of dielectric
A = area of plates
d = distance between plates

Q = CV = charge in coulombs

Storage capacity for various types of storage devices



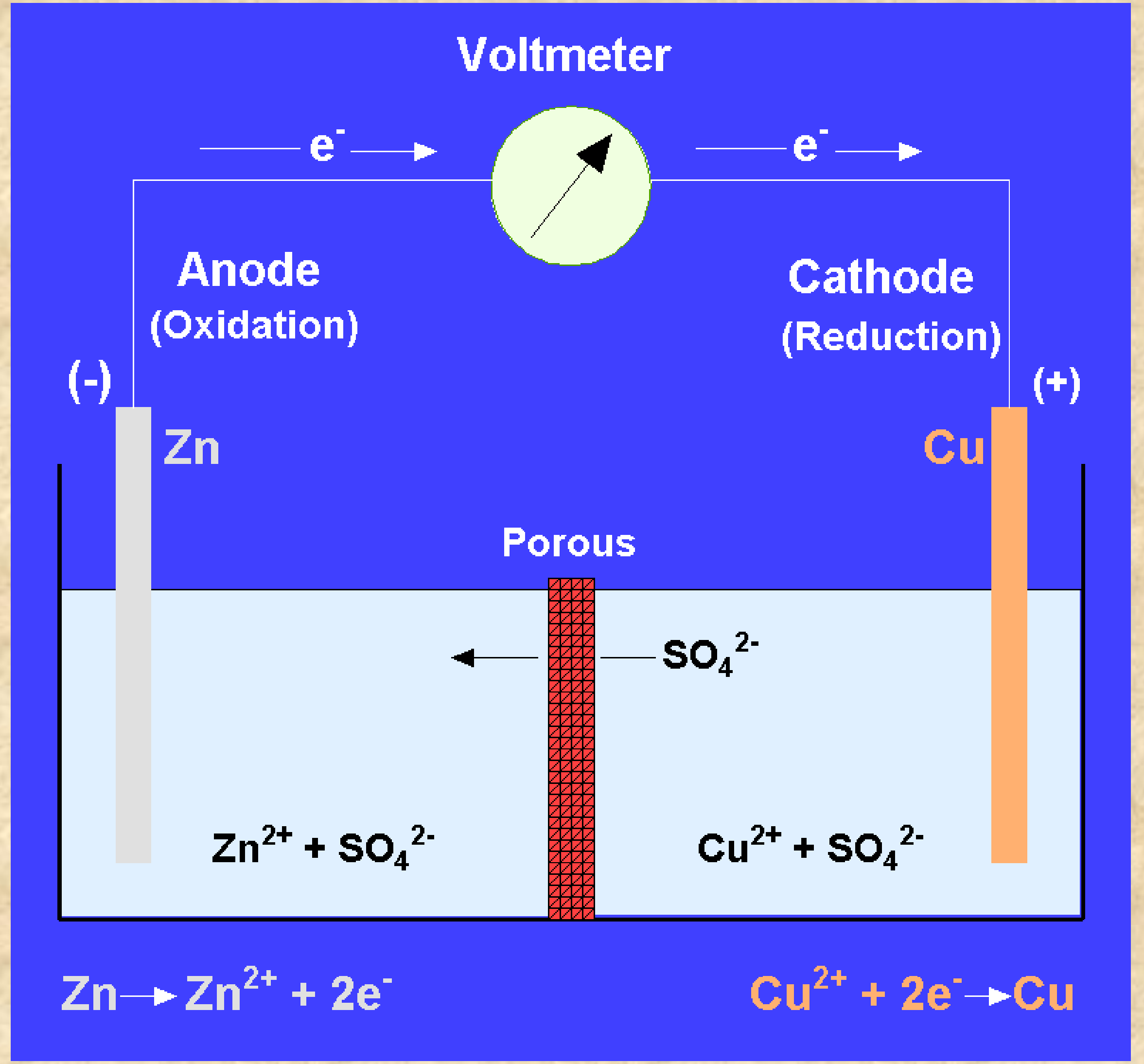
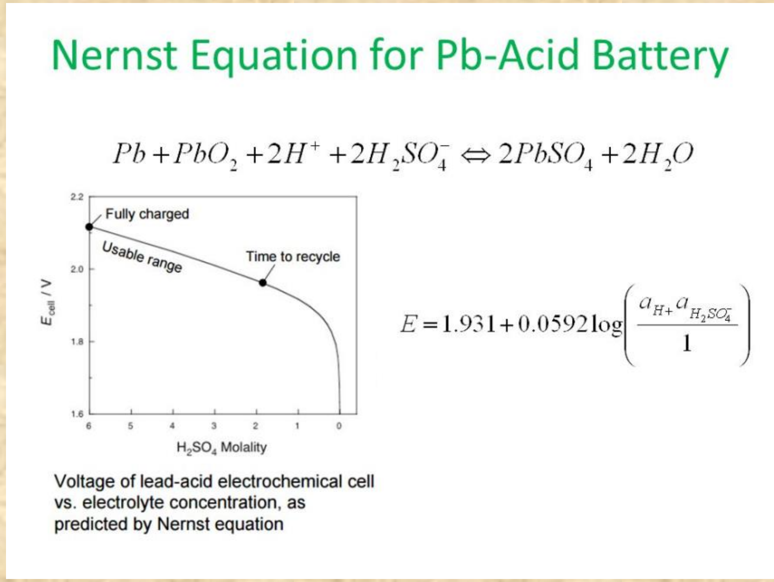


Diagram of a Zn-Cu electrochemical cell. Zn and Cu metal electrodes are immersed in a $CuSO_4$ solution. Electrons flow from left to right and a potential is recorded by the voltmeter. With time, this potential decreases to zero, the concentration of Zn^{2+} increases in the left-hand half of the cell, and the concentration of Cu^{2+} decreases in the right-hand half of the cell.

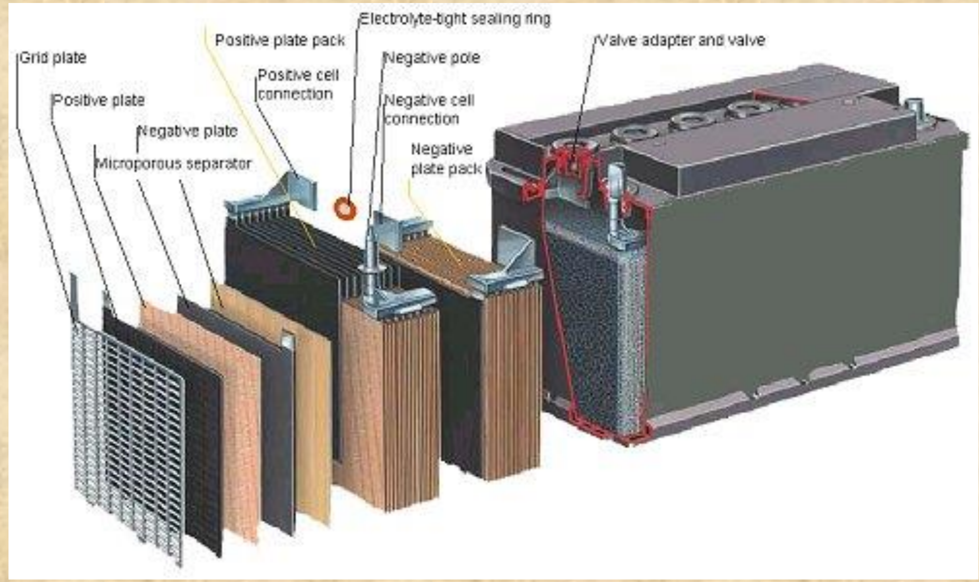


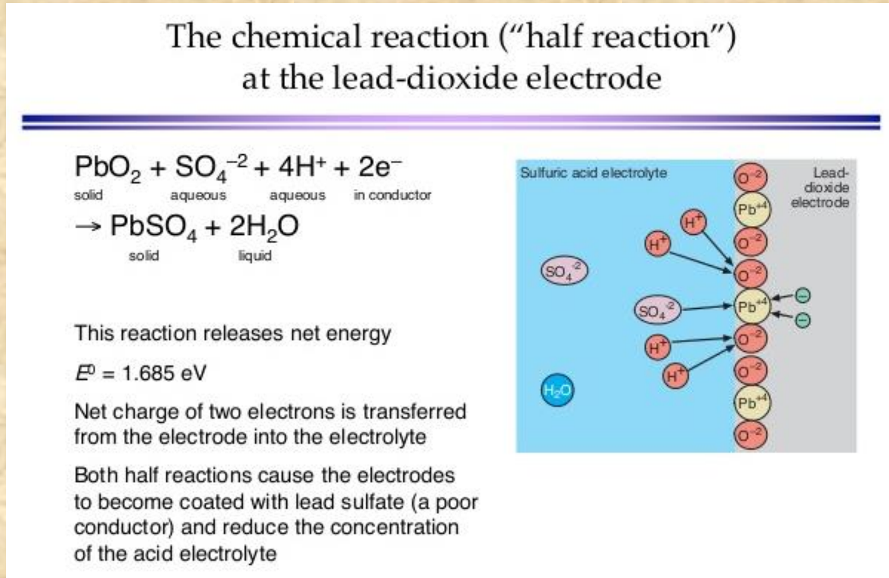
Nernst Equation for Pb-Acid Battery

$$Pb + PbO_2 + 2H^+ + 2H_2SO_4^- \Leftrightarrow 2PbSO_4 + 2H_2O$$

$$E = 1.931 + 0.0592\log\left(\frac{a_{H+}a_{H_2SO_4^-}}{1}\right)$$

Voltage of lead-acid electrochemical cell vs. electrolyte concentration, as predicted by Nernst equation





The chemical reaction ("half reaction") at the lead-dioxide electrode

$PbO_2 + SO_4^{-2} + 4H^+ + 2e^-$ (solid, aqueous, aqueous, in conductor)

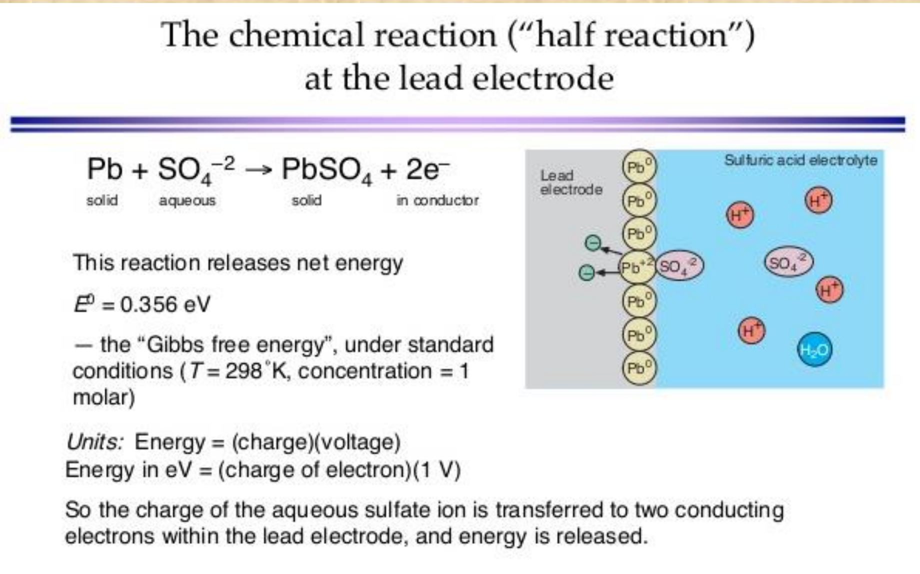
$\rightarrow PbSO_4 + 2H_2O$ (solid, liquid)

This reaction releases net energy

E^0 = 1.685 eV

Net charge of two electrons is transferred from the electrode into the electrolyte

Both half reactions cause the electrodes to become coated with lead sulfate (a poor conductor) and reduce the concentration of the acid electrolyte



The chemical reaction ("half reaction") at the lead electrode

$Pb + SO_4^{-2} \rightarrow PbSO_4 + 2e^-$ (solid, aqueous, solid, in conductor)

This reaction releases net energy

E^0 = 0.356 eV

— the "Gibbs free energy", under standard conditions (T = 298°K, concentration = 1 molar)

Units: Energy = (charge)(voltage)
Energy in eV = (charge of electron)(1 V)

So the charge of the aqueous sulfate ion is transferred to two conducting electrons within the lead electrode, and energy is released.

Lithium ion storage battery

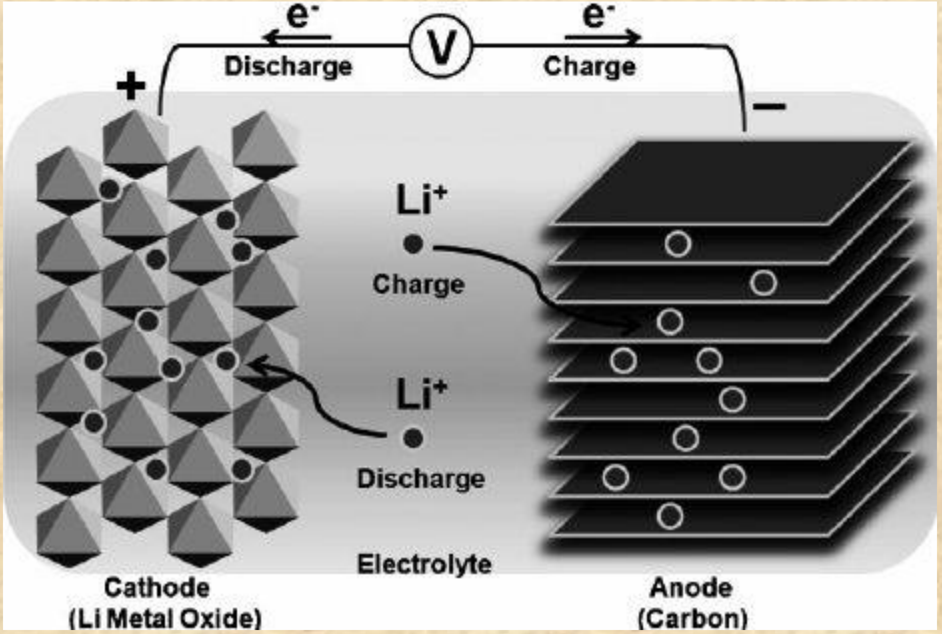
Half-cell reactions:

$LiCoO_2 \rightarrow Li^+ + e^- + CoO_2$

$Li^+ + e^- + 6C \rightarrow LiC_6$

Total reaction:

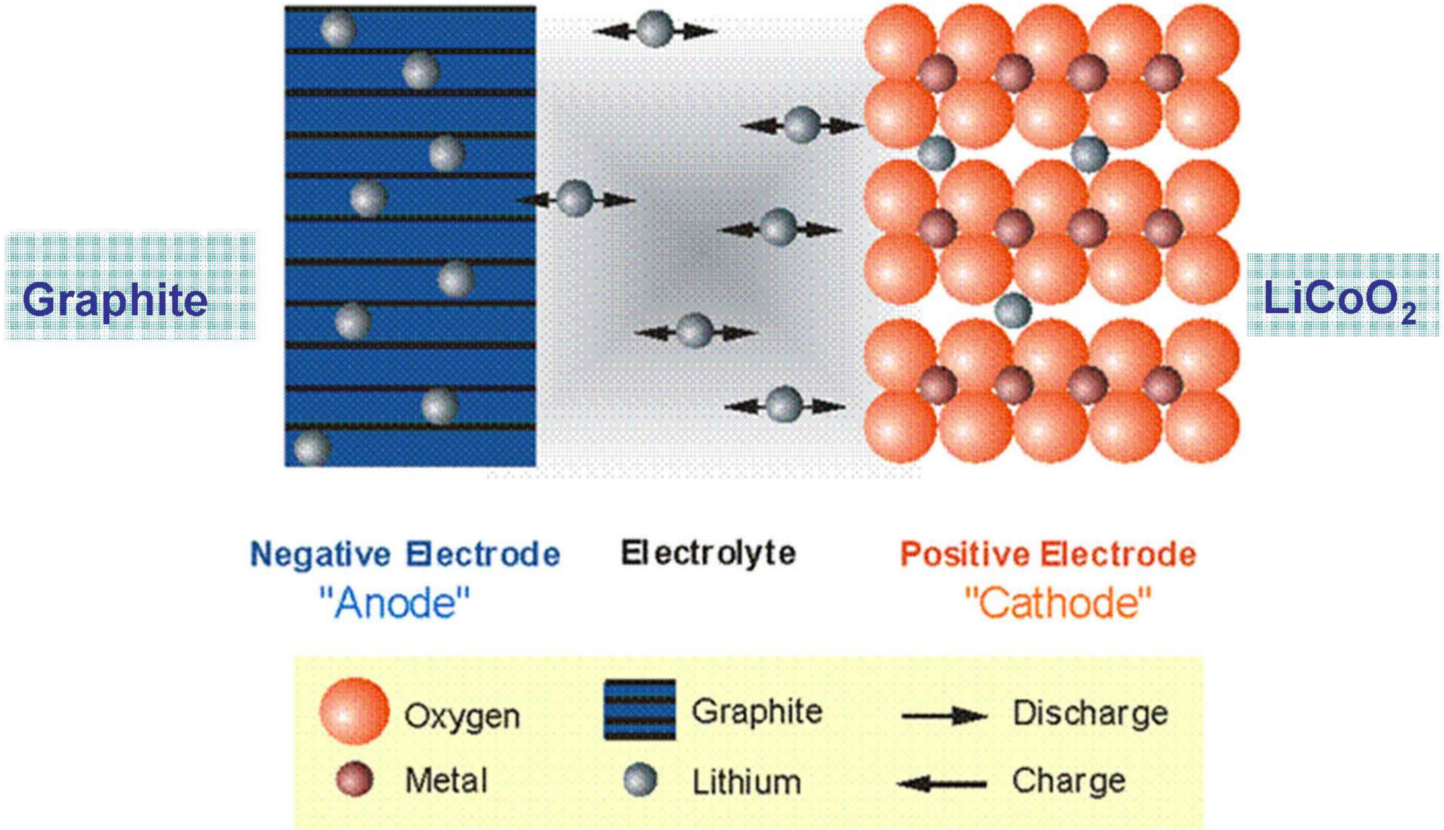
$LiCoO_2 + 6C \rightarrow CoO_2 + LiC_6$



Battery Type	Energy/mass (Wh/kg)	Peak power/mass (W/kg)	Cost ($/kWh)	Efficiency (%)
Lead-acid	40	250	130	80
Lithium-ion	150	250	200	85
Nickel-cadmium	50	110	300	75
Nickel-metal hydride	80	250	260	70
Sodium-sulfur	190	230	330	85

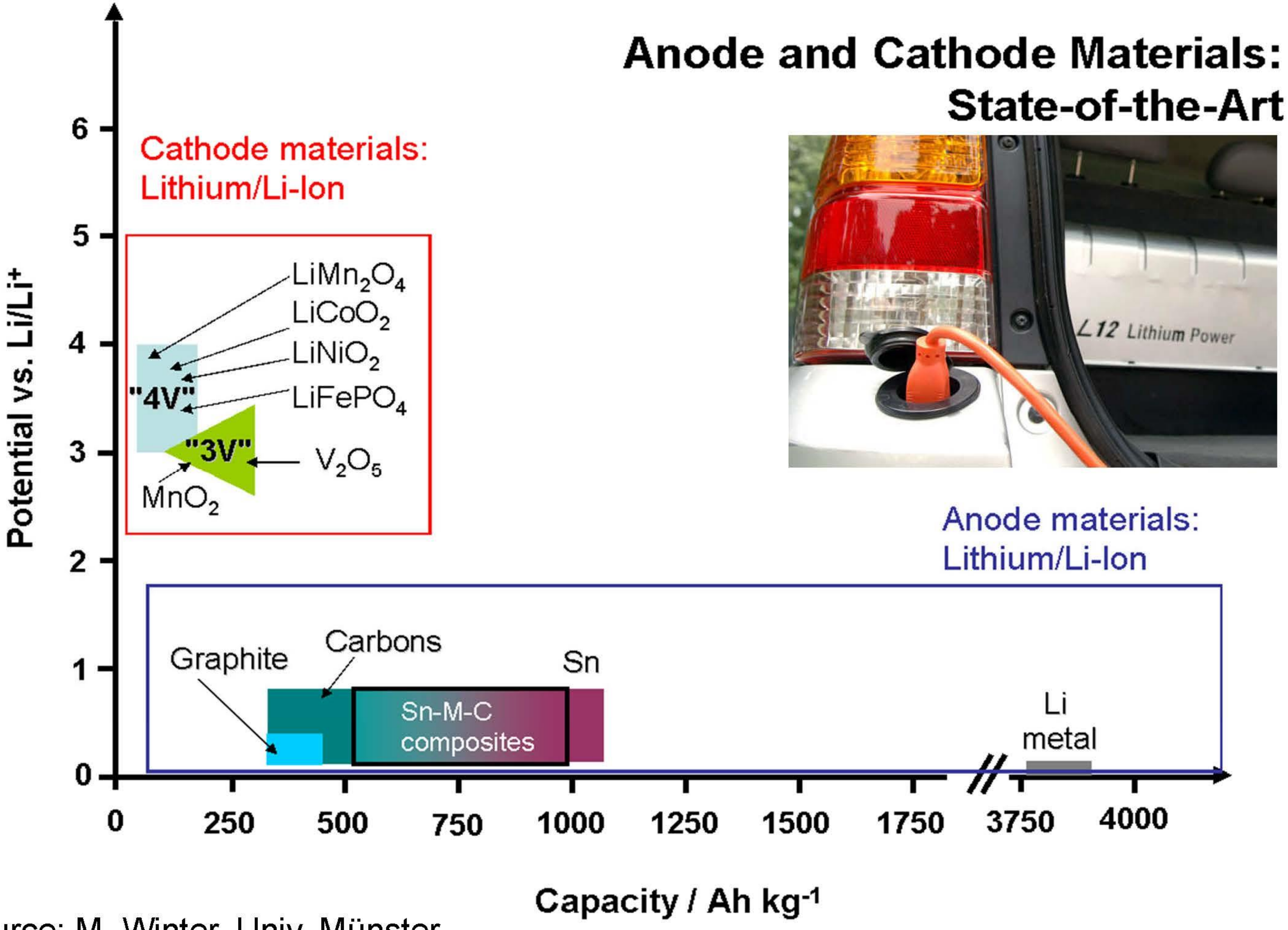
Lithium Ion Batteries – Operation

$Li_xC_n \underset{C}{\overset{D}{\rightleftharpoons}} C_n + xLi^+ + xe^-$ $Li_{1-x}MO_2 + xe^- + xLi^+ \underset{C}{\overset{D}{\rightleftharpoons}} LiMO_2$



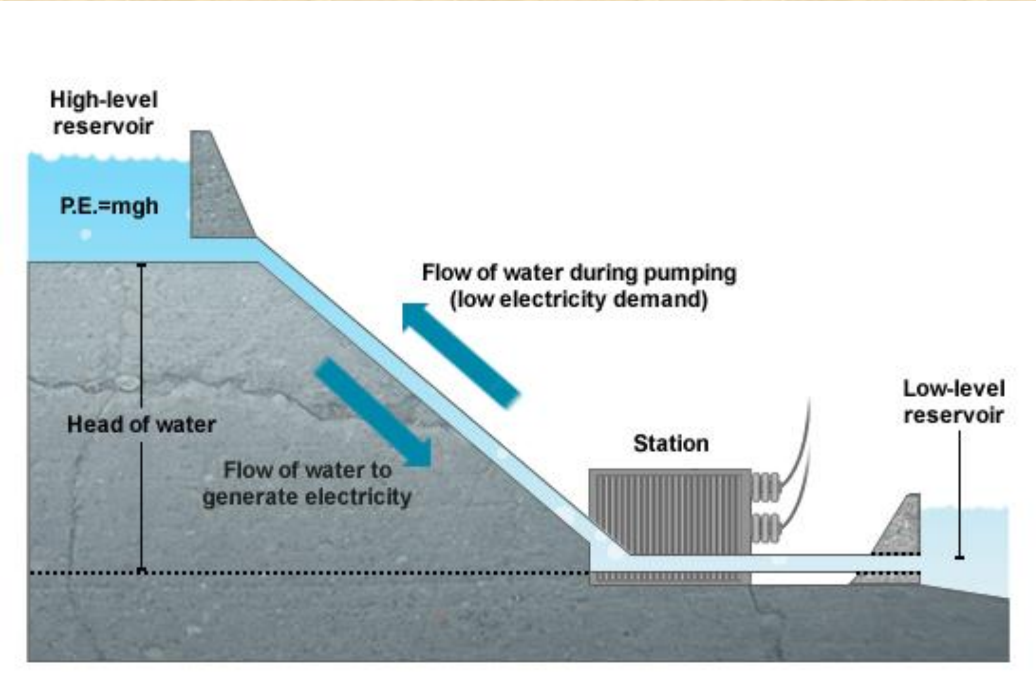
Presently: Anode: graphitic C; Electrolyte: $LiPF_6$ in organic carbonate solvents; Cathode: Co-based $LiMO_2$

Anode and Cathode Materials: State-of-the-Art



Source: M. Winter, Univ. Münster

Pumped Hydropower



P.E. = mass x acceleration of gravity x height

Energy/unit volume = gh/ρ

For an elevation difference of 50 m

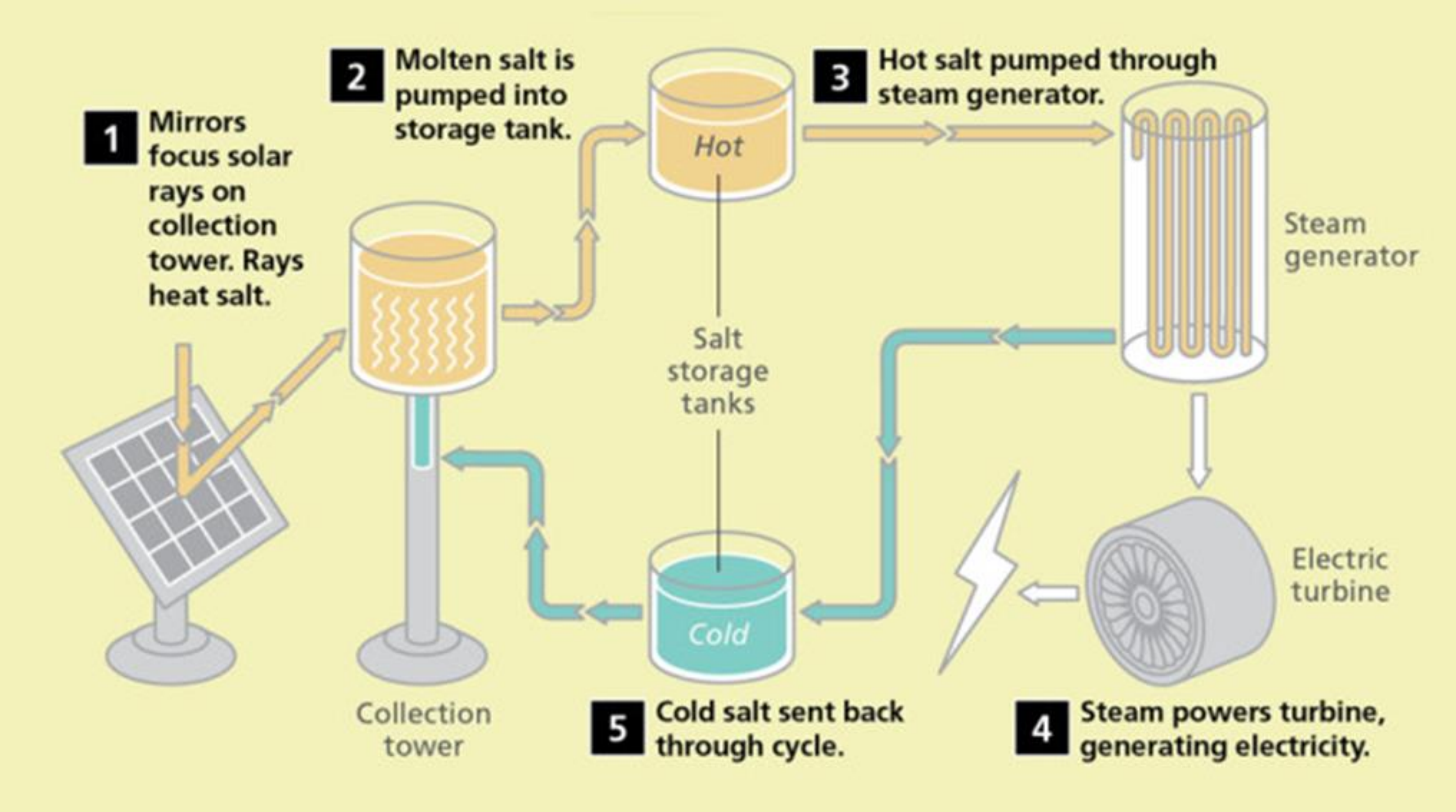
Energy/unit volume = (9.8)(50)/1000 = 0.49 J/kg

Storage capacity = 800,000 m^3 x 1000 kg/m^3 x 0.49J/kg
= 392 x 10^6J = 392 MW

Typical efficiency = 70%

Assume volume = 40,000 m^2 x 20 m = 800,000 m^3

Molten salt energy storage



1 Mirrors focus solar rays on collection tower. Rays heat salt.

2 Molten salt is pumped into storage tank.

3 Hot salt pumped through steam generator.

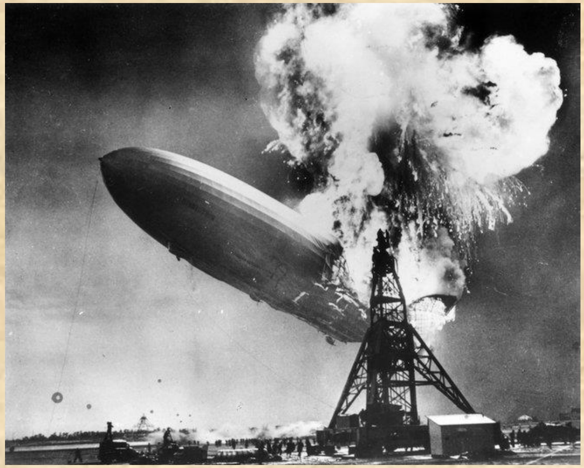
4 Steam powers turbine, generating electricity.

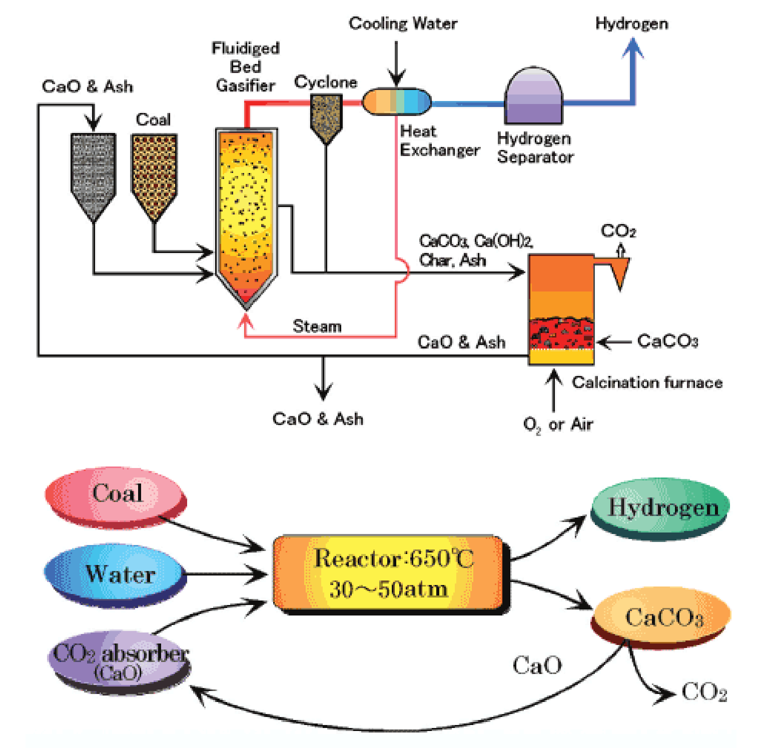
5 Cold salt sent back through cycle.

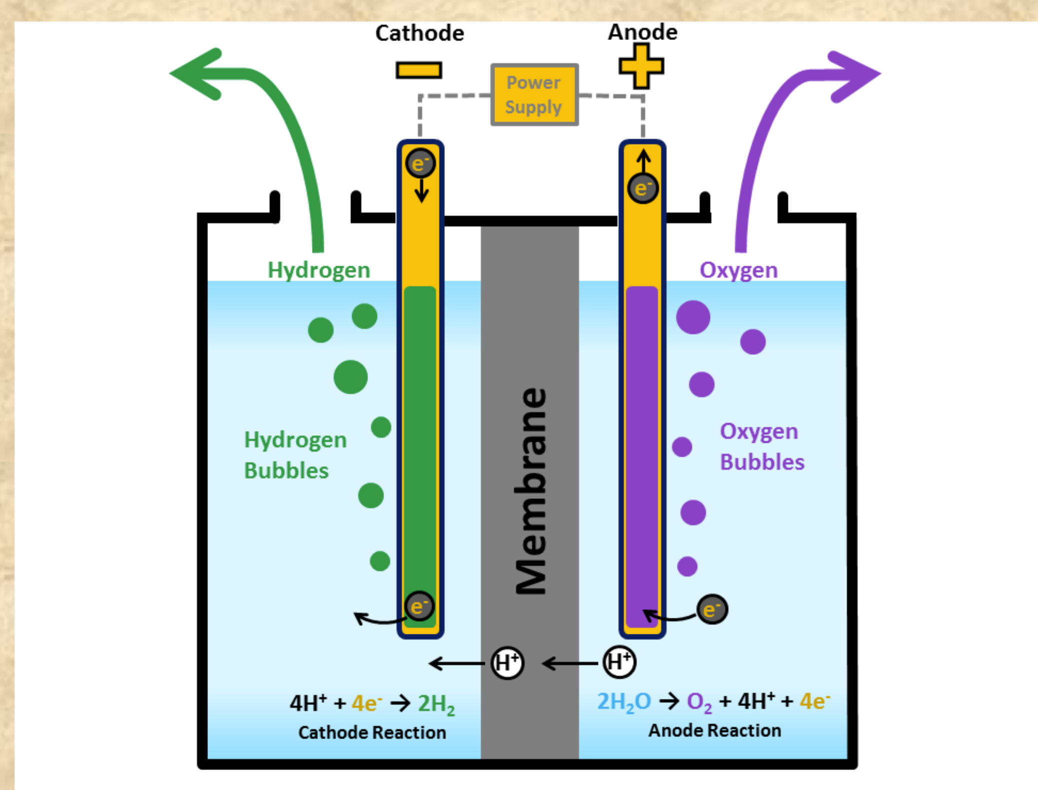
Hydrogen gas can be produced by various processes. Two examples, coal gasification and electrolysis are shown below.

Hydrogen gas is stored either as a compressed gas or a liquid (cryogenic, must be stored at -253°C or 20K).

Hydrogen is highly explosive.

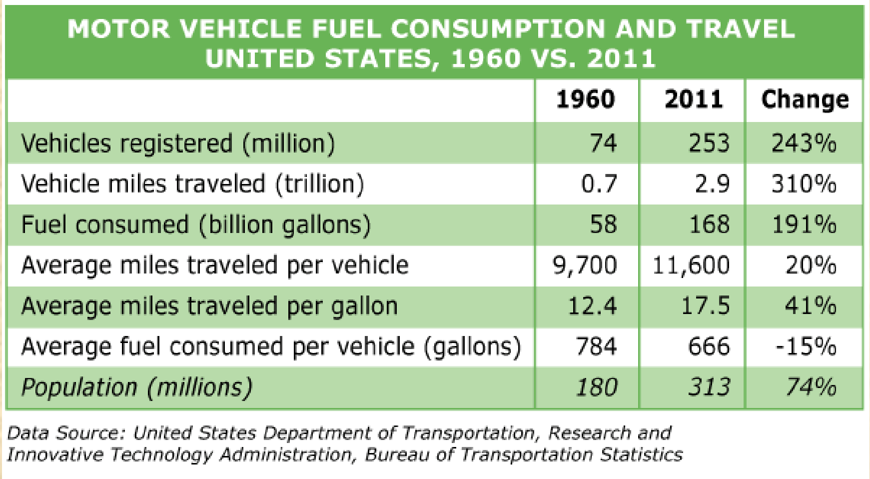






Transportation

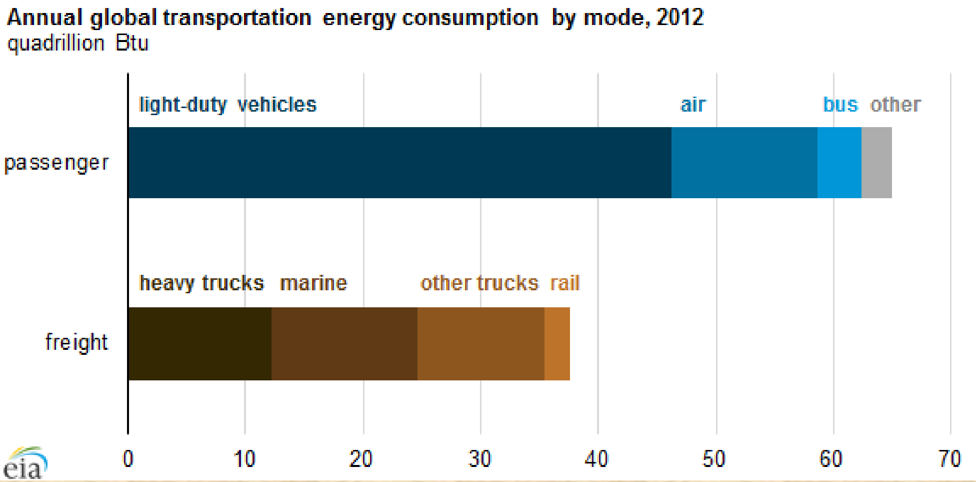
Fuel consumption as a function of type of transport



MOTOR VEHICLE FUEL CONSUMPTION AND TRAVEL UNITED STATES, 1960 VS. 2011

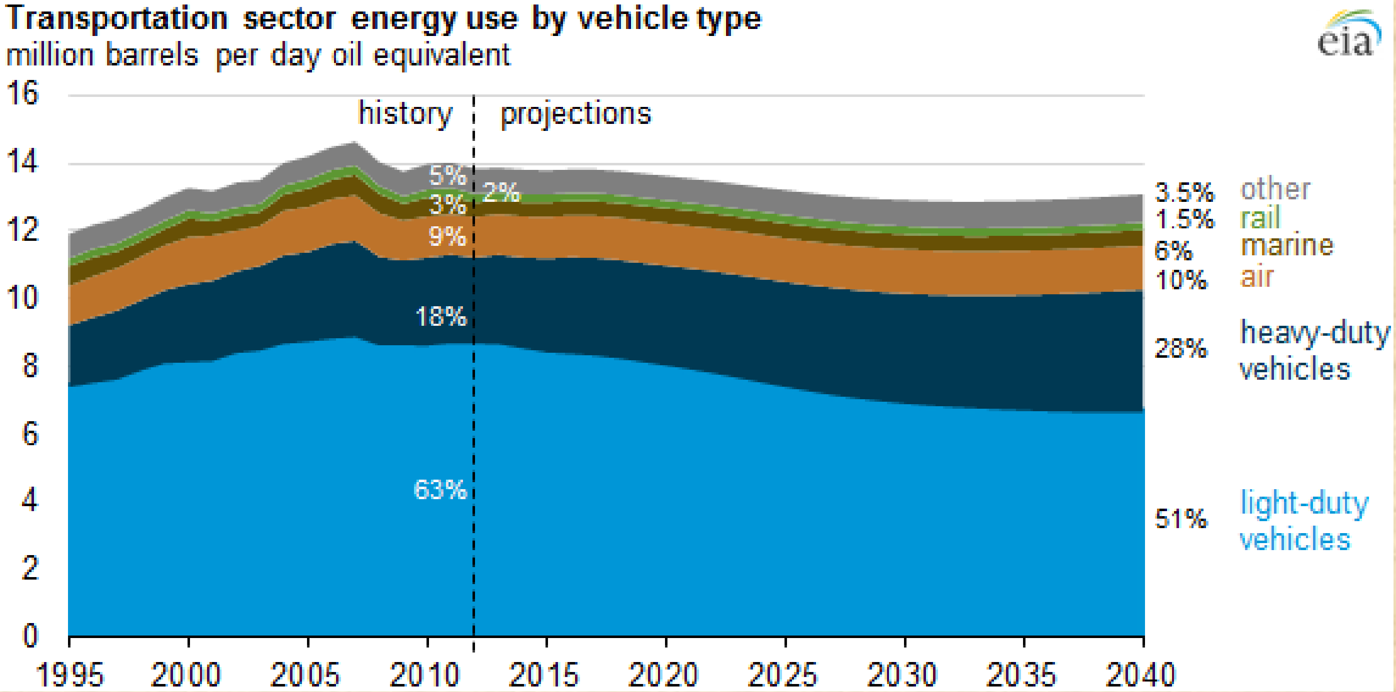
	1960	2011	Change
Vehicles registered (million)	74	253	243%
Vehicle miles traveled (trillion)	0.7	2.9	310%
Fuel consumed (billion gallons)	58	168	191%
Average miles traveled per vehicle	9,700	11,600	20%
Average miles traveled per gallon	12.4	17.5	41%
Average fuel consumed per vehicle (gallons)	784	666	-15%
Population (millions)	*180*	*313*	*74%*

Data Source: United States Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics



Annual global transportation energy consumption by mode, 2012

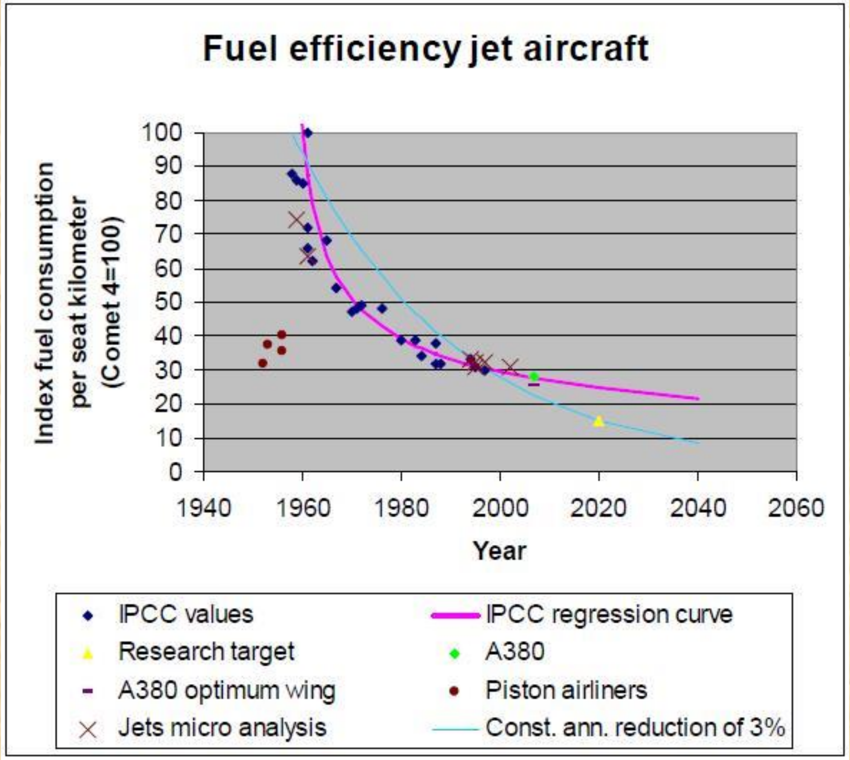
quadrillion Btu

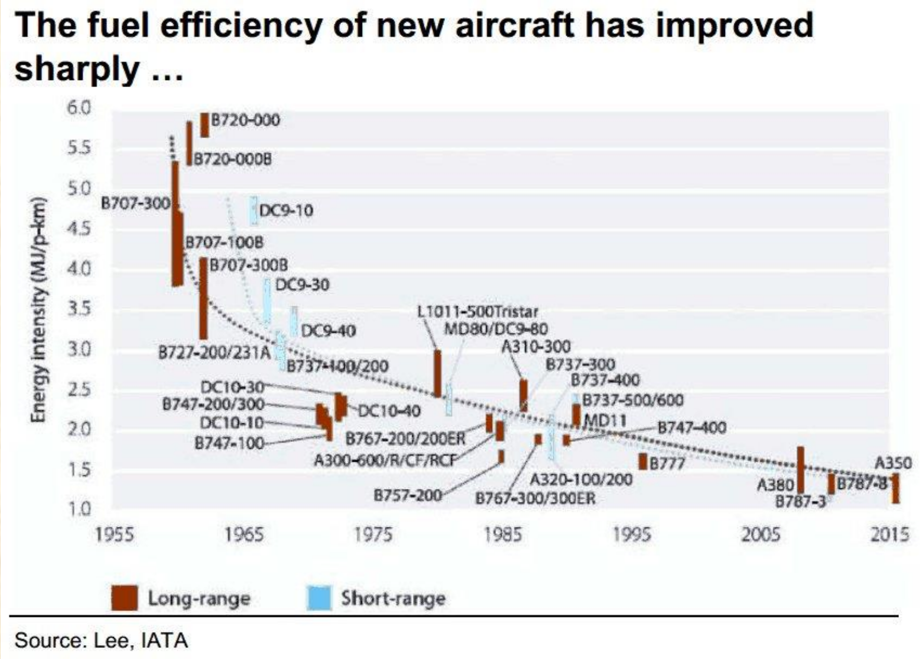


Transportation sector energy use by vehicle type

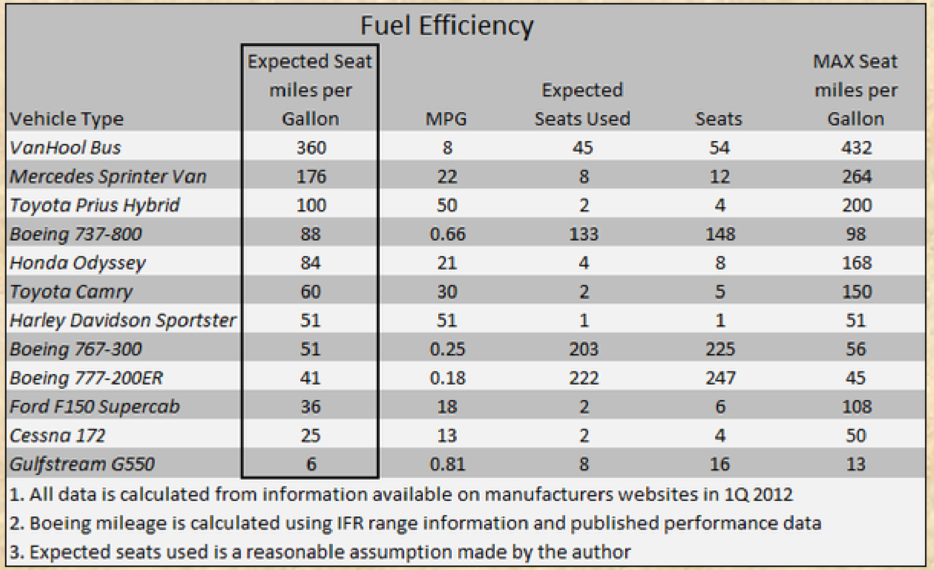
million barrels per day oil equivalent

Efficiency of air travel




The fuel efficiency of new aircraft has improved sharply …

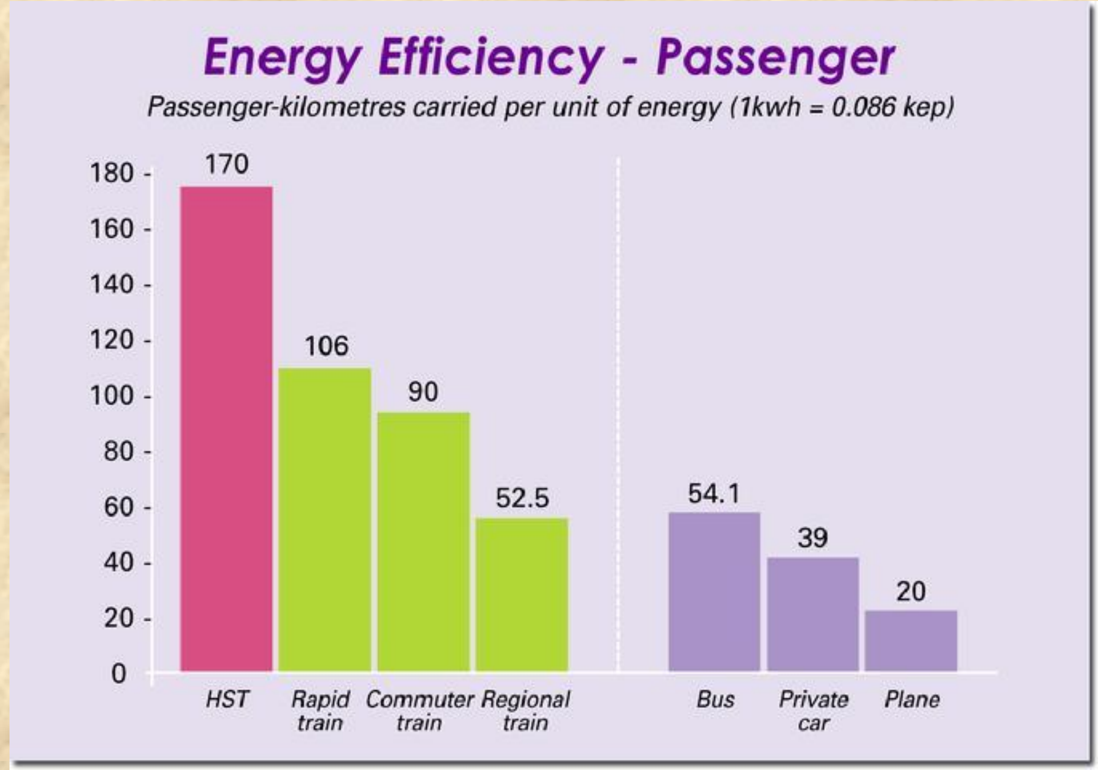
Source: Lee, IATA

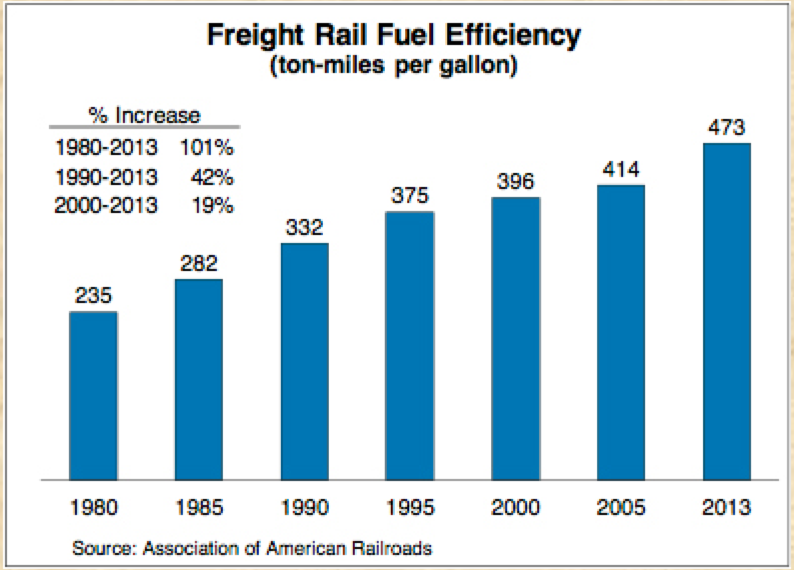

Fuel Efficiency

Vehicle Type	Expected Seat miles per Gallon	MPG	Expected Seats Used	Seats	MAX Seat miles per Gallon
VanHool Bus	360	8	45	54	432
Mercedes Sprinter Van	176	22	8	12	264
Toyota Prius Hybrid	100	50	2	4	200
Boeing 737-800	88	0.66	133	148	98
Honda Odyssey	84	21	4	8	168
Toyota Camry	60	30	2	5	150
Harley Davidson Sportster	51	51	1	1	51
Boeing 767-300	51	0.25	203	225	56
Boeing 777-200ER	41	0.18	222	247	45
Ford F150 Supercab	36	18	2	6	108
Cessna 172	25	13	2	4	50
Gulfstream G550	6	0.81	8	16	13

1. All data is calculated from information available on manufacturers websites in 1Q 2012
2. Boeing mileage is calculated using IFR range information and published performance data
3. Expected seats used is a reasonable assumption made by the author

Comparison of Energy Efficiency for Various Modes of Transport

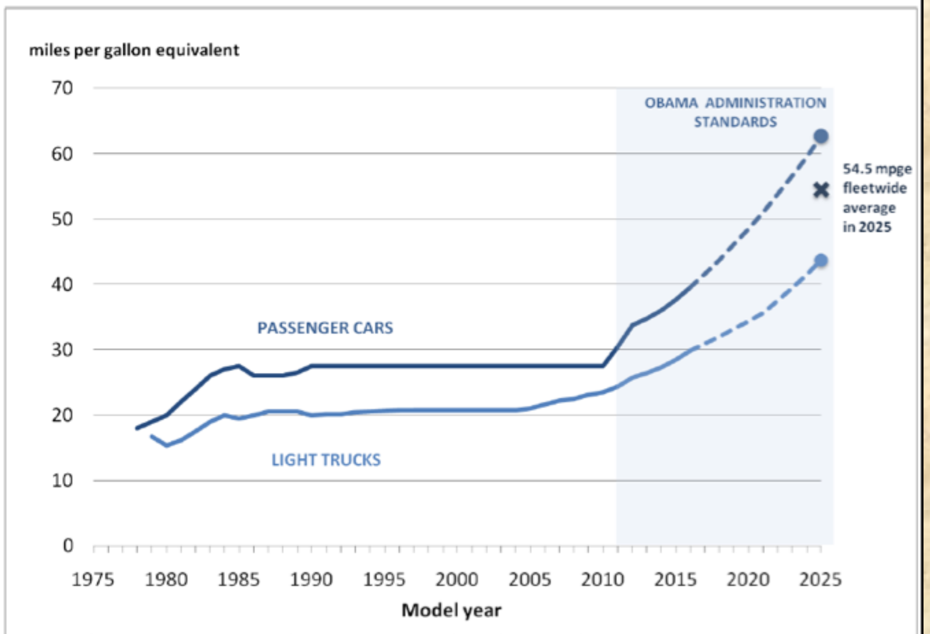




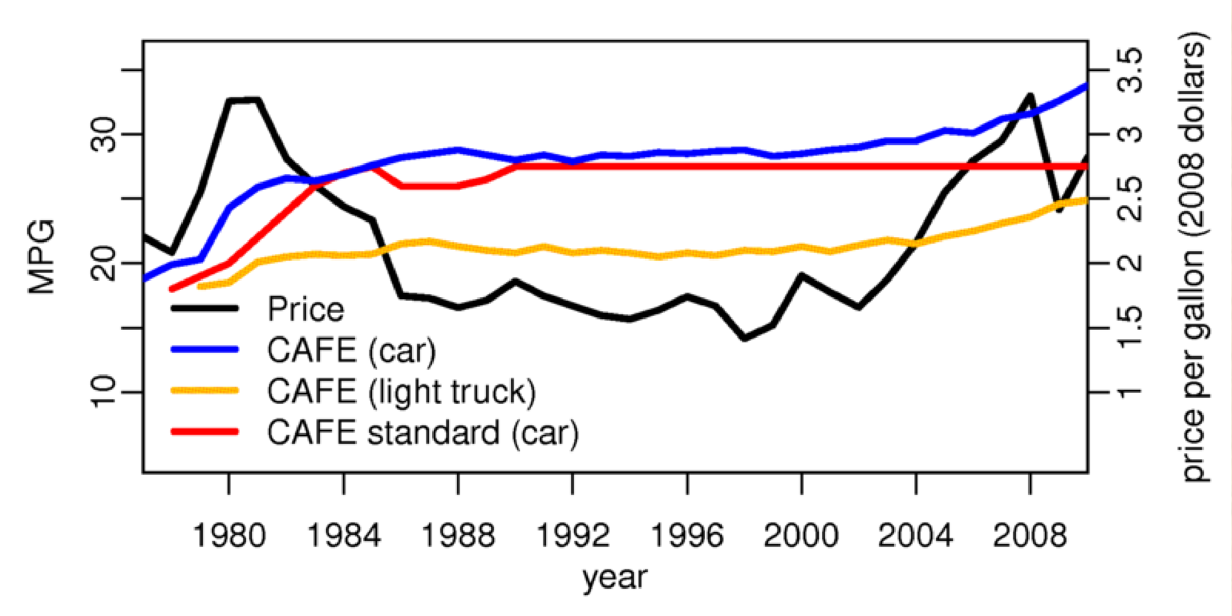
Source: Association of American Railroads

Fuel Economy Standards – Hopes and Dreams versus Reality

CHART 2: LIGHT-DUTY VEHICLE FUEL ECONOMY STANDARDS, 1978-2025

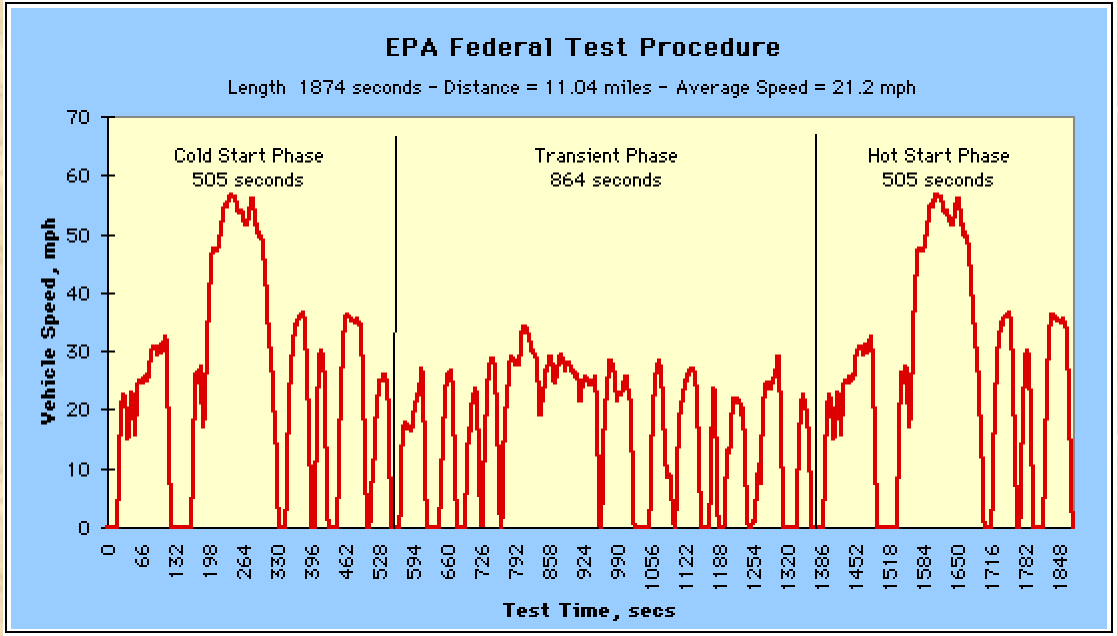


MY1978-2011 figures are NHTSA Corporate Average Fuel Economy (CAFE) standards in miles per gallon. Standards for MY2012-2025 are EPA greenhouse gas emission standards in miles per gallon equivalent, incorporating air conditioning improvements. Dashed lines denote that standards for MY2017-2025 reflect percentage increases in Notice of Intent.

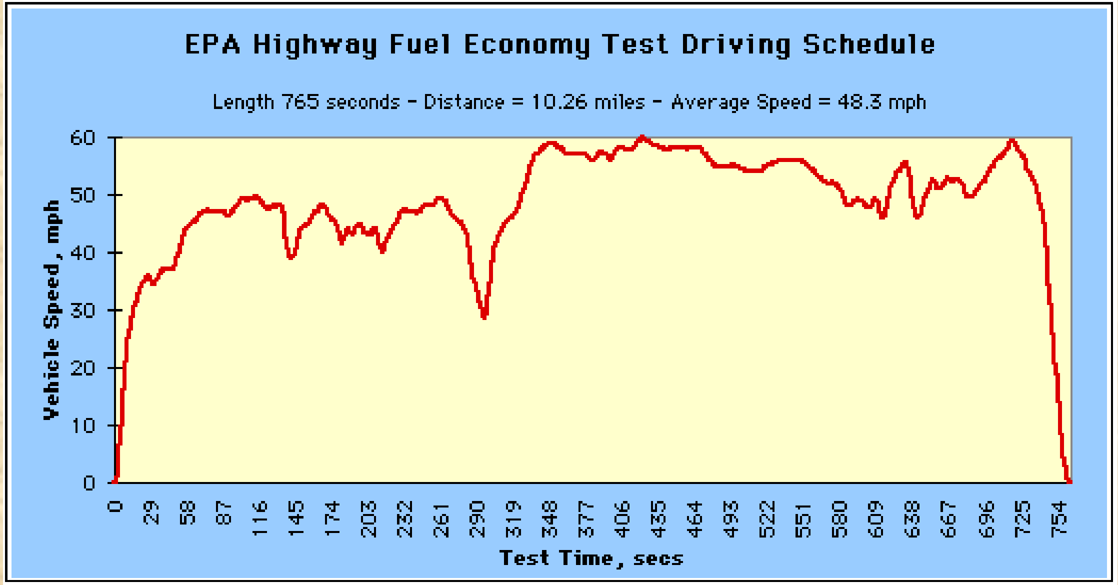


Measuring Fuel Efficiency – EPA urban and highway fuel economy tests.

Urban test

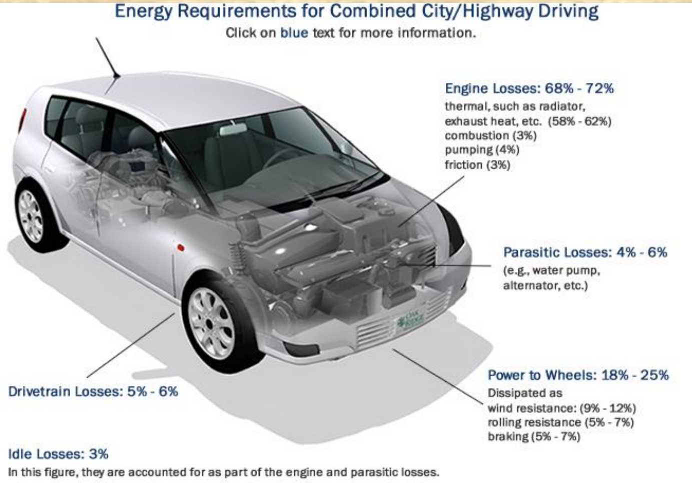


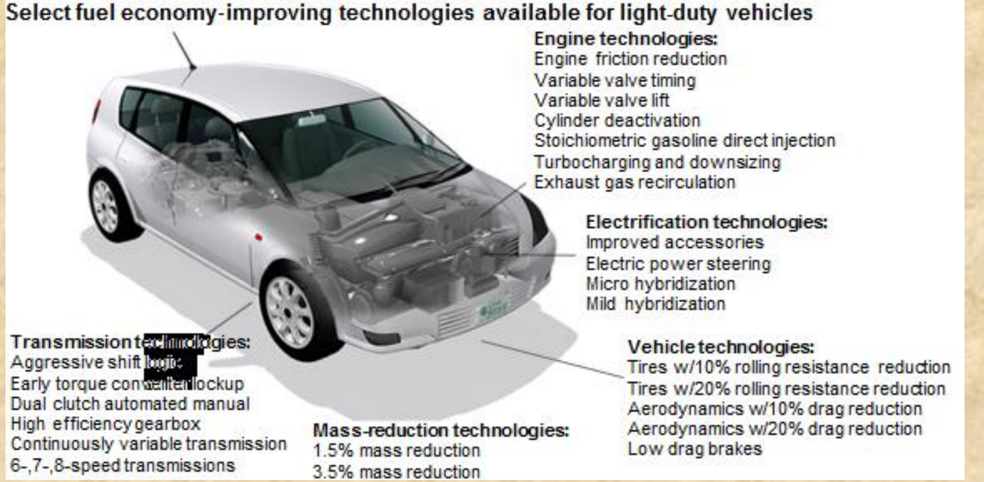
Highway test



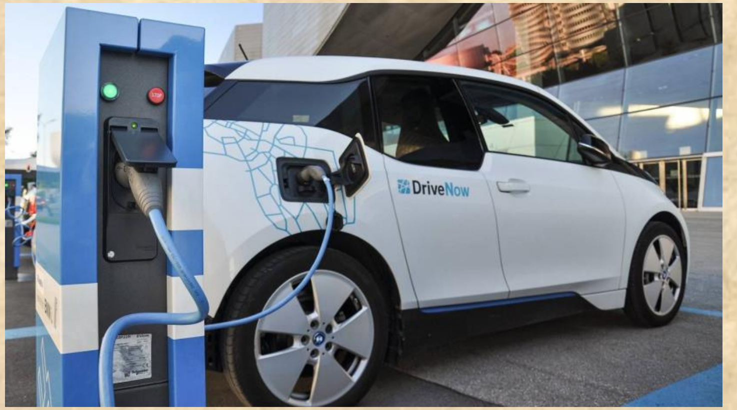
Improving Vehicle Fuel Economy

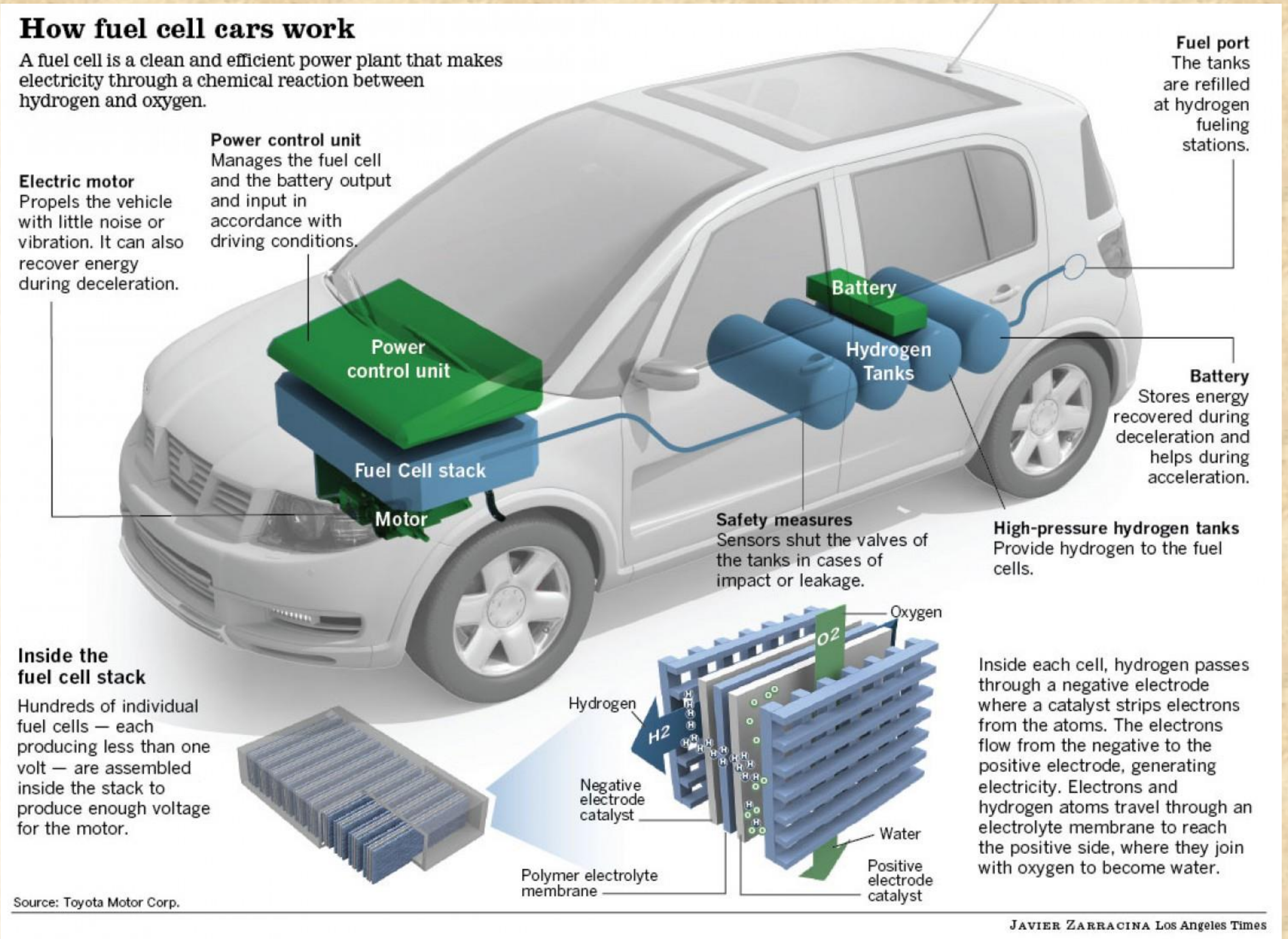
- Vehicle Performance
  - Reduce vehicle mass
  - Reduce aerodynamic resistance
  - Reduce rolling resistance
- Engine Performance
  - Reduce intake stroke losses in SI (spark-ignition) engines
  - Replacing SI engines with CI (compression-ignition) engines which are 25% more efficient
  - Supercharging – air compressor increases density of air leading to greater oxygen content and more complete combustion of fuel
  - Continuously variable transmission
  - Engine idle off





Model	Base price after tax credit	Electric range (miles)	Total range (miles)	MPGe (electric)	Top speed	Hours to charge, 120V	Hours to charge, 240V
Mitsubishi MiEV	$21,625	62	62	112	80	23	7
Nissan Leaf	$27,700	73	73	99	93	20	7
Honda Fit Electric	$29,125	76	76	116	92	15	3
Toyota Prius Plug-In	$29,500	12	540	95	112	3	2
Chevy Volt	$31,645	35	379	93	100	10	4
Ford Focus Electric	$32,495	76	76	105	84	20	4
Tesla Model S 40 kWh	$49,900	125*	125*	108	110	?	~5
Tesla Model S 60 kWh	$59,900	187*	187*	89*	120	?	~7.5
Tesla Model S 85 kWh	$69,900	265	265	89	125	?	~10





How fuel cell cars work

A fuel cell is a clean and efficient power plant that makes electricity through a chemical reaction between hydrogen and oxygen.

Electric motor
Propels the vehicle with little noise or vibration. It can also recover energy during deceleration.

Power control unit
Manages the fuel cell and the battery output and input in accordance with driving conditions.

Fuel port
The tanks are refilled at hydrogen fueling stations.

Battery
Stores energy recovered during deceleration and helps during acceleration.

Safety measures
Sensors shut the valves of the tanks in cases of impact or leakage.

High-pressure hydrogen tanks
Provide hydrogen to the fuel cells.

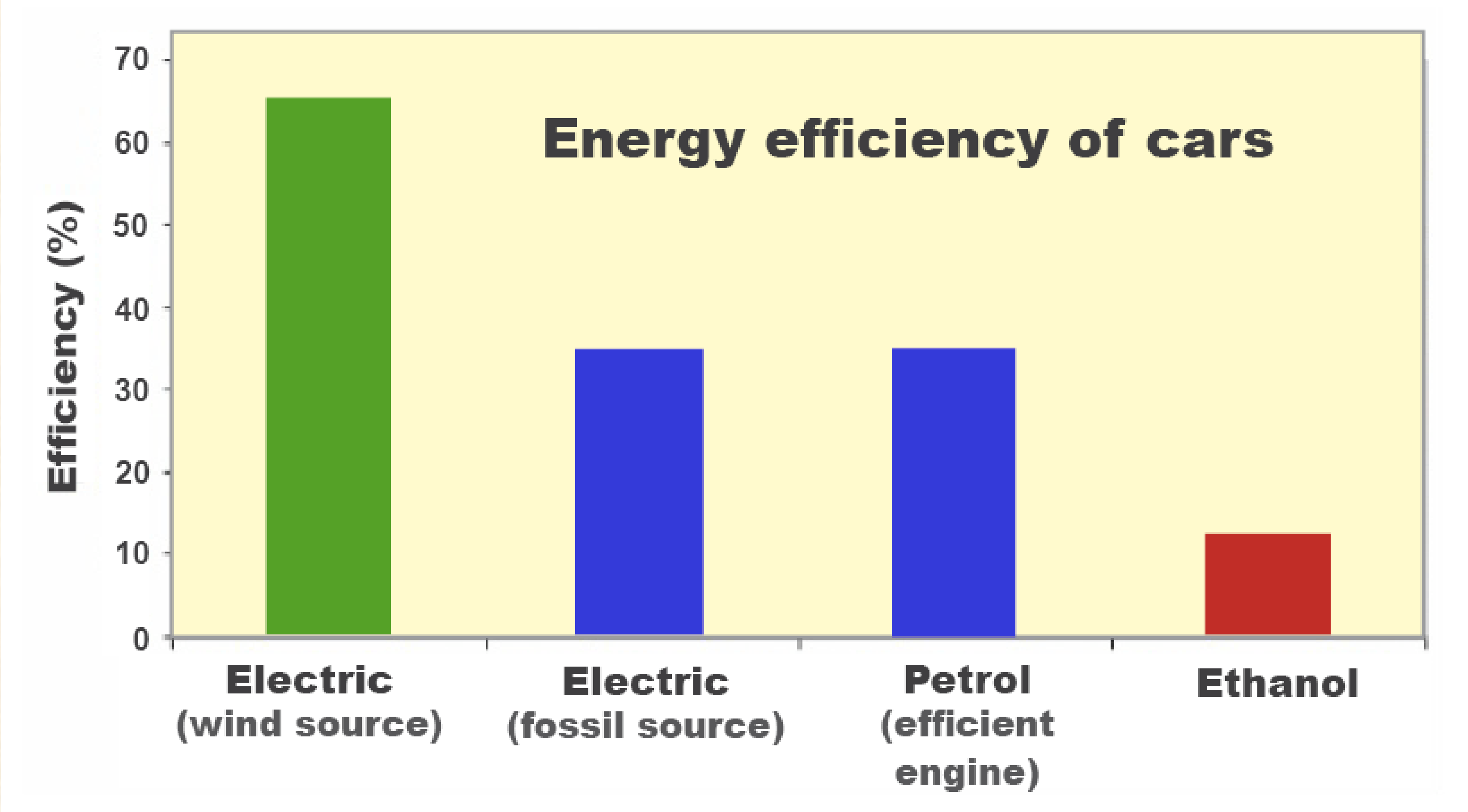
Inside the fuel cell stack

Hundreds of individual fuel cells — each producing less than one volt — are assembled inside the stack to produce enough voltage for the motor.

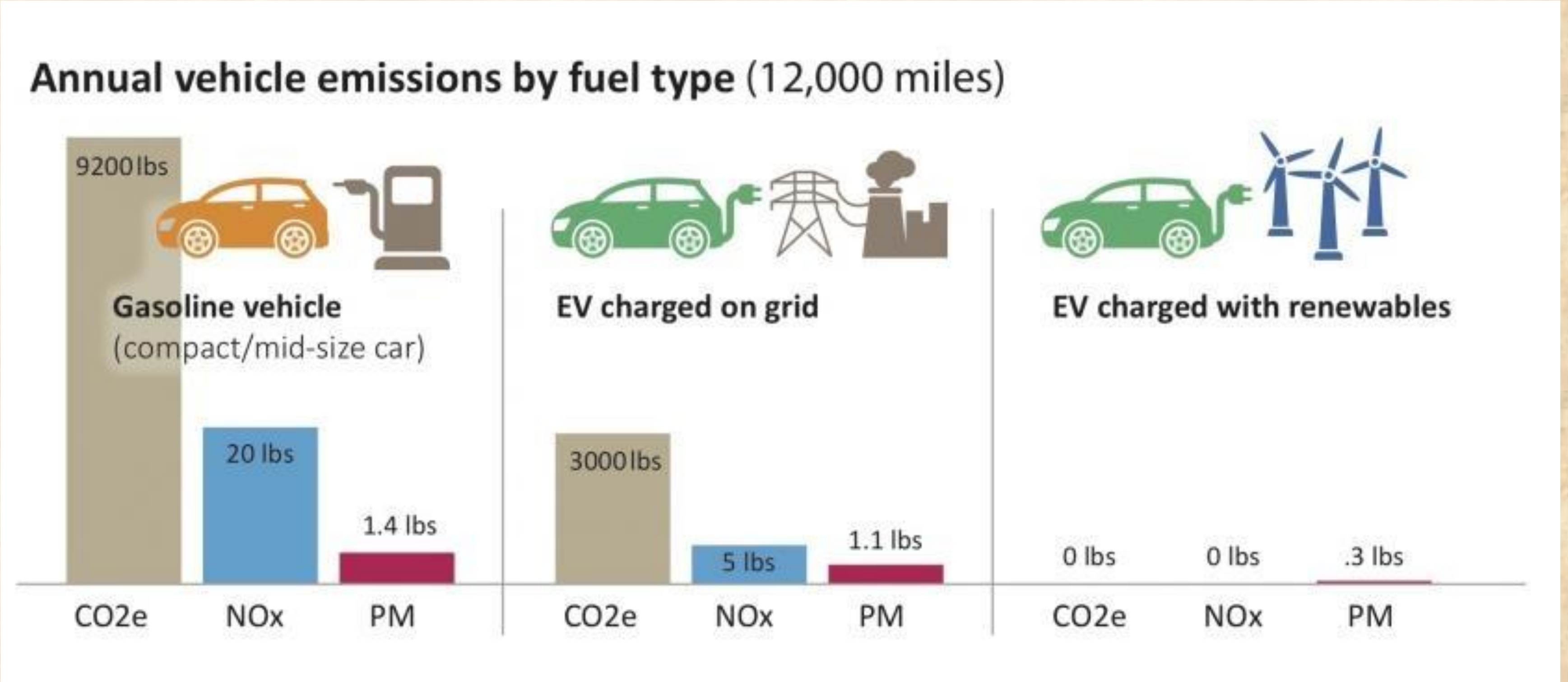
Inside each cell, hydrogen passes through a negative electrode where a catalyst strips electrons from the atoms. The electrons flow from the negative to the positive electrode, generating electricity. Electrons and hydrogen atoms travel through an electrolyte membrane to reach the positive side, where they join with oxygen to become water.

Source: Toyota Motor Corp.

Javier Zarracina Los Angeles Times


Energy efficiency of cars
Efficiency (%)
70
60
50
40
30
20
10
0
Electric (wind source)
Electric (fossil source)
Petrol (efficient engine)
Ethanol

Vehicle Emissions



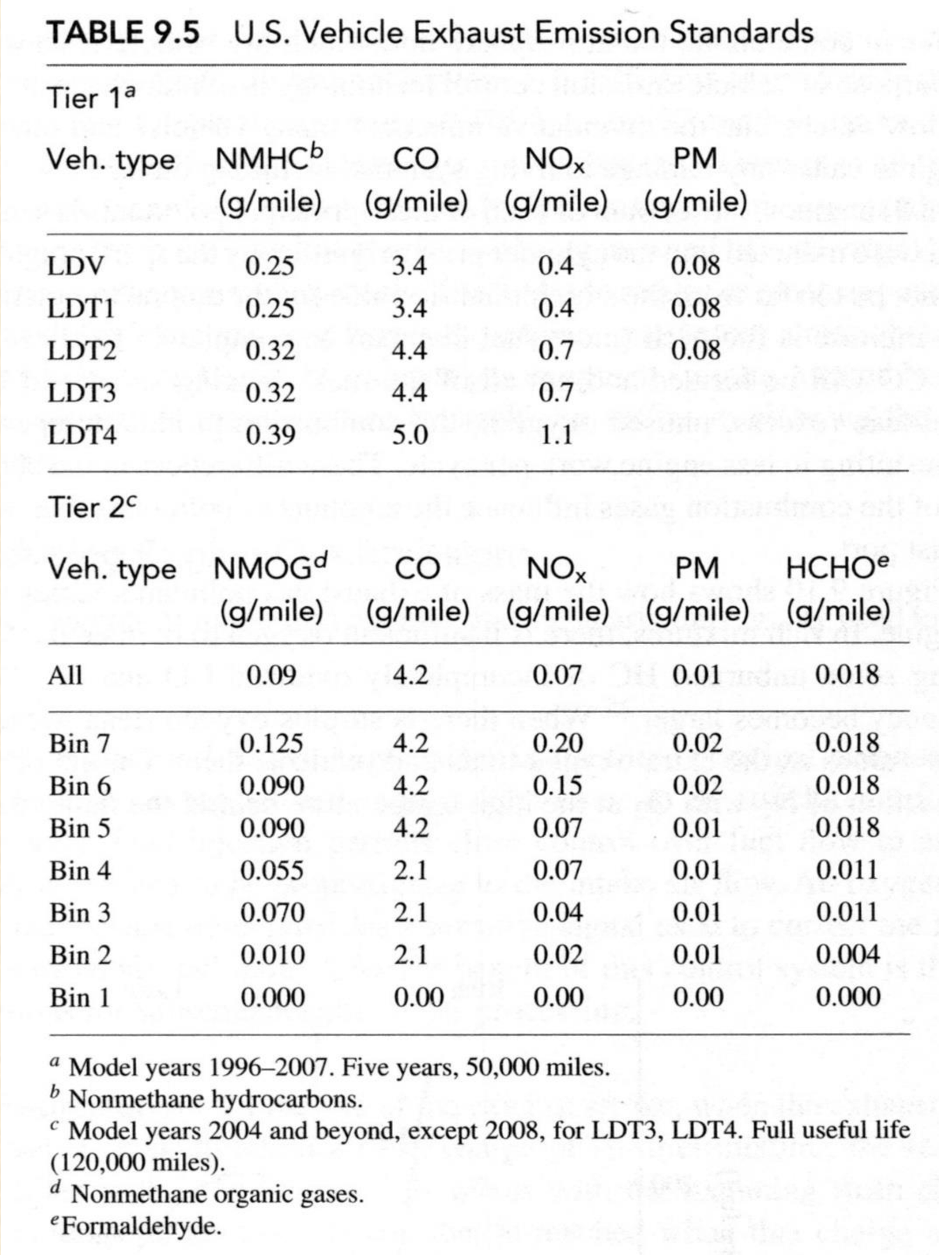


TABLE 9.5 U.S. Vehicle Exhaust Emission Standards

Tier 1[a]

Veh. type	NMHC[b] (g/mile)	CO (g/mile)	NO_x (g/mile)	PM (g/mile)
LDV	0.25	3.4	0.4	0.08
LDT1	0.25	3.4	0.4	0.08
LDT2	0.32	4.4	0.7	0.08
LDT3	0.32	4.4	0.7	
LDT4	0.39	5.0	1.1	

Tier 2[c]

Veh. type	NMOG[d] (g/mile)	CO (g/mile)	NO_x (g/mile)	PM (g/mile)	HCHO[e] (g/mile)
All	0.09	4.2	0.07	0.01	0.018
Bin 7	0.125	4.2	0.20	0.02	0.018
Bin 6	0.090	4.2	0.15	0.02	0.018
Bin 5	0.090	4.2	0.07	0.01	0.018
Bin 4	0.055	2.1	0.07	0.01	0.011
Bin 3	0.070	2.1	0.04	0.01	0.011
Bin 2	0.010	2.1	0.02	0.01	0.004
Bin 1	0.000	0.00	0.00	0.00	0.000

[a] Model years 1996–2007. Five years, 50,000 miles.
[b] Nonmethane hydrocarbons.
[c] Model years 2004 and beyond, except 2008, for LDT3, LDT4. Full useful life (120,000 miles).
[d] Nonmethane organic gases.
[e] Formaldehyde.

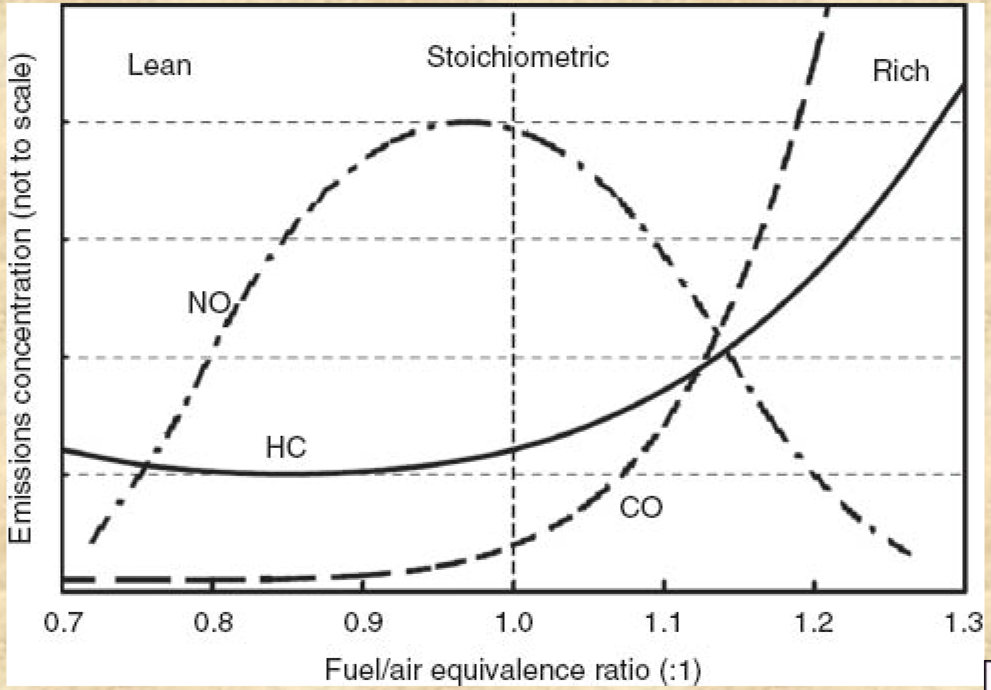
Table 1

Diesel Passenger Car Emissions Standards

EU vs. U.S. (Light Blue, Current Standards)

g/km	Year	PM	NOx	CO
Euro 1	Jul 1992	0.14	-	2.72
Euro 2	Jan 1996	0.08	-	1.00
Euro 3	Jan 2000	0.05	0.50	0.64
Euro 4	Jan 2005	0.025	0.25	0.50
Euro 5a	Sept 2009	0.005	0.18	0.50
Euro 5b	Sept 2011	0.005	0.18	0.50
Euro 6	Sept 2014	0.005	0.08	0.50
U.S. Tier 1	1994-1997*	0.050	0.62	2.11
U.S. Tier 2	2004-2009*	0.006	0.04	1.30

*Phased-in Over This Period

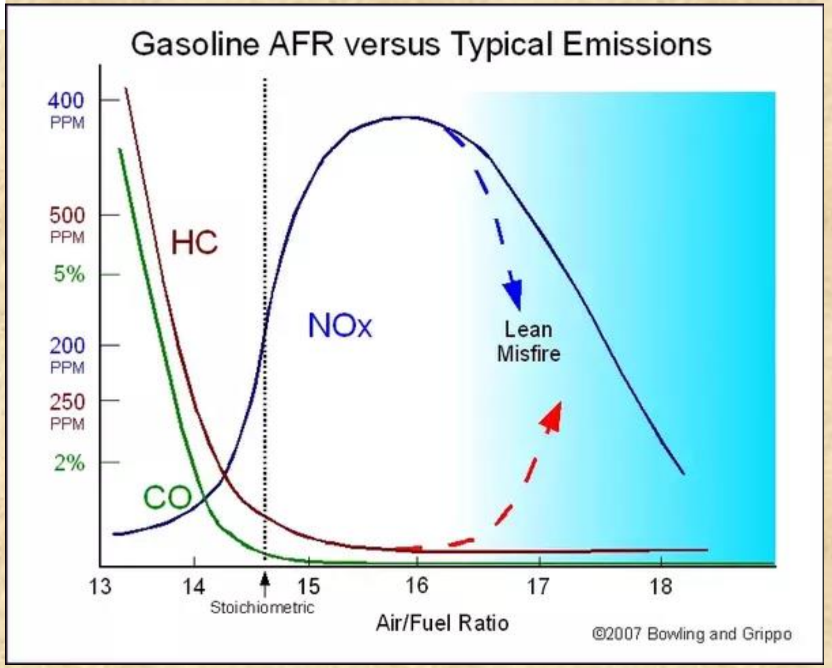


Automobile emissions as a function of the air/fuel ratio (AFR)

- Diagram to left normalized to a 1:1 equivalence ratio.
- Bottom diagram shows stoichiometric AFR

There is no “right answer”

A 'Stoichiometric' AFR has the correct amount of air and fuel to produce a chemically complete combustion event. For gasoline engines, the stoichiometric, A/F ratio is 14.7:1, which means 14.7 parts of air to one part of fuel. The stoichiometric AFR depends on fuel type-- for alcohol it is 6.4:1 and 14.5:1 for diesel.



Controlling emissions from road-vehicle exhaust streams

- Reduce concentration in exhaust gases
  - Precise control of AFR
  - Mix input air with exhaust gases in cylinder and recombust
- Exhaust gas system between engine and tail-pipe – catalytic converter
  - Platinum or rhodium are used for the catalytic surfaces
  - Temperature must be 250°C
  - CO and HC oxidized by NO formed by combining N_2 and O_2
  - Must have the right AFR. Very small rangeT