8.21 The Physics of Energy
Fall 2009

8.21 Lecture 2

Units and the Scales of Energy Use

September 11, 2009

Outline

- The basics: SI units
- The principal players: energy, power, force, pressure
- The many forms of energy
- Translations and scales: units and energy subcultures
- A tour of the energy landscape: From the macroworld to our world
- CO_2 and other greenhouse gases: measurements, units, energy connection
- Perspectives on energy issues --- common sense and conversion factors

SI $\equiv$ International System

MKSA = Meter, Kilogram, Second, Ampere Units

Not cgs or "English" units!

Electromagnetic units

- Charge $\Rightarrow$ Coulombs
- Current $\Rightarrow$ Amperes
- Electrostatic potential $\Rightarrow$ Volts
- Resistance $\Rightarrow$ Ohms

Thermal units

- Temperature $\Rightarrow$ Kelvin (K)

Derived units

- Energy $\Rightarrow$ Joules
- Power $\Rightarrow$ Watts
- Pressure $\Rightarrow$ Pascals
- Force $\Rightarrow$ Newtons

More about these next...

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Force, Energy, Power and Pressure

[X] means "The units of X"

Basics: $m \Leftrightarrow$ kilograms, $l \Leftrightarrow$ meters

$t \Leftrightarrow$ seconds, and $Q \Leftrightarrow$ coulombs

For example: [speed] = l/t = meters/second

We can get the units of any physical quantity by using a definition or physical law that relates it to something we already know...

- Newton's second law   Force = mass $\times$ acceleration

[force] = [mass][acceleration] = $m\ l/t^2$ = kilogram meter/second^2 = kg m/s^2

1 kg m/s^2 = 1 Newton

The force of gravity on you:

$$F_{\text{gravity}} = mg = 80\text{ kg} \times 9.8\text{ m/s}^2 = 784\text{ Newtons}$$

- Kinetic energy   Energy = $\frac{1}{2}$ mass $\times$ velocity-squared

[energy] = [mass][velocity^2] = $m\ l^2/t^2$ = kilogram meter^2/second^2 = kg-m^2/s^2

1 kg m^2/s^2 = 1 Joule = 1 Newton-meter

Your kinetic energy walking at 3 miles per hour:

$$E_{\text{kinetic}} = \frac{1}{2}mv^2 = \frac{1}{2}\ 80\text{ kg}\ \left(3\,\frac{\text{miles}}{\text{hour}} \times 1609\,\frac{\text{meters}}{\text{mile}} \times \frac{1}{3600}\,\frac{\text{hours}}{\text{second}}\right)^2 = 72\text{ Joules}$$

- Power — Power = energy per unit time dE/dt

  [power] = [energy][time^{-1}] = $\left(ml^2/t^2\right)\left(1/t\right)$ = kilogram meter^2/second^3 = kg-m^2/s^3

  1 kg m^2/s^3 = 1 Watt = 1 Joule/second

  Power you exert climbing stairs at 0.5 meters per second

$$\begin{aligned}\Delta E &= mg\Delta h = 80\,\text{kg} \times .5\,\text{m} \times 9.8\,\text{m/s}^2 = 390\,\text{Joules} \\ P_{\text{climbing}} &= \Delta E/\Delta t = 78\,\text{Joules}\,/1\,\text{second} = 390\,\text{Watts}\end{aligned}$$

- Pressure — Pressure = force per unit area dF/dA

  [pressure] = [force][area^{-1}] = $\left(ml/t^2\right)\left(1/l^2\right)$ = kilogram/meter second^2 = kg m^{-1}s^{-2}

  1 kg m^{-1}s^{-2} = 1 Pascal = 1 Newton/meter^2

  You, standing on the ground:

$$p_{\text{gravity}} = \frac{\text{Force}}{\text{Area}} = \frac{784\,\text{Newtons}}{\sim\ 36\,\text{in}^2} = \frac{784}{0.023} =\sim 34,000\,\text{Pascals}$$

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Forms of Energy

- A long time to discover energy conservation.
- Energy disappears? No! Changing form...

  kinetic to potential to chemical to thermal to Einstein's rest energy ...

- In fact it is conservation of energy, a single number characterizing a system or even each part of a system, that can be traced through time and as it flows and changes, that makes energy so important in physics.
- Units: All these different forms must have the same units of mass $\times$ length^2 / time^2)
- Review a little 8.01 & 8.02 and see what's to come

KINETIC ENERGY $\frac{1}{2}mv^2$ mass × [speed]^2

$$[\text{mass}] \times [\text{speed}]^2 = m \times \left(\frac{l}{t}\right)^2 = m\frac{l^2}{t^2}$$

Energy manifest in motion

WORK AND POTENTIAL ENERGY $F\,d$ force × distance

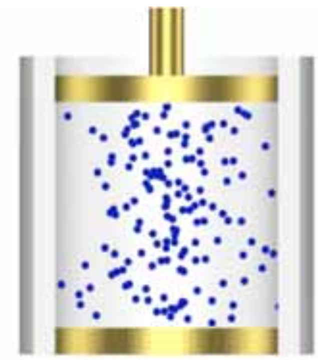
$$[\text{force}] \times [\text{distance}] = \frac{ml}{t^2} \times l = m\frac{l^2}{t^2}$$

When a force acts on an object over a distance it does work that can show up as kinetic energy or be stored as potential energy

Work by pressure

PV $\quad$ $\text{pressure} \times \text{volume} = \frac{\text{force}}{\text{area}} \times \text{volume}$

$$[\text{pressure}] \times [\text{volume}] = \frac{m}{lt^2} \times l^3 = m\frac{l^2}{t^2}$$



Thermal Energy

$\frac{1}{2}NRT \equiv \frac{1}{2}nk_BT$

Thermal energy per degree of freedom at temperature T.

- N — number of moles†
- R — the gas constant $\quad R = 8.31447\ \frac{\text{Joules}}{\text{mole K}}$
- T — temperature in Kelvins

Alternatively,

- n — number of molecules
- k_B — Boltzmann's Constant 1.381×10^{-23} J K^{-1}
- T — temperature in Kelvins

$$[\text{NRT}] = \text{moles} \times \left(\frac{\text{Joules}}{\text{mole K}}\right) \times \text{K} = m\frac{l^2}{t^2}$$

Kinetic energy of all the molecules makes its appearance as heat

† Note that the *mole* departs from MKS units: It is a gram molecular weight, the molecular weight of a compound expressed in grams.

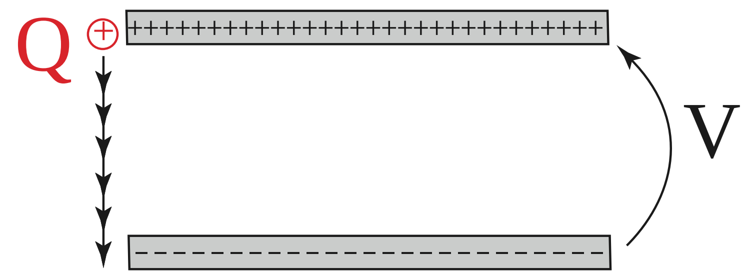
THERMAL ENERGY $NRT \equiv nk_B T$

Convenient, colloquial unit of energy: the BTU

1 BTU = energy to heat 1 pound of H_2O from 60° to 61° F

ELECTRICAL ENERGY $Q \times V$

- Q — CHARGE
- V — ELECTROSTATIC POTENTIAL



Electrostatic potential $\Rightarrow$ Electric field $\Rightarrow$ Force
and the force does work on a charge that is moved.

How to measure electrostatic potential in SI Units?

What potential do you have to move one Coulomb of charge through to get (or lose) 1 Joule of energy:

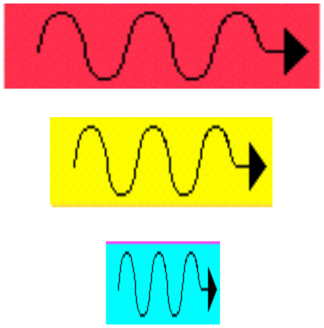
$$1\text{ Volt} = \frac{1\text{ Joule}}{1\text{ Coulomb}} = \frac{1\text{ Joule/sec}}{1\text{ Coulomb/sec}} = \frac{1\text{ Watt}}{1\text{ Ampere}}$$

Two forms of energy that may not be as familiar...

Quantum Energy

$$E = h\nu \qquad h = 6.626 \times 10^{-34}\,\mathrm{J\,s}$$

- h is Planck's constant
- ν is the frequency of light.
- Energy of one quantum of light (photon).



$$[\text{energy}] = [h] \times [\text{frequency}]$$

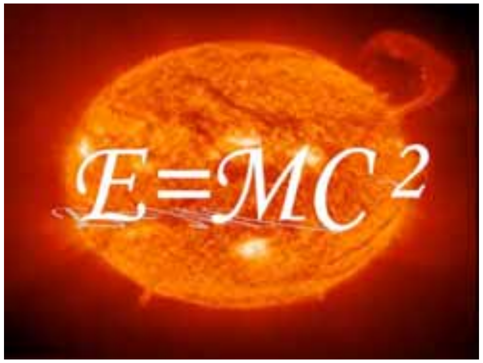
$$\frac{ml^2}{t^2} = [h] \times \frac{1}{t}$$

$$[h] = [\text{energy}] \times [\text{time}] = \mathrm{J\ s}$$

Einstein's rest energy: $E = mc^2$

Einstein's relativity showed that mass itself is a form of energy with the speed of light as the conversion factor...

$$\begin{aligned} E &= mc^2 \\ [E] &= [mc^2] = \frac{ml^2}{t^2} \end{aligned}$$



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There's no other quantity that is described in more different units than energy.

- exajoules, quads, teraWatt-years — GLOBAL UNITS
- tonnes of coal, tons of TNT, barrels of oil, therms, kiloWatt hours — INDUSTRIAL STRENGTH UNITS
- BTU, kilocalories — HUMAN SIZED UNITS
- calories, foot-pounds, Joules — CHILD SIZED UNITS
- ergs, electron-Volts — MICROWORLD UNITS

- ENERGY UNITS
- POWER UNITS

Units of Energy and Power

1 electron volt (eV)	≅ 1.602 x 10^{-19} J
1 eV per molecule	≅ 96.49 kJ mol^{-1}
1 erg	≡ 10^{-7} J
1 foot pound	≅ 1.356 J
1 $calorie_{IT^*}$ (cal_{IT})	≡ 4.1868 J
1 $calorie_{th^*}$ (cal_{th})	≡ 4.184 J
1 BTU_{IT^*}	≅ 1.055 kJ
1 $kilocalorie_{IT^*}$ (kcal) or $Calorie_{IT^*}$ (Cal)	≡ 4.1868 kJ
1 kilowatt-hour (kWh)	≡ 3.6 MJ
1 cubic meter natural gas	~ 36 MJ
1 therm (U.S.)	≅ 105.5 MJ
1 tonne TNT (tTNT)	≡ 4.184 GJ
1 barrel of oil equivalent	≡ 5.8×10^6 BTU ≅ 6.118 GJ
1 ton of coal equivalent	≡ 7 $Gcal_{IT}$ ≡ 29.3076 GJ
1 ton of oil equivalent	≡ 10 $Gcal_{IT}$ ≡ 41.868 GJ
1 quad	≡ 10^{15} BTU ≅ 1.055 EJ
1 terawatt-year (TWy)	≡ 31.56 EJ
1 watt (W)	≡ 1 joule/sec
1 foot pound per second	≅ 1.356 W
1 horsepower (electric)	≡ 746 W
1 ton of air conditioning	≅ 3.517 kW

≡ ↔ definition *th ≡ thermochemical
≅ ↔ four significant figures *IT ≡ International Table
~ ↔ actual value varies

Energy Units

Global Units†,⋆

Unit	SI equivalent	2005 Human Consumption
Exajoule (EJ)	$\equiv 10^{18}$ J	488 EJ
Quadrillion BTU (quad)	$\approx 1.055 \times 10^{18}$ J	463 quads
Trillion Kilowatt-hours	$\equiv 3.6 \times 10^{18}$ J	136 TkWh
Terawatt-years (TWyr)	$\equiv 31.54 \times 10^{18}$ J	14.5 TWyr

World Total Energy consumption (2005)		488 EJ
World Oil consumption (2006)	31.0×10^9 barrels	190 EJ
World Net Electricity consumption (2005)	15.7 TkWh	56.5 EJ
U. S. Total Energy consumption (2005)	101 quads	106 EJ
U. S. Oil consumption (2006)	6.9×10^9 barrels	42 EJ
U. S. Total Electricity consumption (2005)	2.8 TkWh	10.1 EJ
U. S. Transportation energy consumption	28.4 quads	30.0 EJ

† $\equiv$ means it's a definition
$\approx$ means it's given to 4 significant figures
$\sim$ means it's a "nominal" value. Actual value varies, quoted value is often used

⋆ From U. S. DOE Energy Information Administration Website

Industrial Strength Units†

Unit	SI equivalent	Approximate physical significance
1 kWh	$\equiv$ 3.6×10^6 J	
therm	$\approx$ 1.055×10^8 J	10^5 BTU Raise 1000 lb of H_2O 100° F
million BTU	$\approx$ 1.055×10^9 J	
Ton TNT	$\equiv$ 4.184×10^9 J	Definition. Approx chemical energy in 2000 lb of TNT
Barrel of oil	$\sim$ 6.12×10^9 J	Definition: 5.8×10^6 BTU energy of $\sim$159 liters of oil
tonne of coal	$\sim$ 2.9×10^{10} J	Definition: 7 GCal Energy in 1000 kg of coal

Notice how many units are close to 10^9 J — not an accident
— close to one human year of work (see later!)

Human sized and Child sized units†

Unit	SI equivalent	Approximate physical significance
1 calorie	$\equiv$ 4.1868 J	Energy needed to heat 1 gram H_2O 1 °C
1 ft-lb	$\approx$ 1.356 J	Lift one pound 1 foot against earth's gravity
1 BTU	$\approx$ 1.055×10^3 J	Heat 1 lb H_2O from 60° to 61° at one atm
1 Calorie or Kilocalorie	$\equiv$ 4.1868×10^3 J	

Microworld Units

Unit	SI equivalent	Physical significance
erg	$\equiv 10^{-7}$ J	cgs unit $\equiv$ 1 gm-cm/sec^2 $\equiv$ 1 dyne-cm
eV	$\approx 1.602 \times 10^{-19}$ J	Move one electron through one volt

More on the electron volt and erg

- Charge of 1 electron $= 1.602176462(63) \times 10^{-19}$ Coulombs

  1 (electron charge) × 1 Volt = 1 "electron-volt" = 1 eV

  $1 \text{ eV} = 1.602176462(63) \times 10^{-19}$ Joules
- Energy of a single quantum ($E = h\nu$) of green light is 2.5 eV
- Present record computer efficiency is $\sim$ 36 flop/erg†

  which is 2.78 kJ/TFlop

† The "Green 500" website http://www.baselinemag.com/c/b/Projects-Management/ lists a Blue-Gene-L supercomputer at Daresbury Lab, GB, as the most efficient computer in 2007

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Power Units

Unit	SI equivalent	Physical significance
Watt	$\equiv$ 1 J/sec (SI Unit)	One Ampere thru one Ohm resistance (for example)
foot-lb/sec	$\approx$ 1.356 W	Just what it says!
horsepower	$\equiv$ 746 W	Just what it says!

Power back to energy:

1 Watt-second $=$ 1 Joule, or more commonly

1 kilowatt-hour $=$ 1 kWh $=$
$10^3 \times 3600 = 3.6 \times 10^6$ Joules = 3.6 MJ

1 MJ $=$ 1 "MegaJoule" $\approx$ 5-10 hard-working human beings working for an hour

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A guide for our tour: The workingman (or woman).

Although we use Joules for units (as consistently as possible), it will be helpful to relate to a human scale. 100 Watts is an average value for power production by a manual laborer...

100 Watts for 8 hours a day, 200 days a year ⇒ THE HUMAN YEAR = HYR

One  $= 100\frac{\text{Joules}}{\text{second}} \times 8\frac{\text{hours}}{\text{day}} \times 3600\frac{\text{seconds}}{\text{hour}} \times 200\frac{\text{days}}{\text{year}} = 580 \text{ MegaJoules}$

- A typical gamma-ray burst — perhaps the collapse of a neutron star to form a black hole

  10^{44} Joules 1.7×10^{35} 

- Solar energy output in a year

  3.8×10^{26} Watts $\times$ 3.16×10^{7} seconds/year $= 12 \times 10^{34}$ Joules

  (12×10^{34} J/year) / (580 MJ/hyr) 2.1×10^{26} /year

- World annual human energy consumption in 2005

  490 EJ = 884×10^9

  Efforts of > 100 times the earth's population for a year

- Annual energy losses in U. S. (2005)

  56 quads $\times$ 1.055 EJ/quad = 59 EJ

  59 EJ = 102×10^9

  Efforts of ~ 15 times the earth's population for a year

- Rest energy of a person

  80 kg $\times$ $(3\times10^8$ m/sec$)^2$ = 7.2 EJ

  7.2×10^{18} J = 12.4×10^9

  Efforts of 2 times the earth's population for a year

- Solar radiation arriving at the top of the earth's atmosphere per second

  1.7×10^{17} J = 2.93×10^8

  Efforts of ~ U. S. population for a year

- Annual output of typical nuclear power plant

  1 GW $\times 3.6 \times 10^7$ sec/year = 3.6×10^{16} J

  .036 EJ = 6.2×10^7

  Efforts of 2 times California's population for a year

- U. S. per capita yearly energy consumption in 2005

$$106 \text{ EJ} / \ 300 \times 10^6 \text{ people} = 350 \text{ GJ/person}$$

350 GJ/person = 600 /person   Compare to world: 130 /person

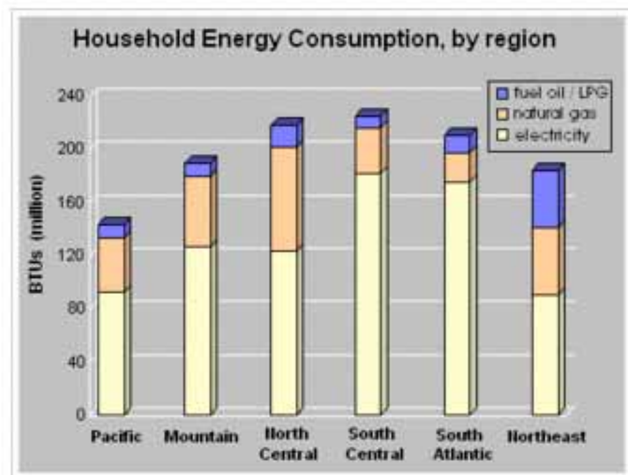
Per day? 1 GJ/(person-day) ≈ 2 /(person-day)

- Average yearly Northeast U. S. household energy consumption

$$180 \times 10^6 \frac{\text{BTU}}{\text{year}} \times 1.06 \times 10^3 \frac{\text{Joule}}{\text{BTU}}$$

= 191 GJ/year

191 GJ/year = 329 /household



http://en.wikipedia.org/wiki/Energy_use_in_the_United_States

- Energy required per person BOS-LAX via Boeing 747

$$0.01 \text{ gallon/mile} \times 2600 \text{ miles} = 26 \text{ gallons}$$
$$142 \text{ MJ/gallon of Jetfuel} \times 26 \text{ gallons} = 3.692 \text{ GJ}$$
$$3.692 \text{ GJ} \Rightarrow 6.36$$

http://travel.howstuffworks.com/question192.htm

A plane like a Boeing 747 uses approximately 1 gallon of fuel (about 4 liters) every second. Over the course of a 10-hour flight, it might burn **36,000 gallons** (150,000 liters). According to Boeing's Web site, the 747 burns approximately **5 gallons of fuel per mile** (12 liters per kilometer).

This sounds like a tremendously poor miles-per-gallon rating! But consider that a 747 can carry as many as 568 people. Let's call it 500 people to take into account the fact that not all seats on most flights are occupied. A 747 is transporting 500 people 1 mile using 5 gallons of fuel. That means the plane is burning 0.01 gallons per person per mile. In other words, the plane is

- One tank of gasoline

$$15 \text{ gallons} \times 3.79 \text{ liters/gallon} = 56.9 \text{ liters}$$
$$56.9 \text{ l} \times 34.8 \text{ MJ/l} = 1.98 \text{ GJ} = 3.4$$

http://en.wikipedia.org/wiki/Gasoline#Energy_content

Fuel type	MJ/litre
Regular Gasoline	34.8
Premium Gasoline	39.5
Autogas (LPG) (60% Propane + 40% Butane)	26.8

- Recommended U. S. dietary energy intake

  2,000 – 2,500 kCal/person-day

  $2000 \text{ kCal/day} \times 4.187 \times 10^3 \text{ J/kCal} \times 365 \text{ days/year} = 3.1 \text{ GJ/ (person-year)}$

  Result: One year's energy intake per person, 3.1 – 3.9 GJ ⇒

  Yearly energy input per person amounts to 5.3 – 6.7 

* Percent Daily Values are based on a 2,000 calorie diet. Your Daily Values may be higher or lower depending on your calorie needs.

	Calories:	2,000	2,500
Total Fat	Less than	65g	80g
Sat Fat	Less than	20g	25g
Cholesterol	Less than	300mg	300mg

Or ≈ 10 MJ/(person-day)

- Energy input to produce average Swedish (where I could find data) diets

  Complex definitions of system boundaries

  Include: crop production, processing, storage, transportation, storage, preparation, cooking...

  Exclude: Capital cost of equipment, packaging, waste, human labor ...

  Result: 6.9 — 21.0 GJ/person-year ⇒ 12 – 36 /person

Ecological Economics 44 (2003) 293–307

ANALYSIS

Food and life cycle energy inputs: consequences of diet and ways to increase efficiency

Annika Carlsson-Kanyama[a,*], Marianne Pipping Ekström[b], Helena Shanahan[b]

The system boundaries in the study included farm production with production of farm inputs, drying of crops, processing, storage and transportation up to the retailer. They also included storage, preparation and cooking in households. The system boundaries excluded production of capital goods such as machinery and buildings, packaging material, waste treatment, transportation from the retailer to the consumer and dishwashing. The economic value of products and by-products was the basis for allocation of energy use during processes with multiple outputs. The energy use was calculated as process energy with no inclusion of production and delivery energy, conversion and transmission losses. Only commercial energy inputs were considered, e.g., inputs derived from electricity, fuel oil, coal or gasoline. Energy inputs from the sun or from human labour were not considered

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Measurement of CO_2 (and other greenhouse gases)

In later lectures we will have much to say about global climate change, its origins and relation to energy use and to CO_2. Here...

- Properties of CO_2.
- Important measures of CO_2.
- Other greenhouse gases.

Properties of CO_2

- Atomic weight 12+16+16=44. Compared to air ≈ 78% N_2 and 21% O_2. Atomic weight 28.6. So CO_2 has density 44/28.6 = 1.54 × density of air.
- Sublimes (directly from solid to gas) at -70°C at atmospheric pressure.
- No liquid state at pressures below 5 atm. At higher pressures CO_2 melts at -57°C.

Important measures of CO_2

- In the atmosphere — in parts per million (ppm)
- Transfer and production through human activity and in earth's carbon cycle — usually in millions of metric tonnes (MMT)
- Emissions in energy processes: kilograms CO_2 per Joule of energy produced (kg/J). (Usually energy produced at the source, not including losses and other inefficiencies.†)

CO_2 in the atmosphere

Pre-industrial concentration: 280 ± 10 ppm.

Present concentration: ≈ 383 ppm.

Increase due to human activity

† For example: Find quoted CO_2 emission per kWh of coal produced electricity. Does not include efficiency of power plant ($\sim 35\%$) or transmission losses, or conversion losses in application.

CO_2 produced by human activity (millions of metric tonnes!)

- Total CO_2 in the atmosphere: 2,996,000 MMT
- World CO_2 emissions from fossil fuel (2007): 28,190 MMT
- Emissions as a fraction of total: 0.94%
- Leading emitters from fossil fuel (2007):

Region	CO_2 (MMT)
United States	5,957
China	5,322
Europe	4,675

- CO_2 emission in U. S. by sector (2006):

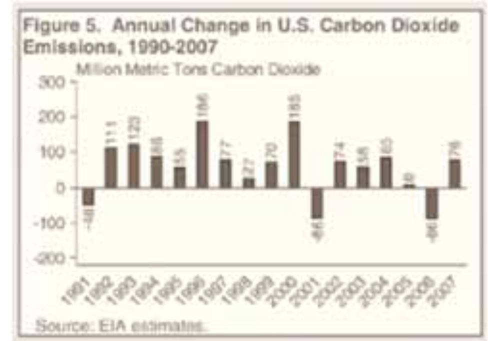
Sector	CO_2 (MMT)
Residential	1,204
Commercial	1,045
Industrial	1,650
Transportation	1,990
Electric Power	2,344

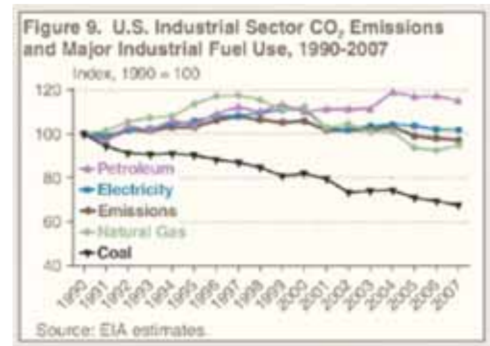
- CO_2 emissions per person in U. S. per year:

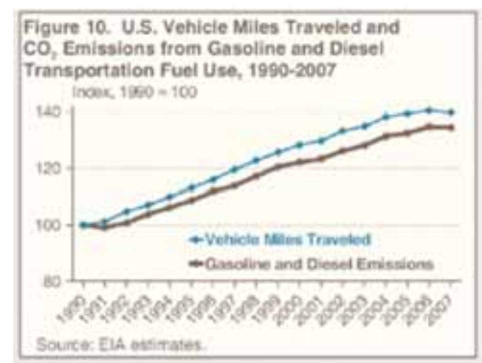
$$\sim \frac{6 \times 10^9 \text{ tonnes}}{3 \times 10^8 \text{ persons}} = 20,000\,\text{kg/person}$$

Staggering!

Some U. S. data







http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html

CO_2 emission in energy processes

Different fossil fuels have different carbon and energy content.

Data typically given in standard unit of kilograms of carbon per million BTU of energy produced at the source. We'll convert to kilograms of CO_2 per GJ of energy.

Fuel	CO_2 emission factor	
	kg(C)/Million (BTU)	kg(CO_2)/GJ
Coal	~ 26	90
Jet fuel, kerosene, gasoline	~ 19	66
Liquified petroleum gas	~ 17	59
Natural gas	~ 14.5	50

Other greenhouse gases:†

- Methane (CH_4), nitrous oxide (N_2O), and a variety of chloro- and fluorocarbons (collectively *halocarbons*) contribute significantly to the greenhouse effect.

Gas	Current concentration	GWP	Atmospheric lifetime (years)	Increased radiative forcing (W/m^2)
Carbon dioxide	383 ppm	1	Variable (5 – 200)††	1.66
Methane	$\sim$ 1800 ppb	23	$\sim$ 12	0.5
Nitrous oxide	319 ppb	296	114	0.16
Halocarbons	$\sim$ 1 ppb	140 — 10,000	5 – 250	0.34

- GWP is a measure of "global warming potential" (per unit mass) with CO_2 defined as 1.
- "Increased radiative forcing" is the increase in the rate that energy is made available at the earth's surface due to this greenhouse gas, measured in W/m^2 and can be compared with the solar energy input.
- Source: *Carbon Dioxide Information Analysis Center*, cdiac@ornl.gov.

† Water, while an important greenhouse gas, is omitted from the table.

†† Atmospheric lifetime of CO_2 is hard to estimate because so many different processes affect it.

Outline

- The basics: MKSA units
- The principal players: energy, power, force, pressure
- The many forms of energy
- Translations and scales: units and energy subcultures
- A tour of the energy landscape: From the macroworld to our world
- CO_2 and other greenhouse gases: measurements, units, energy connection
- Perspectives on energy issues --- common sense and conversion factors

1. The energy content of matter is enormous

Matter equivalent of annual human energy budget:

$$\begin{aligned} 4.9 \times 10^{20}\ \mathrm{J} &= Mc^2 \\ c &= 3.0 \times 10^{8}\ \mathrm{m/sec} \\ M &= 4.9 \times 10^{20}/9.0 \times 10^{16} \\ &= 5.4 \times 10^{3}\ \mathrm{kg} \end{aligned}$$

not even heavy lifting!

What does one gram buy?

$$10^{-3}\,\mathrm{kg} \times (3 \times 10^{8}\,\mathrm{m/sec})^2 = 9 \times 10^{13}\ \mathrm{J}$$

enough to run a 2.86 megawatt powerplant for a year.

2. The solar energy incident on the earth is enormous

Sun's energy incident at the top of the earth's atmosphere varies between 1321 and 1412 watts/m^2 throughout the year. Average of 1366 watts/m^2. Solar power incident on the earth

$$1366\ \text{W/m}^2 \times \pi R_\oplus^2 \approx 1.74 \times 10^{17} W = 0.174\ \text{EJ/sec}$$

so in 488/(.174) seconds = 47 minutes the sun delivers all the energy used by humanity in a year.

3. Estimate what area of solar would provide U. S. annual energy budget at 100% efficiency?

- Find data: National Renewable Energy Laboratory has solar radiation atlas.
  (www.nrel.gov/gis/solar.html)

- Convert to SI units: Units are "kWh/m^2/day", 1 day = 24 hours,

$$1\,\text{kWh/day} = 1\,\text{kWh} \div 24\text{h/day} \approx 42\,\text{W}$$

AVERAGE POWER

So insolation is 42 W/m^2 times the factor, I, in the table. Compute area needed for $E = 1.05 \times 10^{20}$ J/year

- Take $I = 6.5$ (looks typical for American southwest),

$$1.05 \times 10^{20}\text{J/year} \div (3.15 \times 10^{7}\ \text{sec/year}) \div (6.5 \times 42\ \text{W/m}^2)$$

$$= 1.2 \times 10^{4}\ \text{km}^2$$

$$\text{Collector area} = 1.2 \times 10^4\ \text{km}^2$$

Looks pretty promising. It's the reason why we believe solar energy is the best long-term energy source. Warning, big multiplication factor from inefficiencies (stay tuned).

4. What's the ratio of typical carbon based energy source to typical nuclear energy source?

- Atomic energy scales are eV — energy necessary to ionize hydrogen is 13.6 eV.
- Nuclear energy scales are MeV — energy necessary to remove a proton from a typical nucleus is $\sim$ 8 MeV.
- Energy of reaction for $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ is $\sim$ 3 eV/reaction.
- Energy of reaction for fission of uranium is $\sim$ 200 MeV/reaction.

Nuclear fuels have roughly 1 million times the energy density of carbon fuels.