SSC 2030: Energy Systems & Sustainability

4. Forms of energy

4.1 Kinetic energy
4.2 Potential energy
4.3 Thermal energy
4.4 Chemical energy
4.5 Energy density
4.6 Electromagnetic radiation
4.7 Nuclear energy
4.8 Power
4.9 Summary of forms of energy

4. Forms of energy

4.1 Kinetic energy

What is kinetic energy?

Kinetic energy: *the energy of a moving mass or object*

KE = (1/2)(m)(v^2)

kinetic energy (J)

mass (kg)

velocity (m/s)

<u>Problem</u>:
If the 130 lb cyclist slows from 20 mph to 10 mph, how much does her kinetic energy change?

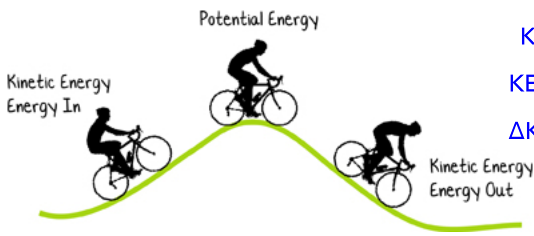
$\frac{130\ \text{lb}\quad 1\ \text{kg}}{2.2\ \text{lb}} = 59$ kg

$\frac{20\ \text{miles}\quad 1.6093\ \text{km}\quad 1\ \text{E3 m}\quad 1\ \text{hr}}{1\ \text{hr}\quad 1\ \text{mile}\quad 1\ \text{km}\quad 3600\ \text{s}} = 9$ E-3 m/s

KE = (1/2)(59 kg)(9 E-3)^2 = 2.4 E-3 J

KE = (1/2)(59 kg)(4.5 E-3)^2 = 6 E-4 J

ΔKE = 2.4 E-3 J - 6 E-4 J = 1.8 E-3 J



Energy Systems & Sustainability, 2/e, Chapter 4; http://science.jrank.org/

Kinetic rotational motion

Kinetic rotational energy: *a form of kinetic energy used to spin generators to make electricity or flywheels to store energy*

Erot = (1/2)(I)(ω^2)

kinetic energy (J)

jntertia (kg m^2)

angular velocity (m/s)

This 1802 steam locomotive used a flywheel to even out the power produced by it's single cylinder engine.

- Today, flywheels are being investigated by NASA.

Energy Systems & Sustainability, 2/e, Chapter 4; wikipedia

4. Forms of energy

4.2 Potential energy

What is potential energy?

Potential energy: *stored energy caused by attractive forces*

- gravity (aka position)
- electrostatic attraction

work (creates PE)

$$PE = \overbrace{(m)(g)}^{\text{work (creates PE)}}(h)$$

Potential energy (J) | mass (kg) | gravity (m/s^2) | height (m)

Problem:
If an elevate water tank holds 100,000 gallons of water at a height of 200 feet, how much potential energy is created?

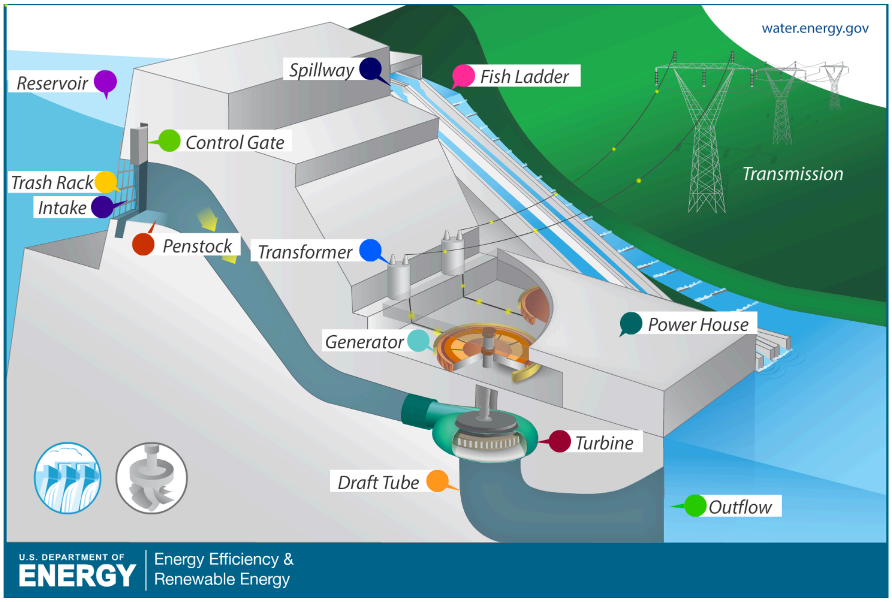
$$\frac{100{,}000 \text{ gallons}}{} \cdot \frac{3.7854 \text{ L}}{1 \text{ gallon}} \cdot \frac{1 \text{ m3}}{1 \text{ L}} \cdot \frac{1000 \text{ kg}}{1 \text{ m3}} = 3.7854 \text{ E8 kg water}$$

$$\frac{200 \text{ feet}}{} \cdot \frac{12 \text{ inches}}{1 \text{ foot}} \cdot \frac{2.54 \text{ cm}}{1 \text{ inch}} \cdot \frac{1 \text{ m}}{100 \text{ cm}} = 61 \text{ m}$$

$$PE = (3.7854 \text{ E8 kg})(9.8 \text{ m/s}^2)(61 \text{ m}) = 2.26 \text{ E11 J}$$

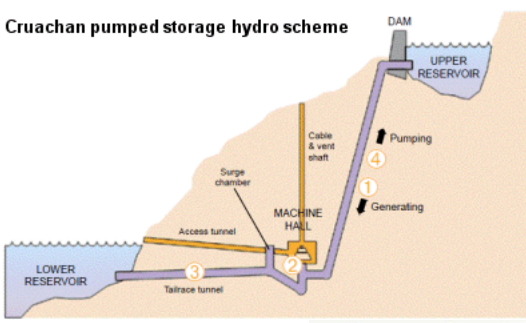
Energy Systems & Sustainability, 2/e, Chapter 4; http://science.jrank.org/

Hydropower uses potential energy



Energy Systems & Sustainability, 2/e, Chapter 4; energy.gov

Pumped storage uses potential energy



Scotland's Cruachan pumped storage hydro facility pumps water to an upper reservoir when surplus electricity is available. When electricity is needed, water is released to generate electricity.

The upper reservoir can store:
- 7 gigawatt-hours of energy
- 25 TJ of energy

Energy Systems & Sustainability, 2/e, Chapter 4; scotsrenewables.com

4. Forms of energy

4.3 Thermal energy

'...not that heat generates motion or that motion generates heat (though both are true in certain cases), but that heat itself, its essence and quiddity, is motion and nothing else.'

- Frances Bacon, 1620

What is thermal energy?

Thermal energy: *an object's energy measured by temperature (J)*

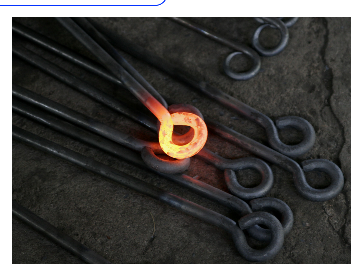
Molecular kinetic theory: *the average kinetic motions of atoms depend only on heat. Thus, heat is the kinetic motion of atoms or molecules.*

$$\underbrace{Q}_{\text{heat (J)}} = \underbrace{(m)}_{\text{mass (kg)}}\underbrace{(C)}_{\text{specific heat capacity (J/kg-°) or (Btu/lb-°)}}\underbrace{(\Delta T)}_{\text{change of temperature (degrees °)}} \dashrightarrow \Delta T = \frac{Q}{(m)(C)}$$

$$Q = \underbrace{(V)}_{\text{volume (L) or (gallons)}}(C)(\Delta T)$$

Find specific heat with volumetric units

specific heat of water = 4810 J/kg-°
= 8.314 Btu/gal-°



Energy Systems & Sustainability, 2/e, Chapter 4

Thermal energy example

Problem: How much energy does it take to increase the temperature of water in a 400 gallon tank from 50 to 140°F?

Note that since ΔT is the difference in temperature rather than an absolute value, the units can be F, C or K.

$Q = (V)(C)(\Delta T)$

$Q = (400 \text{ gallons})(8.314 \text{ Btu/gal-°})(140 – 50°\text{F}) = 2.99 \text{ E5 Btu}$

Energy Systems & Sustainability, 2/e, Chapter 4; wikipedia

4. Forms of energy

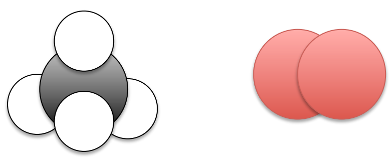
4.4 Chemical energy

What is chemical energy?

Chemical energy: *the energy stored in inter- & intra-molecular* <u>*bonds.*</u>

- <u>Heat is released by when bonds are *made*</u> during:
  - combustion or…
  - reduction-oxidation reactions.

Compounds / molecules: two or more atoms combined (bonded) at a constant ratio



methane (CH_4)   oxygen gas (O_2)

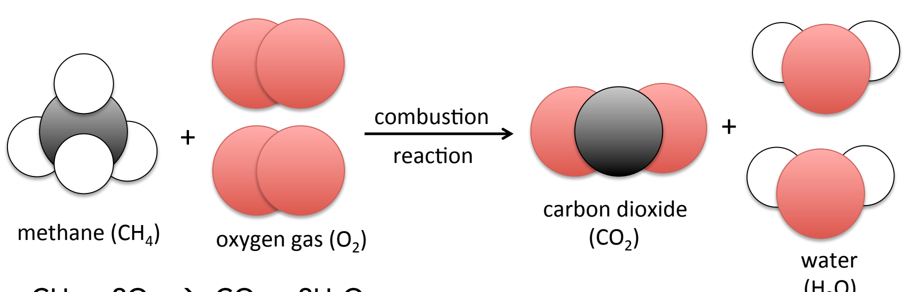
Energy Systems & Sustainability, 2/e, Chapter 4; wikipedia

Chemical reactions & chemical energy

Chemical reactions rearrange atomic connections (bonding) by breaking bonds and create new molecules by forming new atomic bonds.

- Reactions obey the law of conservation of mass, but often involved changes in energy depending on the ratio of bonds broken to the bonds made.

Combustion reactions: *burn carbon- & hydrogen-based fuel in the presence of oxygen gas to produce carbon dioxide, water & energy.*



$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

Energy Systems & Sustainability, 2/e, Chapter 4; wikipedia

Exothermic reactions release energy

Exothermic reactions release energy as they occur.

- Heat is a product.
- Combustion reactions are exothermic.

Negative ΔH means that heat is released (exothermic).

ΔH is enthalpy or heat energy

$C + O_2 \rightarrow CO_2$ ΔH = - 32.8 MJ/kg

Burning 1 kg of pure carbon (approximating coal) releases 32.8 MJ.

$C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$ ΔH = - 29.8 MJ/kg

Burning 1 kg of pure ethanol (approximating coal) releases 29.8 MJ.

Endothermic reactions require energy to occur.

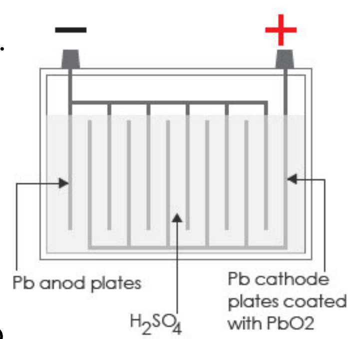
- Heat is a reactant.
- Can be used to store energy rather than make it.

Energy Systems & Sustainability, 2/e, Chapter 4; wikipedia

Batteries: redox chemistry

Batteries: *linked voltaic cells (redox half-cells) that store chemical energy until the half-cells are linked by a conductor*

- Some have finite power (non-rechargeable).
- Others are rechargeable.



Example: lead-acid batteries used in cars

- Discharge (produce) energy to start the car.
  - $Pb(SO_4)$ coats the electrodes.
- Charged when the car runs.
  - $Pb(SO_4)$ is redoxed back to plates.

Discharging:

$PbO_2 + Pb + 2H_2(SO_4) \rightarrow 2Pb(SO_4) + 2H_2O$

cathode anode Builds up on anode & cathode plates.

Charging:

$2Pb(SO_4) + 2H_2O \rightarrow PbO_2 + Pb + 2H_2(SO_4)$

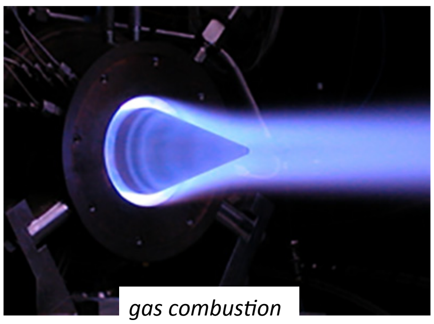
anode & cathode

Energy Systems & Sustainability, 2/e, Chapter 4
http://www.astragrp.com/bateriku/images/battery_safety_handling.jpg

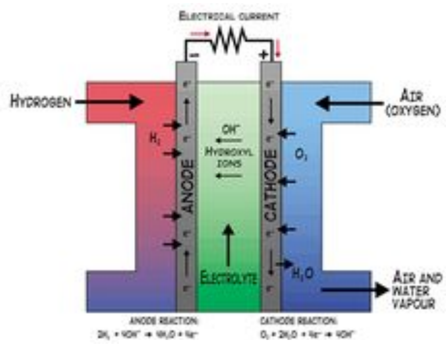
Combustion vs. redox reactions

Both type of reactions can use traditional fuels like methanol & methane.

- Redox reactions can also use non-traditional fuels like H_2 gas.
- **Redox reactions are more efficient at converting fuel to electricity**.
  - Internal combustion engine: 30% (so 70% 'waste' heat)
  - Fuel cells: 70%



gas combustion



Redox hydrogen fuel cell

Energy Systems & Sustainability, 2/e, Chapter 4; wikipedia

Fuel cells are in commercial use

The **Bloom box** is a fuel cell that passes natural gas (methane) over thin ceramic plates coated with a proprietary redox 'powder.

- As of 2015, installed boxes were producing 160 MW at….
- Apple, ebay, Fedex, etc.,.
- New design doubles power output.
- Revenue, but still little profit.

Source: University Delaware

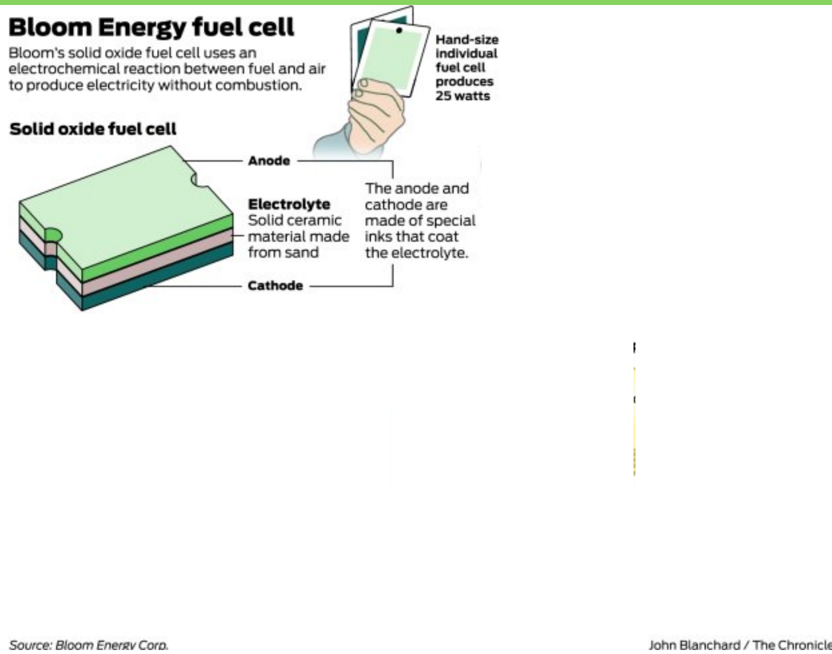
Redox 25 kW power system

Redox (backed by Microsoft) may be big competition.

- Closer to being competitive with combustion.
- Technology may provide 100x power for the same cost.

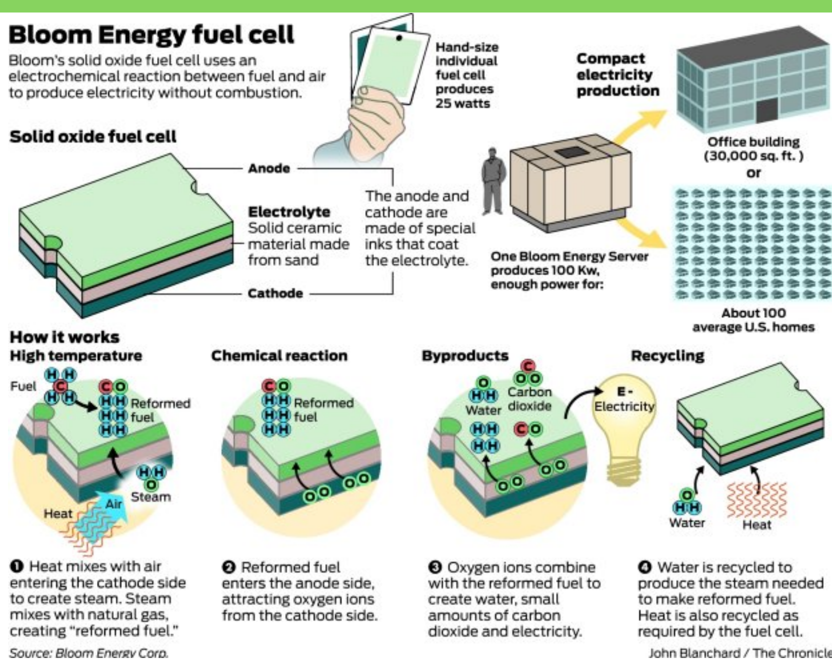
Energy Systems & Sustainability, 2/e, Chapter 4;
http://www.delawareonline.com/story/news/local/2015/07/22/new-bloom-box/30475483/
http://www.dailytech.com/Microsofts+New+Fuel+Cell+Partner+is+Ready+to+Blow+Away+the+Bloom+Box/art

Bloom box schematic



http://www.dailytech.com/Microsofts+New+Fuel+Cell+Partner+is+Ready+to+Blow+Away+the+Bloom+Box/article36118.htm

Bloom box schematic

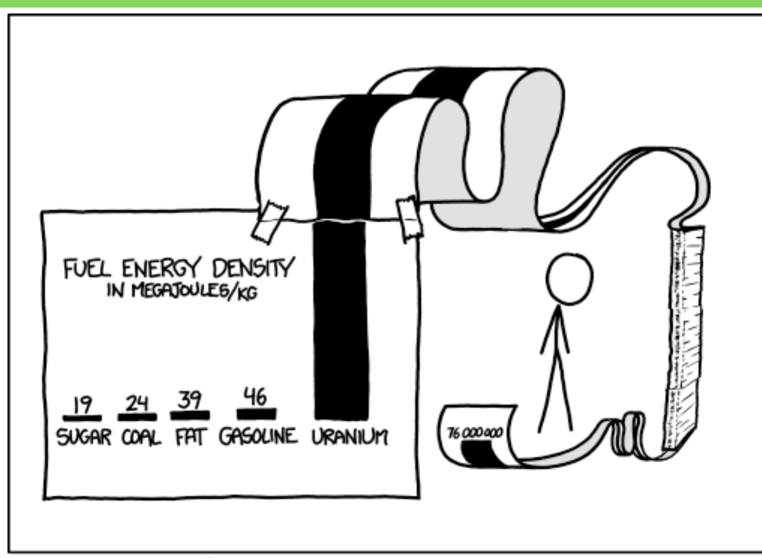


http://www.dailytech.com/Microsofts+New+Fuel+Cell+Partner+is+Ready+to+Blow+Away+the+Bloom+Box/article36118.htm

4. Forms of energy

4.5 Energy density / heat content

Relative energy densities



SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT *PROPERLY.*

Energy Systems & Sustainability, 2/e, Chapter 4; http://xkcd.com/1162

Chemical energy density

Storing energy is **'expensive'** in terms of quantities of chemical or potential energy needed.

fuel (=chemical energy)	MJ/kg	pounds to store 10 gas gallon equivalents
hydrogen gas	130	22
natural gas	55	52
gasoline	45	
oil	42	68
coal	28	105
ethanol	27	
wood	15	191
lead-acid batteries		6,578
water at 80c		11,440
pumped storage (h = 370 m)		762,667

Energy Systems & Sustainability, 2/e, Chapter 4

HHV vs. LHV heat values?

There are two 'flavors' of heat values (or energy densities) for combusted fuels.

HHV (high heat values) used when the steam is condensed after use; condensing steam to water releases additional energy.

- Aka HCV or GCV

LHV (low heat values) used when the steam is <u>not</u> condensed after use.

- Aka LCV or NCV

Fuel	HHV (MJ/kg)	LHV (MJ/kg)
hydrogen	141.80	119.96
methane	55.50	50.00
propane	50.35	46.35
diesel	44.80	43.40
wood	21.20	17.0

Energy Systems & Sustainability, 2/e, Chapter 4; wikipedia

Example: storing energy as H_2 (1)

Problem: How much hydrogen gas would be required to store the energy equivalent of 10 gallons of gasoline, and what pressure would be required to store the gas a standard temperature?

Gasoline has a density of 719.7 kg/m³.

$$\frac{10\text{ gallons gasoline}}{} \cdot \frac{3.7854\text{ L}}{1\text{ gallon}} \cdot \frac{1\text{ m}^3}{1000\text{ L}} \cdot \frac{719.7\text{ kg}}{\text{m}^3} = 27.2\text{ kg}$$

$$\frac{27.2\text{ kg}}{} \cdot \frac{45\text{ MJ}}{1\text{ kg}} = 1224\text{ MJ in 10 gallon of gasoline}$$

$$\frac{1224\text{ MJ}}{} \cdot \frac{1\text{ kg}}{130\text{ MJ}} \cdot \frac{1\text{ E3 g}}{1\text{ kg}} \cdot \frac{1\text{ L}}{0.08988\text{ g}} \cdot \frac{1\text{ m}^3}{1000\text{ L}} = 104.8\text{ m}^3\ H_2\text{ gas at STP}$$

Ideal gas law: $PV = nRT \rightarrow P = mRT/V$

$$P = \frac{mRT}{V} = \frac{(9.42\text{ kg})(4124.18\text{ Nm/kg-°K})(298\text{ °K})}{104.8\text{ m}^3} = 1.10\text{ E5 Pa} = 16\text{ psi}$$

Problem: this is a massive volume!!!

Example: storing energy as H_2 (2)

Commercial 'low pressure' hydrogen storage tanks are rated at 440 psi. How much would this higher pressure storage decrease to volume required to store the hydrogen gas?

Ideal gas law: $PV = mRT \rightarrow V = mRT/P$

Pa = N/m² | m³ | kg | 4124.18 N-m/kg-°K | °K

$$1\text{ psi} = 6894.76\text{ Pa} \rightarrow \frac{440\text{ psi}}{} \cdot \frac{6894.76\text{ Pa}}{1\text{ psi}} = 3.034\text{ E6 Pa}$$

$$V = \frac{mRT}{P} = \frac{(9.42\text{ kg})(4124.18\text{ Nm/kg-°K})(298\text{ °K})}{3.034\text{ E6 Pa (=N/m}^2)} = 3.8\text{ m}^3$$

What if a commercial compressed gas tank (2000 psi) were used?

2000 psi = 1.38 E8 Pa

$$V = \frac{mRT}{P} = \frac{(9.42\text{ kg})(4124.18\text{ Nm/kg-°K})(298\text{ °K})}{1.38\text{ E8 Pa (=N/m}^2)} = 8.4\text{ E-2 m}^3$$

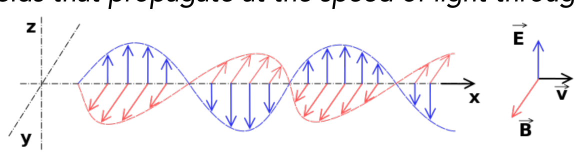
Energy Systems & Sustainability, 2/e, Chapter 4

4. Forms of energy

4.7 Electromagnetic radiation & electricity

Electromagnetic radiation

Electromagnetic radiation: '*Classically, electromagnetic radiation consists of electromagnetic waves, which are synchronized oscillations of electric and magnetic fields that propagate at the speed of light through a vacuum '*



1820 Oersted: electric current can deflect the needle of a compass

1820 Ampere: two parallel wires carrying electric current generate magnetic force

1821 Faraday: a wire carrying current will spontaneously rotate around a magnet

1832 Faraday: moving a bar magnet in a coil of wire causes current to flow in a coil

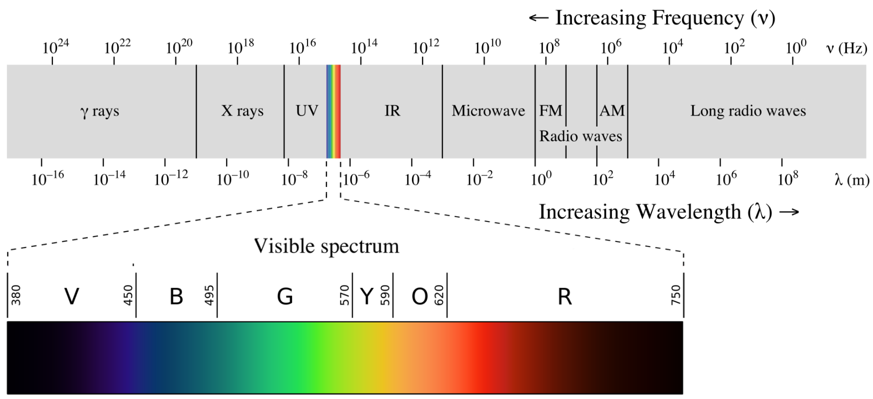
1864 Maxwell: EM waves are simply oscillating electric & magnetic fields that can travel through empty space at nearly the speed of light
- The source of all EM radiation are oscillating electric charges
- EM radiation is 'pure energy'

1900 Plank / 1905 Einstein: EM radiation is quantized

Energy Systems & Sustainability, 2/e, Chapter 4; wikipedia

Spectrum of electromagnetic radiation

EM radiation includes a broad spectrum of types of radiation defined by their wavelengths.
- *Visible light is a small part of the EM spectrum*



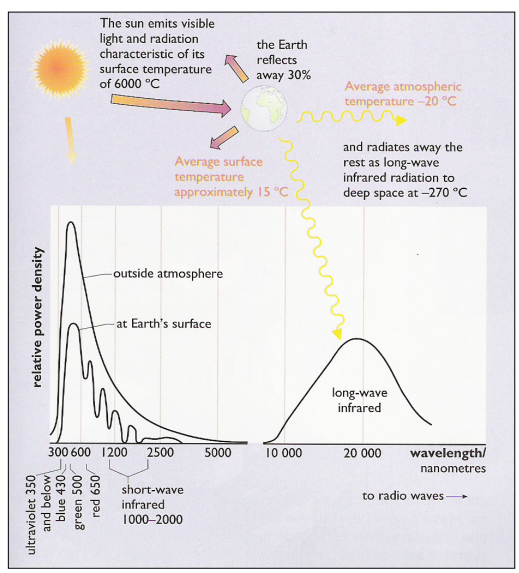
Energy Systems & Sustainability, 2/e, Chapter 4; wikipedia

Solar energy (insolation)

The solar energy that reaches the earth represents a small part of the EM spectrum & includes:
- UV light (mainly A & B)
- visible
- Short-wave infrared
- Long-wave infrared

Maximum insolation power:
= 1000 W/m^2
- Power of sunlight hitting the earth's surface.

Solar energy <u>is responsible for</u>:
- Photons (PV power)
- Molecular vibration (heat)
- Photosynthesis (biomass)



Energy Systems & Sustainability, 2/e, Chapter 4; XXXX

Electricity: movement of electrons

Electricity: *a flow of electrons*

Electrons flow in response to pressure (an electrical field) or as the result of a chemical reaction; a reduction-oxidation reaction.

- Ultimately, it's all about the law of electrostatic attraction.

Metals conduct electricity. How?

- Metal atoms are easily oxidized: lose electrons & become + cations.
- Free electrons mill about, attracted to the cations.
- Free electrons will move (flow) in response to a stronger attractive force.

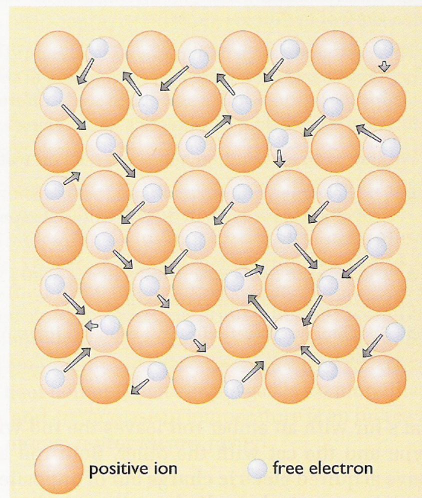


Figure 4.10 Ions and electrons in a metal

Energy Systems & Sustainability, 2/e, Chapter 4

Electric power?

Electricity power: *rate of transfer of electric energy into a circuit*

- Voltage (~pressure): the difference in electrical potential between terminal (source & destination); a measure of energy (V = volt)
- Current (~ flow rate): the flow of electrons (I; units = amperes, A)
- Resistance (~friction): material's ability to slow electron flow (Ω; V/A)

P = (V) (I)

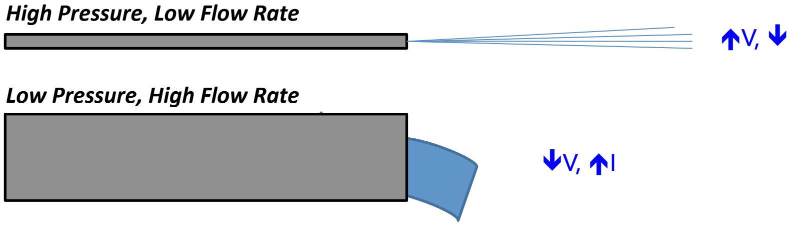
power (W) | voltage (V) | current (Amp)

V = (I)(R)

voltage (V) | current (Amp) | resistance (Ω)

High Pressure, Low Flow Rate

Low Pressure, High Flow Rate



Energy Systems & Sustainability, 2/e, Chapter 4; xxx

Electric power example

Problem: A bulb is labelled 1.5 V, 0.3 A. What is the bulb's resistance and power when it is connected to a 1.5 V battery?

$$R = V/I = \frac{1.5\ V}{0.3\ A} = 5.0\ \Omega$$

$$P = (V)\ (I) = (1.5\ V)\ (0.3\ V) = 0.45\ W$$

4. Forms of energy

4.8 Nuclear energy

Nuclear energy: background

Quick <u>review</u> of basic atomic structure & chemistry:

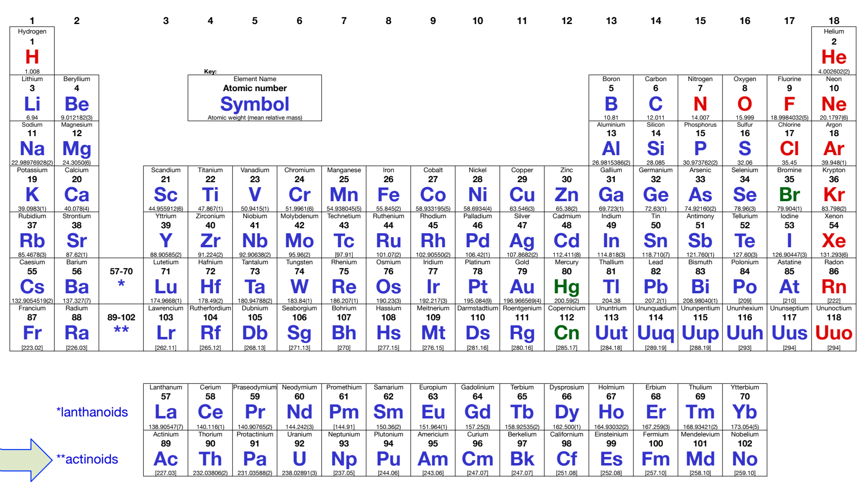
- Matter is made of **atoms**.
- Atoms have **nuclei** made of positively charged <u>protons</u> and neutral <u>neutrons</u> & surrounded by negatively charged <u>electrons</u>.
- **Atomic number** is the number of protons in the atoms of an element.
- **Atomic mass** is the mass of the atoms of an element.
- **Isotopes** are atoms with a variant number of neutrons & thus mass that is slightly higher or lower than the average mass of atoms of that element.
- What hold nuclei together? After all, since protons are positively charged, the should repel one another when packed together into the nucleus!
  - **Strong nuclear force** (the 3rd force)
  - *The nuclei of most atoms are stable & do not change.*

Energy Systems & Sustainability, 2/e, Chapter 4

Periodic table

Most **actinide** isotopes with odd numbers of neutrons are fissile.

Nuclear fuels: U-233, <u>U-235</u>, Pu-239, Pu-241



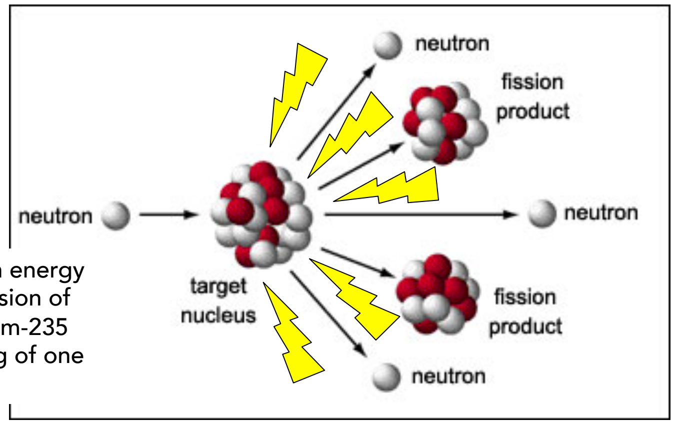
Energy Systems & Sustainability, 2/e, Chapter 4; webelements.com

Nuclear fission

Nuclear fission: *nuclei of certain elements split into two nearly equal parts*

Since the energy of the two fission products is lower than the energy of the atom which is split, energy is released.

- And because the intranuclear forces are very **strong**, lots of energy is released.



1 E8 times as much energy is released from fission of one atom of uranium-235 as from the burning of one carbon atom.

Energy Systems & Sustainability, 2/e, Chapter 4

Special theory of relativity

Einstein's special theory of relativity sought to resolve conflicts between Newton's laws of motion and Maxwell's laws of electromagnetism.

The special theory has two big tenets:

1. **Mass is not a fixed quantity:** the mass of objects in motion is larger than the mass of objects at rest.
   - The increased mass is equal to the object's kinetic energy.

2. Therefore, mass and energy are the **equivalent and mutable**.

$$E = (m)(c^2)$$

energy (J)

mass (kg)

speed of light (3 E8 m/s^2)

Energy Systems & Sustainability, 2/e, Chapter 4

Mass is energy is power?

So, if mass and energy are equivalent then **just convert** to harvest energy!

- Hypothetically, a small, 20 g, marble contains as much energy as a 500-kiloton hydrogen bomb.

Problem: releasing (converting) nuclear energy is very hard to do because the nuclear force is so darned strong.

So how can we accomplish conversion?

1. Matter/anti-matter annihilation? *Not enough anti-matter …*
2. Chemical reactions like combustion? *Very little mass lost*
3. **Nuclear fission**?
   Result in a 100,000 greater loss of mass than chemical reactions, thus produce more energy!

Energy Systems & Sustainability, 2/e, Chapter 4
https://www.brightstorm.com/science/physics/nuclear-physics/mass-energy-equivalence/

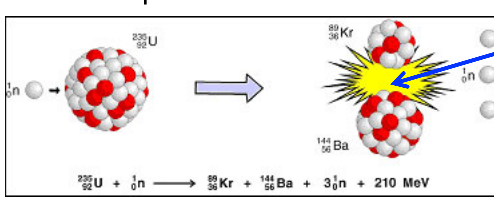
Nuclear energy

Nuclear energy: *is the energy that holds protons and neutrons together in the nucleus*

- Much greater than the usual chemical energy.
- Released during fission or fusion.

The amount of energy released is related to changes in the total mass of the system, per Einstein's equation:

$$E_{exo} = (\Delta m)(c^2)$$



Mass lost = energy released

Problem: When 1 metric tonne of uranium-235 undergoes fission, its mass is decreased by 6.6 g. How much energy is this loss of mass produce?

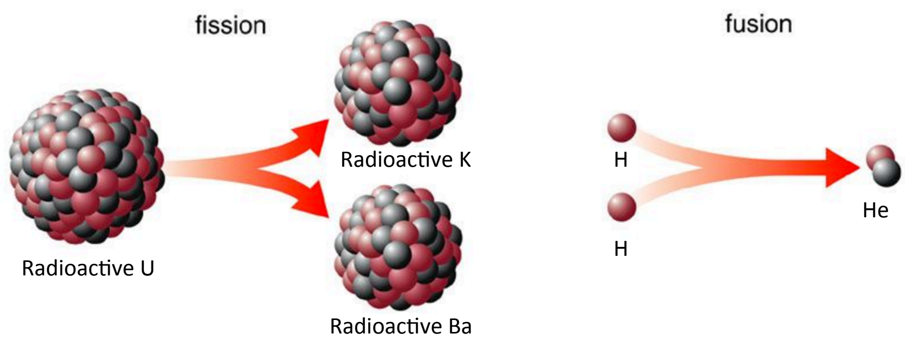
$E_{exo} = (0.0066\text{ kg})(3\text{ E}8\text{ m/s}^2)^2 = 5.94\text{ E}14\text{ J} = 600\text{ TJ}$

Energy Systems & Sustainability, 2/e, Chapter 4; www.euronuclear.org

Fusion vs. fission

Nuclear fusion: *the process of fusing two atoms to create a new atom*

- Enormous amounts of energy is needed to make fusion happen, but more energy is released: net energy yield.
- Fusion is safer because no radioactive products are produced.
- Not yet practical or applied.



https://nuclear.duke-energy.com/2013/01/30/fission-vs-fusion-whats-the-difference

4. Forms of energy

4.8 Power

Power

Power: *is the rate of energy flow (energy / time)*

- Unit = watt (W) = 1 Joule/second = kg-m^2/s^3
- In many cases, power is created when mass flows:
  - wind is flow of air;
  - hydro is flow of water; &
  - combustion depends on the flow rate of fuel to an engine.

When the flow of mass is involved in producing power, the flow rate of mass (Qmass) can be substituted for mass in energy equations, **converting energy equations into power equations**.

- Qmass = mass flow rate (kg/s)

Example:

Kinetic energy (KE) = ½(m)(v^2) = $\frac{kg\text{-}m^2}{s^2}$ = J

Power of KE (P_{KE}) = ½(Qmass)(v^2) = $\frac{kg\text{-}m^2}{s^3}$ = J/s = W

Power equations

Kinetic power P_{KE} = (1/2)(Qmass)(v^2) = W

Potential power P_{PE} = (Qmass)(g)(h) = W

Chemical power P_{fuel} = (Qmass)(H) = W

Electrical power $P_{electrical}$ = (V)(I) = W

Q_{mass}	flow rate	kg/s, gallons/s, etc.
v	velocity	m/s
g	gravitational acceleration	m/s^2
H	heat content	J/kg
V	voltage	V
I	current	A

4. Forms of energy

4.8 Summary of forms of power

Summary: forms of energy

Kinetic energy: *motion*	$KE = (1/2)(m)(v^2)$
Potential energy: *gravity (positional energy)*	$PE = (m)(g)(h)$
Thermal energy: *heat (Δ temperature)*	$Q = (m)(c)(\Delta T)$
Chemical energy: *fuels & batteries*	$Q = (H)(\text{fuel quantity})$
Electrical energy: *flow of electrons*	$P = (V)(I)$
Nuclear energy: *change in mass*	$E = (m)(c^2)$