$$\frac{5 \text{ liters}}{\text{Second}} * \frac{60 \text{ second}}{\text{min}} * \frac{60 \text{ min}}{\text{hour}} * \frac{24 \text{ hour}}{\text{day}} * \frac{365 \text{ day}}{\text{year}} * \frac{1000 \text{ cm}^3}{\text{liter}} * \frac{\text{m}^3}{10^6 \text{ cm}^3} = \frac{2\text{x}10^5 \text{ m}^3}{\text{year}}$$

Practice: How much energy is produced by a wind turbine running at 7 kW for 20 minutes?

7 kW * (20min) * (1hr/60min) = (7 * 1/3) kWh = 2.33 kWh = **2 kWh**

Practice: Fossil fuels are so useful because they pack a large amount of potential energy into a relatively small volume. Consider, for example, the 40-liter gasoline tank of my car.

a. How many hours of manual labor would it take to expend the same amount of energy contained in a full tank of gas? (The average person expends about 300 Calories per hour performing yard work.)

$$40 \text{ L gasoline x } \frac{35x10^6 J}{1\, L\, gas} \text{ x } \frac{1\, kcal}{4187\, J} \text{ x } \frac{1\, hour\ of\ labor}{300\, kcal} = \textbf{1100 hours of labor}$$

b. If I use a full tank of gas after five hours of driving, what is the average *input* of power (in kW) to the motor during that period?

$$\frac{40\, L\, gas}{5\, hours} \text{ x } \frac{35x10^6 J}{1\, L\, gas} \text{ x } \frac{1\, hour}{3600\, sec} \text{ x } \frac{1\, W}{1\, J/s} \text{ x } \frac{1\, kW}{1000\, W} = \textbf{78 kW}$$

c. Assume that the average household requires about 1000 W of power. How long would 40 liters of *diesel* provide power to a household? (Assume that 30% of the energy in diesel is converted into electrical energy by a generator.)

$$\frac{40\, L\, diesel}{1\, household} \text{ x } \frac{39x10^6 J_{th}}{1\, L\, diesel} \text{ x } \frac{0.30\, J_e}{1\, J_{th}} \text{ x } \frac{1\, W}{1\, J/s} \text{ x } \frac{1\, household}{1000\, W} \text{ x } \frac{1\, hour}{3600\, sec} = \textbf{130 hours}$$

Practice: Suppose a family spends \$100/month on their electricity bill. How much coal (in kilograms) went into producing their yearly electricity consumption? Assume the price of electricity is 10 cents per kWh and the power plant has a conversion efficiency of 30%. Coal has an energy density of $29.3\text{x}10^6$ J/kg. *Before solving the question, guess the order of magnitude of the answer. This will help hone your intuition.*

$$\left(\frac{\$100}{month}\right) \times \left(\frac{1kWh_{electricity}}{\$0.1}\right) \times \left(\frac{12 months}{yr}\right) = 12{,}000 \frac{kWh_{electricity}}{yr}$$

$$\left(12{,}000 \frac{kWh_{electricity}}{yr}\right) \times \left(\frac{1kWh_{coal}}{0.3kWh_{electricity}}\right) \times \left(\frac{3{,}600{,}000 J_{coal}}{kWh_{coal}}\right) = 1.44 \times 10^{11} \frac{J_{coal}}{yr}$$

$$\left(1.44 \times 10^{11} \frac{J_{coal}}{yr}\right) \times \left(\frac{1kg_{coal}}{29.3 \times 10^6 J_{coal}}\right) = 4{,}915 \frac{kg_{coal}}{yr} = 5x10^3 \frac{kg_{coal}}{yr}$$

Practice: Could the chemical energy content in one teaspoon of sugar be sufficient to heat a cup of water to prepare tea or coffee? Assume that there are 4 grams of sugar in a teaspoon and that 1/20

of a gram of sugar contains about 1,000 J of chemical energy. One cup ~ 250 ml and one teaspoon ~5ml. It takes 4.2 J (or one calorie) to raise the temperature of 1 gram of water by 1 °C.
Before solving the question, take a guess at the answer. Roughly speaking, does this amount of sugar have abundant energy for heating a cup of water, about the right about of energy, or nowhere near enough?

One approach is to use the C_p of water = 4.18 J/g·°C and remind them of $Q=C_p m\Delta T$

Energy in a teaspoon of sugar = $4g \times \left(\frac{1{,}000J}{0.05g}\right) = 80{,}000J$

Energy needed to raise one cup by 1 °C = 250 ml x 1 g/ml x 4.2 J/g·°C = 1050 J/°C

Temperature change in cup = 80,000 J x 1 °C/1050 J = 76 °C = **80 °C**

How hot could we make the water by using the sugar for fusion? Use the famous mass-energy equivalence formula ($E=mc^2$), and assume it takes 2 J to raise the temperature of 1 gram of water by 1 °C[1]. *What kind of units do you need to make this equation work properly if energy is expressed in terms of joules?*

A joule, defined with SI units, is a kg-m^2/s^2. If c, the speed of light, is 2.99×10^8 m/s, then our mass value should be expressed in kg. 4 g = 0.004 kg

$E = 0.004$ kg x $(2.99 \times 10^8 \text{ m/s})^2 = 3.576 \times 10^{14}$ J

Energy needed to raise one cup by 1 °C = 250 ml x 1 g/ml x 2 J/g·°C = 500 J/°C

Temperature change in cup = 3.576×10^{14} J x 1 °C/500 J = **700,000,000,000 °C** (nb: Blow on it first or you might burn your mouth.)

<u>Bonus Question:</u>[2] In lecture, Professor Kammen made the statement that a regular-sized vehicle, driven an average amount, will emit its own weight (about 2 tonnes) in CO_2 each year. Perform a back-of-the-envelope calculation to verify (or refute!) this claim. Assume the vehicle is fueled by octane (C_8H_{18}) and use basic combustion chemistry to inform your calculations.

Assume: 10,000 mi/yr driven
40 mpg fuel economy (a new car, as opposed to an average-aged car)

$C_8H_{18} + O_2 \rightarrow CO_2 + H_2O$ is the general combustion reaction
$C_8H_{18} + 12.5O_2 \rightarrow 8CO_2 + 9H_2O$ is the balanced combustion equation

10^4 mi/yr x 1 gal gas/40 mi = 250 gal gas/yr

250 gal gas/yr x 3.78 L/gal x 0.75 kg gas/L gas x 1 mol C_8H_{18}/0.114 kg C_8H_{18} x 8 mol CO_2/1 mol C_8H_{18} x 44 g CO_2/1 mol CO_2 x 1 tonne/10^6 g = **2 t**

---

[1] The specific heat of water changes depending on its temperature, and in its gaseous form, the value is lower than that of liquid water. With the galactic temperatures we're contemplating here, there isn't really a single sensible number to plug in. Given the extreme scenario we're considering here, there are lots of factors that we're not considering with this simple calculation.
[2] This question is slightly more advanced that material covered on the current problem set. It's here as a challenge problem, so something to come back to in a week or two.

Practice Problems:

1. If a rural community consumes 5 Ha of wood in 2004 and 15 Ha in 2008, what is the rate of growth in their consumption, assuming exponential growth (and continuous growth)?

   Solutions:
   Set up: N(0) = 5 Ha @ t=0 and N(t) = 15 Ha @ t = 4 years
   Solve for r using…

   Exponential growth: $N_t = N_0(1+r)^t$
   $15 = 5(1+r)^4$
   $3 = (1+r)^4$
   $1.32 = 1+r$
   r = 0.32 = 30%/year (1 significant digit)

   Continuous growth: $N_t = N_0 e^{rt}$
   $15 = 5e^{4r}$
   $3 = e^{4r}$
   $\ln 3 = 4r \times \ln e$
   $r = (\ln 3)/4 = 0.27$ = 30%/year

   Note the difference between the exact results from exponential and continuous growth equations, which in this case happen to round to the same answer.

2. It has been observed that in East Africa that an individual may consume 1 ton/year of wood for heating and cooking. If we imagine that wood is $C_6H_{12}O_6$, how many tons of CO_2 per year is this?

   Solution:
   $C_6H_{12}O_6$ = 180 g/mol or 0.180 kg/mol

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

$$1000kg \times \frac{1mol(C_6H_{12}O_6)}{0.180kg(C_6H_{12}O_6)} \times \frac{6mol(CO_2)}{1mol(C_6H_{12}O_6)} \times \frac{0.044kg}{mol(CO_2)} = 1466kg = 1ton$$

   Note that since the problem was 1 ton, we should keep 1 sig dig, but we lose a lot of info, so keeping 1.5 tons (with an explanation) may be more useful….

3. If they are using traditional combustion methods, which may be 10% efficient, and 1 kg of wood has 15×10^6J, what are their daily heating needs in kWh?

$$0.1 \times \frac{15 \times 10^6 J}{kg} \times \frac{1{,}000kg}{1ton} \times \frac{1ton}{1yr} \times \frac{1yr}{365days} \times \frac{1kWh}{3.6 \times 10^6 J} = 1.14 \, {}^{kWh}\!/_{day} = 1 \, {}^{kWh}\!/_{day}$$

AGENDA:

I. Recap: Energy Forms
II. Quick Conversion/Efficiency Problem
III. Harvesting Chemical Potential Energy: Combustion Energy
IV. In-Class Exercise

I. RECAP: ENERGY FORMS

Potential Energy
- Gravitational: hydropower, tidal energy
- Chemical: combustion (*e.g.*, of hydrocarbons, of H2, etc), batteries, food digestion
- Nuclear: fission, fusion, other forms of nuclear decay
- Electric: lightning, heating, cooling etc.

Kinetic Energy
- Wind
- Ocean waves

Wave Energy
- Solar Power (electromagnetic waves)

Other form?

II. QUICK CONVERSION/EFFICIENCY PROBLEM

On September 20, 2013, last Friday, the U.S. Environmental Protection Agency (EPA) proposed Clean Air Act standards to cut **carbon pollution** (yes, it is carbon pollution, not carbon emission) from new power plants in order to combat climate change and improve public health. The standard, which would be finalized in a year, would require new coal plants to emit no more than 1,100 pounds of carbon dioxide per megawatt-hour. New, large gas-fired plants (with a heat input rating of 850 million British Thermal Units per hour) would be restricted to 1,000 pounds of carbon dioxide per megawatt-hour, and smaller gas turbines would be limited to 1,100 pounds. The average U.S. coal plant emits 1,768 pounds of carbon dioxide per megawatt-hour. Natural gas plants emit 800 to 850 pounds. Assume a common coal power plant produces electricity at a rate of 500 MW with 70% capacity factor. If the plant has an efficiency of 33%, what mass of coal is burned every hour? (Coal has an energy density of 30 MJ/kg.) What mass of carbon pollution is discharged each year? (in metric tons per year.) What mass of carbon pollution it has to capture to meet the EPA proposed standard?

Solution:

An efficiency of 33% means that for every 100 units of *thermal* energy put into the generator, 33 units of *electrical* energy is produced. Writing the subscripts *th* and *e* to indicate thermal and electrical energy, respectively, can help keep track of this conversion.

You know that the plant has an output of 500 MW, which means that it produces 500 MJ_e/s. This is a good place to start the conversion, which works form electrical output to thermal input as follows (we don't apply capacity factor for hourly calculation):

$$500MW_e = \frac{500MJ_e}{s} \times \frac{100MJ_{th}}{33MJ_e} \times \frac{1kg\_coal}{30MJ_{th}} \times \frac{3600s}{1hr} = 1.8 \times 10^5 kg/hr = 2 \times 10^5 kg/hr(sig.dig.)$$

Electrical output = (unit conversion) x (1^{st} law efficiency) x (energy density) x (unit conversion)

Use of subscripts, combined with a recognition of whether the problem begins at the thermal input or electrical output side of the power plant, can help to clarify the mechanics of solving many Energy and Society questions.

Annual carbon emission of the typical power plant in the U.S.:

$$\mathrm{CO2}\frac{\mathrm{t}}{\mathrm{yr}} = 500\mathrm{MW} \times \frac{8760h}{yr} \times 0.7(CF) \times \frac{1768pound}{1MWh} \times \frac{1t}{2205pound} = 2.5\ \frac{Mt}{yr}$$
$$= 3Mt\ (sig.fig.)$$

Carbon pollution to capture:

$$\text{Carbon capture} = 2.5\ \frac{\mathrm{Mt}}{yr} \times \frac{(1768 - 1100)}{1768} = 0.94\mathrm{Mt} = 1\mathrm{Mt(sig.fig.)}$$

III. HARVESTING CHEMICAL POTENTIAL ENERGY: COMBUSTION CHEMISTRY

What is a mole? 1 mole of a substance always contains 6.02×10^{23} or Avogadro's number of representative particles.

$$\text{Moles} = \frac{Mass(in\ grams)}{Molecular\ Weight\ (in\ grams/mol)}$$

1 mole of an ideal gas occupies 22.4L or $22.4 \times 10^{-3} m^3$ at STP. Alternatively, there are 44.6 mol of ideal gas in 1 m^3.

Simple combustion (in a pure oxygen environment)

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

Real combustion:

$CH_4 + \alpha(O_2 + 3.78N_2) \Rightarrow CO_2 + n/2H_2O + 3.78\alpha N_2$

Example: The most common method of producing hydrogen today is by steam reforming of methane. What are the value of x, y and z in the reaction below?

$CH_4 + x\ H_2O \Rightarrow y\ CO + z\ H_2$

A fun way to think about the example above: suppose you are trying to make various food items. You can buy a "European snack pack" which consists of one vegetable cutlet (C) and four slices of Havarti cheese (H_4). You can also buy bagels, which always come as two halves and are shaped like rings (O_2). For methane combustion, the question is, how can you combine the snack packs and bagel sandwiches to make closed culet sandwiches (CO_2) and open faced cheese sandwiches (H_2O)? For hydrogen production, the question is, how can you combine snack packs and open faced cheese sandwiches to make open faced culet sandwiches (for vegan), and slices of cheese (for carb-counters)?

More practice problems:
Example 1: What mass of carbon dioxide would be produced if 100g of butane (C_4H_{10}) are completely oxidized to carbon dioxide and water?
Example 2: Worldwide combustion of methane CH_4 (natural gas) provides about 8.2×10^{16}KJ of energy per year. If methane has an energy content of 39×10^{3}KJ/m3 (at STP), what mass of CO_2 is emitted into the atmosphere each year? Also, express that emission rate as metric tons of carbon (not CO_2).
Example 3: Diesel ($CH_{1.8}$) engines are used to generate electricity on a stand by basis (i.e. when there is a power cut) or in remote areas where there is no access to electricity. Balance the combustion equation for diesel. How much carbon is emitted for every kg of diesel burned? What is the mole fraction of CO_2 in the exhaust?

Solutions:

Example 1:

$C_4H_{10} + 6.5O_2 \Leftrightarrow 4CO_2 + 5H_2O$

$$100gC_4H_{10} \times \frac{1molC_4H_{10}}{58gC_4H_{10}} \times \frac{4molCO_2}{1molC_4H_{10}} \times \frac{44gCO_2}{1molCO_2} = 3.0\times10^2 gCO_2$$

Example 2:

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

$$8.2\times10^{16}\,\tfrac{kJ}{yr} \times \frac{1m^3CH_4}{39\times10^3 kJ} \times \frac{44.6molCH_4}{1m^3CH_4} \times \frac{1molCO_2}{1molCH_4} \times \frac{44gCO_2}{1molCO_2} \times \frac{1tCO_2}{10\times10^6 gCO_2} = 4.1\times10^9\,\tfrac{tCO_2}{yr}$$

$$4.1\times10^9\,\tfrac{tCO_2}{yr} \times \frac{12tC}{44tCO_2} = 1.1\times10^9\,\tfrac{tC}{yr}$$

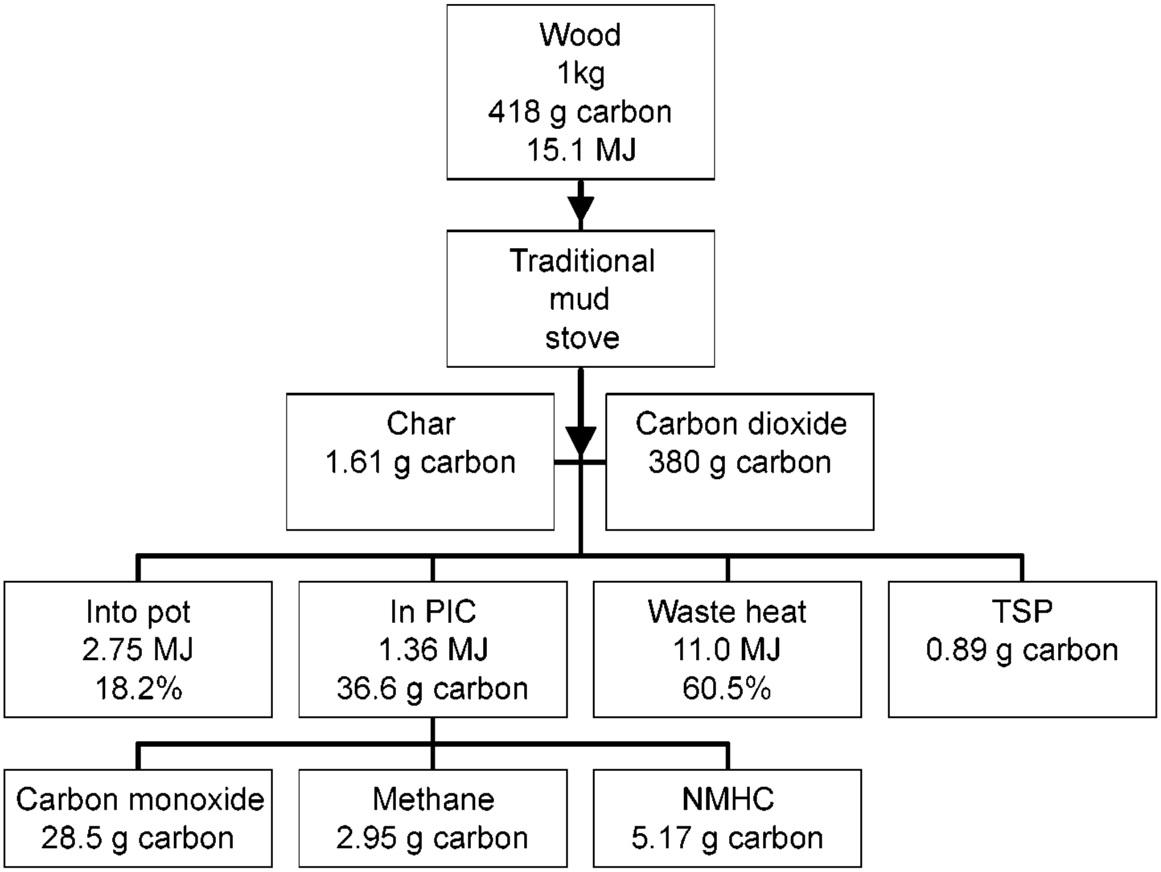
Example 3:

$CH_{1.8} + 1.45O_2 \Leftrightarrow CO_2 + 0.9H_2O$

$$1000.gCH_{1.8} \times \frac{12gC}{13.8gCH_{1.8}} = 870gC$$

$$\frac{1molCO_2}{1.9mol(exhaust\_gas)} =$$ mole fraction of 0.53

V. IN-CLASS EXERCISE



Note: NMHC: Non-Methane Hydrocarbon; TSP: Total Suspended Particulates; PIC: Products of Incomplete Combustion.
Adapted from: Smith, K.R., *et. al.*, 2000. Greenhouse Implications of Household Stoves: An Analysis for India. Annual Review of Energy and the Environment 25, 741–763.

1. Write the balanced reaction of the complete combustion of wood/cellulose in air.

$C_6H_{10}O_5 + 6(O_2 + 3.78N_2) \Rightarrow 6CO_2 + 5H_2O + 3.78N_2$

2. Calculate the number of moles of wood in 1 kg. Balance the reaction with this number of moles.

$1000g/(12\times6 + 1\times10 + 16\times5)g/mol = 6.2$ mol
$6.2C_6H_{10}O_5 + 37.2(O_2 + 3.78N_2) \Rightarrow 37.2CO_2 + 31H_2O + 141N_2$

3. Consulting the chart, was the combustion complete? How can you tell?

4. How many moles of air are required for *ideal* combustion? How many moles of gases [CO_2, CO, CH_4, non-methane hydrocarbons (modeled as CH_6)] are created via *real* combustion?

Air required: 37.2 moles
CO: 2.4 moles
NMHC: 0.43 moles
CO_2: 32 moles
CH_4: 0.25 moles

5. H_2O, O_2, and N_2 are not accounted for on the chart. How many moles of H_2O were produced by the combustion described by the chart? How many moles of O_2 did not react? (Hint: All of the hydrogen from the wood and all of the oxygen from the wood and air had to go somewhere.)

6.2 moles of wood contains 62 moles of H. from question 4, we know that 0.25*4 moles of H are in CH_4 and 0.43*6 moles of H in NMHC. This sums to 3.6 moles. That means that 62-3.6 = 58 moles of H exist as water. Since there are 2 moles of H per mole of H_2O, there are 58/2 = 29 moles of H_2O produced.

Similarly, the reaction started with 5*6.2 + 37.2*2 = 105.4 moles of O. CO and CO_2 account for 66.4 moles of O, and the 29.2 moles of water add 29.2 moles. Since 66.4 + 29.2 = 95.6 moles of O. This leaves 105.4 – 95.6 = 9.8 moles O. Since there are 2 moles of O per mole O_2, there are 9.8/2 = 4.9 moles of O_2.

6. CO concentrations above 200 ppm (or 0.02% of the gas in the room) are considered dangerous. If 1 kg of wood were burned in an 18 m^3 kitchen, would the associated release of CO pose a health risk? 1 mole of an ideal gas occupies 22.4 L or $22.4x10^{-3}$ m^3.

$18m^3$ x 1 mol / 22.4 x 10^{-3} m^3 = 800 moles of air in the kitchen.

2.4 moles CO / 800 moles air = ~3000 ppm. Health risk!

AGENDA:

I. Energy & Energy Balances
II. Heat Engines
III. Efficiencies
IV. Property Diagrams and Power Cycles
V. Reference:
VI. Practice Problems

I. ENERGY AND ENERGY BALANCES

Our brief foray into *thermodynamics* will give us a more formal definition of energy, get us into *enthalpy* and *entropy*, and give us a foundation for understanding *energy conversion*. Much of thermodynamics concerns the transformation of heat into mechanical energy. At the heart of this transformation is the *heat engine*, a device that converts heat into mechanical energy (think about trying to convert heat to work directly). Regardless of whether the heat engine is a spark ignition engine, a natural gas-fired power plant, a nuclear reactor… the basic principles governing heat engines are the same and we will devote much of this week to understanding heat engines and their thermal (First Law), Carnot, and Second Law efficiencies.

We've been working so far without a formal definition of energy, but here it is:

$$E = U + KE + PE$$

For a change in energy:

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

In words, the energy of a system is equal to the sum of its internal energy (U), its kinetic energy (KE), and its potential energy (PE). In stationary systems (*e.g.*, a power plant) ΔKE and ΔPE are typically zero, in which case ΔE = ΔU. In words, the change in system energy is equal to the change in its internal energy.

Internal energy is a function of temperature, which in closed systems we can represent by:

$$\Delta U = mc_v\Delta T = mc_v(T_2 - T_1)$$

where m is the mass of the substance and c_v is specific heat at constant volume (*i.e.*, assuming the system stays at constant volume).

For solids and liquids the above equation is a fair representation, but gases often involve work done in expansion and compression ("boundary work") in addition to changes in internal energy. The notion of enthalpy (H) was created to account for this boundary work:

$$H = U + PV$$

For the change in enthalpy:

$$\Delta H = mc_p\Delta T + P\Delta V$$

where this time the system is assumed to be at constant pressure. Note that if the PΔV term is zero, as it will be for solids and liquids, ΔH = ΔU and $c_p = c_v = c$. The value of c for water, which is the substance that you'll be most interested in for this course, is 4.184 J/g-ºC.

Using the ideal gas law and a bit of manipulation you can also show that the change in enthalpy is a function of temperature only, which means that:

$$h_2 - h_1 = mc_p(T_2 - T_1)$$

where the lower case h's are specific enthalpy (h = H/m, in units of kJ/kg). This equation is very useful in analyzing power cycles, as we will see below. This equation is also useful when we want to determine how many degrees a nearby power plant increases the temperature of a river or other body of water.

EMPHASIS HERE: For a closed system its change in energy will be the balance between the heat transferred *to* (Q_{in}) and the work done *on* (W_{in}) the system, and the heat transferred *from* (Q_{out}) and work done *by* (W_{out}) the system:

$$\Delta E = (Q_{in} - Q_{out}) - (W_{out} - W_{in}) = Q_{net,in} - W_{net,out}$$

This equation is a generalization of the principle of conservation of energy (First Law of Thermodynamics, see below), which allows us to treat energy as an accounting problem and do energy balances. Note the signs on W.

For stationary systems (where ΔKE and ΔPE are zero) that operate in a cycle ΔU = PE = 0

$$\Delta E = 0 = Q_{net,in} - W_{net,out}$$

and

$$W_{net,out} = Q_{in} - Q_{out}$$

We've already been using this equation (implicitly) in our power plant calculations.

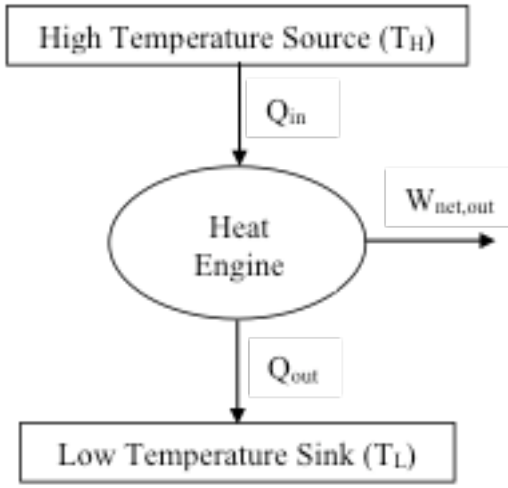
Many problems in thermodynamics involve solving problems where you use information that you have for several states of a system to calculate unknown states. "For instance" (*i.e.*, as in the third problem here), you might know $Q_{net,in}$, $W_{net,out}$, and U_1, and then calculate U_2:

$$U_2 = U_1 + Q_{net,in} - W_{net,out}$$

III. HEAT ENGINES

A heat engine comprises three characteristic processes:

1. Heat is absorbed from a high temperature source (reservoir)
2. Part of this heat is converted to work (usually a rotating shaft)
3. Heat is given off to a lower temperature sink (*e.g.*, rivers, the atmosphere…)



Different heat engines work in different ways but this pattern is always the same. Note that a refrigerator is essentially a heat engine operating in reverse, *i.e.*, taking heat from a lower temperature sink and transferring it to a higher temperature source.

We are going to spend most of our time talking about heat engines that operate in a thermodynamic cycle (*e.g.*, a power plant) – most power producing devices do. Closed systems (*e.g.*, a steam power plant) have a working fluid (*e.g.*, water or air), and the heat is transferred to and from this fluid as it cycles through the system. In open systems (*e.g.*, an internal combustion engine), the working fluid (*e.g.*, air) is continuously brought in from outside the system and released as exhaust outside the system.

Heat engines are governed by two general principles:

- *First Law of Thermodynamics*: Energy cannot be created or destroyed, but can be converted from one form to another.
- *Second Law of Thermodynamics*: It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

The Second Law definition is not particularly intuitive, but can be interpreted in two ways:

1. Heat transfer requires a temperature difference.
2. When work is done there is some inherent inefficiency.

We'll see what this means in practice in our exploration of efficiencies.

IV. EFFICIENCIES

We're going to focus on three primary efficiencies:

1. *First Law or Thermal Efficiency*
   Thermal efficiency is derived from the First Law of Thermodynamics and is the ratio of useful energy – or the net work done by a system – to the total heat put into the system. First Law efficiency is what you use when you talk about the efficiency of a power; you can think of this ratio as describing how efficiently a heat engine converts heat input into work output.

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

Or in the symbols we've defined above:

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

Note from the diagram above that Q_{in} is the heat absorbed from the high temperature source.

Also note that you can substitute the $W_{net,out} = Q_{in} - Q_{out}$ equation into the η_{th} definition:

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

2. *Carnot Efficiency*
   Carnot efficiency is the theoretical maximum efficiency that a heat engine can achieve operating between hot and cold reservoirs with temperatures T_H and T_L, respectively

$$\eta_c = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}$$

   The temperatures here should be in Kelvin → K = ºC + 273.15 or Rankin = 460 + ºF.

3. *Second Law Efficiency*
   Second Law efficiency is a measure of how much of the theoretical maximum (Carnot) you achieve. The Second Law efficiency will always be between the Carnot and First Law efficiencies.

$$\eta_s = \frac{\eta_{th}}{\eta_c}$$

V. PROPERTY DIAGRAMS AND POWER CYCLES

It's important to understand what's happening to temperature (T), pressure (P), volume (V), entropy (S), and heat exchange (ΔQ) in energy conversion systems. For P, V, and T, the ideal gas law is a helpful guide:

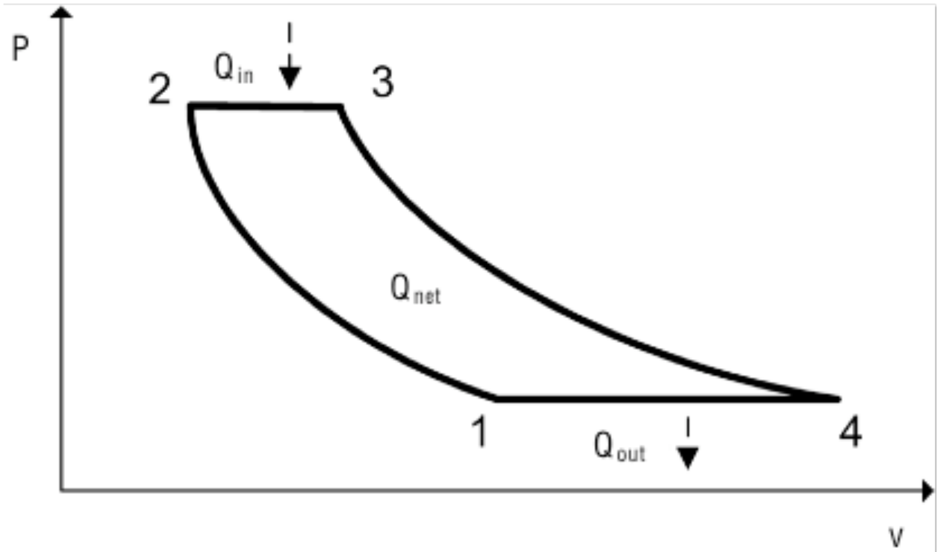
$$PV = nRT$$

where R is the ideal gas constant, which has a value of 8.314 J/K-mol. For instance, in a constant-pressure process an expansion in volume will lead to an increase in temperature. Expansion in an isothermal process requires a drop in pressure, etc.

We're going to look at a gas power cycle (the Brayton cycle in section, but the same general principles and approaches apply to vapor power cycles as well (*e.g.*, the Rankine cycle). The diagram below is a Pressure-Volume (P-V) diagram for the Brayton cycle, which shows how pressure changes with changes in volume during the cycle.

As the diagram shows, there are four processes (the line segments) in the Brayton cycle:

- 1-2 Isenropic compression (compressor)
- 2-3 Constant-pressure heat addition (combustion chamber)
- 3-4 Isentropic expansion (turbine)
- 4-1 Constant-pressure heat rejection (exhaust or heat exchanger)



See the discussion about reversible processes in the Cengel and Bowles to get a better sense of what isentropic means here.

In class example problem: A tank containing water is stirred with a paddle. If we consider the tank to be our control system, and work INTO the tank is 500J, and heat loss from the tank is 100 J, what is the change in internal energy of the tank?

Since there is no KE or PE change in the tank, we can write: $\Delta U = \Delta Q - \Delta W$ **= -100J – (-500J) = 400J**

V. THERMODYNAMIC TERMS AND VARIABLES

Symbol	Term	Definitions and Subscripts
U	Internal Energy	Internal energy is the sum of all forms of microscopic energy for a substance, which depend on molecular structure and molecular activity.
C	Specific Heat	Specific heat is the amount of energy needed to raise a unit mass of a substance by 1 degree, with SI units of kJ/kg-°C. The subscript tells you whether the specific heat is at constant pressure (c_p) or constant volume (c_v)
H	Enthalpy	From the Greek enthalpien (to heat), enthalpy is the sum of internal energy and the absolute pressure times the volume (*i.e.*, the flow work) of a system, H = U + PV. We use enthalpy to account for boundary work (expansion or compression) done by the system.
Q	Heat	Heat is energy transferred between two systems by virtue of a temperature difference. The subscript tells you the direction of heat transfer. Q_{in}, in other words, is heat transfer into the system; Q_{out} is heat transferred out of the system.
W	Work	Work is defined as force acting over a distance in the direction of the force (W = Fd), typically in units of J or Btu. The subscript characterizes work and gives a direction. Wnet,out, for instance, is the net work done by the system.
S	Entropy	Entropy is a measure of disorder in a system, defined formally as:

		$\Delta S = \Delta Q/T$.
η (eta)	Efficiency	The subscript tells you what kind of efficiency eta represents. η_{th} is thermal efficiency, for instance.

Term	**Formal Definition**	**Descriptive Definition**
Adiabatic	$\Delta Q = 0$	No transfer of heat
Isentropic	$\Delta S = 0$	No change in entropy; for a process to be isentropic it must be adiabatic and reversible
Isothermal	$\Delta T = 0$	Constant temperature
Isobaric	$\Delta P = 0$	Constant pressure

VI. PRACTICE PROBLEMS

1. How many Joules are required to heat 5 L of water from 20ºC to 33ºC?

   Using the formula:

   $$\Delta U = mc_v \Delta T = mc_v (T_2 - T_1)$$

   you get:

   $$5\text{L } H_2O \times \frac{1{,}000 gH_2O}{L} \times \frac{4.184J}{g°C} \times (33°C - 20°C) = 3 \times 10^5 J$$

2. Consider a power plant with typical efficiency of 33% and plant electrical output of 1000 MW. Suppose15% of waste heat goes up the smokestack and 85% is taken away by cooling water drawn from a nearby river, which has a flow rate of 100 m^3/sec and a temperature of 20°C. Environmental guidelines suggest the plant limit coolant water temperature rise to 10 °C. What flow rate is needed from the river to carry the waste heat away? What will be the rise in river temperature?

   Wnet,out = Qin-Qout
   Qout=Qin-Wnet,out
   Qout = (1000 MW/.33-1000MW)=2000MW
   Qout,river = 2000MW*.85=1700MW
   mcΔT = Q = 1700 MW = 1.7x109 J/s
   m = 1.7x109 J/s /[(4184J/ kg °C)(10 °C)] = 40.6x103 kg/s of water
   so 40.6x103 kg/s(1 m3/103 kg H20) = 40.6 m3/s of water

   You need 40.6 m3/s of water with the water heating 10 °C
   The river has a flow of 100 m3/s
   Thus the river temperature will rise 40.6/100 = 4.1°C
   The final river temperature will be 24.1 °C

3. A steam power plant with a power output of 150 MW consumes coal at a rate of 60 tons/h. If the heating value of the coal is 30,000kJ/kg, determine the overall efficiency of this plant (from Cengel and Bowles).

With the coal consumption rate and the heating value you can find the total rate of thermal output:

$$\frac{60\text{ tons}}{\text{hour}} \times \frac{1{,}000\text{ kg}}{\text{ton}} \times \frac{30{,}000\text{ kJ}}{\text{kg}} \times \frac{1\text{ hour}}{60\text{ min}} \times \frac{1\text{ min}}{60\text{ sec}} = 500\text{ MW}$$

Since you know that your electrical output is 150 MW, the overall efficiency is:

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{150\text{ MW}}{500\text{ MW}} = 30\%$$

4. A heat engine takes in energy at a rate of 1600 W at a temperature of 1000 K. It exhausts heat at a rate of 1200 W at 400 K. What is the actual efficiency and maximum theoretical efficiency of this engine?

The actual efficiency of this heat engine is:

$$\eta_{th} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{1600\text{ W} - 1200\text{ W}}{1600\text{ W}} = \frac{400\text{ W}}{1600\text{ W}} = 0.25 = 25\%$$

However, its maximum theoretical efficiency is:

$$\eta_c = 1 - \frac{T_L}{T_H} = 1 - \frac{400\text{ W}}{1000\text{ W}} = 0.60 = 60\%$$

So 2nd law efficiency is:

$$\eta_s = \frac{\eta_{th}}{\eta_c} = \frac{0.25}{0.50} = 0.42 = 42\%$$

5. Which segments in the P-V diagram for the Brayton Cycle are adiabatic? Isobaric?

Under the diagram, it tells you that segments 1-2 and 3-4 are isentropic, which means that they have to be adiabatic as well. Segments 2-3 and 1-4 are isobaric.

6. Where in the P-V diagram for the Brayton Cycle is T the highest?

T will be the highest at point 3, after the combustion stage is complete.

7. Based on the discussion in Energy and Energy Balances (in the section handout), how would you write the equation for the changes in enthalpy between 2 and 3? If h_3 is 1400 kJ/kg, h_2 is 500 kJ/kg, T_2 is 500 K, and c_p (for air) is 1.005 kJ/kg-K, what is the value of T_3?

This question is somewhat more challenging to set up, and we wouldn't ask you to do something like this on an exam. We're going to assume that air is an ideal gas. Then, from the section handout you know that:

$$\Delta h = c_p(\Delta T) \quad \text{or} \quad h_3 - h_2 = c_p(T_3 - T_2)$$

Solve for T_3:

$$T_3 = \frac{h_3 - h_2}{c_p} + T_2 = \frac{1400 kJ/kg - 500 kJ/kg}{1.005 kJ/kgK} + 500K = 1400K$$

Energy and Society
Section Handout – Week of October 7, 2013

Content:
1. Economic Analysis
2. *Power Loss* Questions
3. Bonus Problems

1. Economic Analysis

Techniques students should have mastery of:

- Calculating simple payback
- Converting between present and future values
- Converting between NPV and annualized representations of costs
- Calculating (and interpreting) per unit costs (*e.g.*, $/kWh) and costs of conserved energy (value of negawatts)

Important terms and concepts:

Present value	P	The value of any past, future or current costs or benefits at the present time
Time periods	n	Typically defined on a monthly or annual basis, though any financial calculations can be based on continuous analysis too.
Interest/discount rate	r	You may also see as i or d.
Future amount/value	F	Relates a present value (P) to some future value F assuming interests rate r applies for a given time period and n periods have passed. $$F = P(1+r)^n$$
Uniform series	U	Relates a series of n uniform payment each equivalent to U over given time period to a present value P at interest rate r. Use this to determine the annual payments on a loan. $$U = P\frac{r(1+r)^n}{(1+r)^n - 1} = P\frac{r}{1-(1+r)^{-n}}$$
Capital recovery factor	CRF	The factor relating U to P $CRF = \frac{r}{1-(1+r)^{-n}}$ note $\lim_{n\to\infty} CRF \approx r$
Net present value	NPV	The present value of the sum of all expected future cost (Ct) and benefits (Bt) assessed at regular intervals (t) for a time period (n) $$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t}$$

Simple payback, as the name suggests, is a way of calculating how many years it would take to regain what you paid for the technology through the savings incurred by using the technology. This is often used for energy efficient equipment like CFL light bulbs.

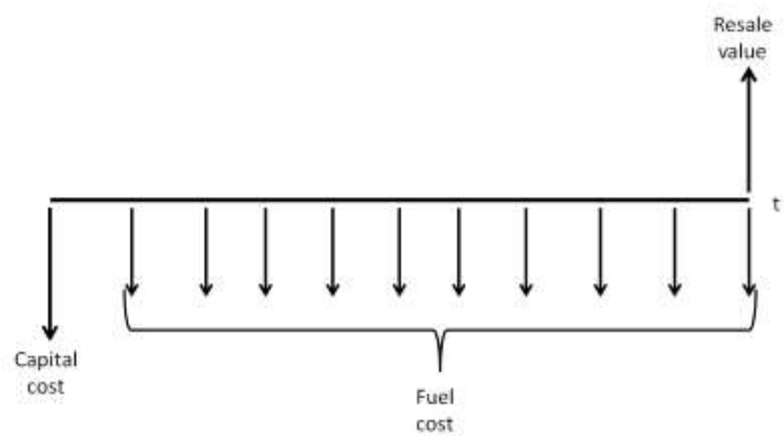
N = P/U

where N= number of years it would take to be paid back, and P and U are the initial capital cost and annual savings, respectively.
Levelized annual cost converts NPV to a uniform series of payments. This is like a mortgage on a house where you pay a monthly installment of the house's total value. Levelized annual cost includes the annual operation and maintenance costs for a technology plus the annualized capital cost (i.e. capital cost converted to a series of uniform payments). It is often useful to draw a cash flow diagram to figure out all these costs.

Practice problems:

1. You buy a car for $20,000, use it for 10 years, drive 10,000 mi/yr, gas costs $4.00/gallon, and the car gets 20 mi/gallon. After ten years, the car can be sold for $2,000. Draw a cash-flow diagram for 10 years. What is the levelized cost of the car per mile driven if we use an interest rate of 3%?

Cash-flow diagram:



Annual cost of gas:

10,000 mi/yr x $\frac{gal}{20\ mi}$ x $\frac{\$4.00}{gal}$ = $2,000/yr

Annualized capital cost:

$$CRF = \frac{0.03}{1-(1+0.03)^{-10}} = 0.1172$$

Present value of $2000 in 10 years = $2000/(1+0.03)^{10} = $1488.19

Total Cap Cost NPV = $20,000 - $1488.19 = $18,511.81

Cap Cost x CRF = Annualized Cost
$18,511.81 x 0.1172 = $2,170.15/yr

Total annual cost = $2,000/yr + $2,170.15/yr = $4,170.15/yr

Cost per mile = \$4,170.15/yr/10,000 mi/yr = **\$0.42/mi**. This is the levelized cost of driving the vehicle, given on a per mile basis.

2. (Based on Ex. 13.9 from Rubin)
An auto repair shop purchases pollution control equipment to capture VOC emissions. The equipment cost \$15,000. It will last seven years and cost an additional \$1,000 per year in O&M costs. After seven years, the owner hopes to get \$2,000 for the salvageable equipment.

a. If the owner of the shop takes a loan to pay for the capital cost of the equipment, how much should she expect her yearly payments to be in order to repay the loan in seven years at 6% interest? (What would her monthly payments be?)

CRF(annual) = 0.1791/yr

Annual payment = Cap Cost x CRF = \$15,000 x 0.1791/yr = \$2,687.03/yr

If r is the annual interest rate, let m be the monthly interest rate:

$(1+m)^{12} = (1+r)^{1}$
m = 0.004868/month

CRF(monthly, with n =7x12=84 periods) = 0.01543

Monthly payment = Cap Cost x CRF = \$217.99

b. If the owner uses her own savings to pay for the equipment, what is the total present value of owning and operating the system? Assume the owner is foregoing a 4% return on her savings.

Present value of capital cost = -\$15,000
Present value of salvage = $\$2,000/(1.04)^{7}$ = \$1519.84
Present value of O&M = \$1,000/yr/0.1666/yr = -\$6,002.05
CRF = 0.1666/y

Total present value = -\$19,482.20

3. An environmental life cycle assessment reveals a number of opportunities where a company can reduce its energy consumption. It is estimated that a total capital investment of \$25 million can reduce annual O&M costs by \$4.5 million a year. What is the simple payback of this investment?

Simple payback = $\$25\text{x}10^{6}/(\$4.5\text{x}10^{6}/\text{yr})$ = 5.6 years

4. A business wants to calculate its savings per year from switching from incandescent flood lights (150 W) to compact florescent lamps (CFLs) (60W)—each to run 3000 hours/year at an electricity price of \$0.07/kWh. The incandescent bulb costs \$4.50 and lasts two years; the CFL costs \$14.50 and lasts eight years—the annual interest rate for both scenarios is 8%. Calculate the savings per year.

Incandescent energy cost = 3000 hr/yr x 0.150 kW x $0.07/kWh = $31.50/yr
CFL energy cost = 3000 hr/yr x 0.060 kW x $0.07/kWh = $12.60/yr

Annualized cap cost of incandescent = $4.50 x 0.5608/yr = $2.52/yr
    CRF = 0.5608/yr
Annualized cap cost of CFL = $14.50 x 0.1740 = $2.52/yr
    CRF = 0.1740

Savings per year = Incandescent cost – CFL costs = ($2.52/yr + $31.50/yr) – ($2.52/yr + $12.60/yr) = $18.90/yr

2. *Power Loss*

What was the "utility consensus"?
What were the technical, economic, and social factors that converged and promoted the consistent reduction of costs and increase of supply?
What are the advantages of vertical integration? When might vertical integration NOT be advantageous?
What factors "stressed" the utility consensus?
How did utilities co-evolve with regulators and consumers?
How did reaching technical limits in generation size impact electric utilities?
What are benefits to smaller generators?
Why didn't utilities have a strong reason to innovate?
Our local utility, PG&E, is a strong promoter of energy efficiency. During the Carter administration, why were utilities so opposed to measures like those that required them to provide their customers with home energy audits?
Do you see any parallels between the process the Carter administration went through with its energy policies in 1977-8 and the experience of the Obama administration with its energy proposals?

Relevant Terms (*for reference*):

Natural monopoly: persistent situation where a single company is the only supplier of a particular kind of product or service due to the fundamental cost structure of the industry i.e. one firm can supply the entire market at a lower price than two or more firms can. Natural monopolies are often contrasted with coercive monopolies, in which competition would be economically viable if allowed but potential competitors are barred from entering the market by law or by force. Two motivations: (1) the standard economic argument that it is simply more efficient to allow large firms exclusive franchises to operate in specific areas and regulate them to ensure all customers are served and monopoly power is not abused and (2) the popular argument that such firms needed to be regulated in order to prevent victimization of powerless consumers.
Vertical integration: the same company owns all the different aspects of making, selling and delivering a product or service. In the electric industry, it refers to the historically common arrangement whereby a utility would own its own generating plants, transmission system, and distribution lines to provide all aspects of electric service.

Utility consensus: set of arrangements for the dominant structure of the utility industry as a regulated monopoly arrived at tacitly by policy makers, utility managers and politicians (no consumer interests mentioned). Froze the industry in a vertically integrated structure that took advantage of huge economies of scale, which enabled them to offer lower costs to consumers over time. Regulation saved utilities from municipal takeovers.
Ideology of growth: bigger-is-better attitude that pervades many aspects of US culture – an unchallenged and hegemonic view. Depicted electricity as a public good, a right of all, a critical aspect of modern living. The power sector became so crucial to the economy that it obtained special status among industries.
Technological momentum: a mass of technical, organizational, and attitudinal components that maintain steady growth and direction. In utility consensus, momentum was built on manufacturers, consulting firms, universities.
Technological stasis: condition that occurs when a technology reaches a limit beyond which improvements in efficiency or output are prohibitively expensive or physically impossible (see Fig. 3.1 on p.57 in Power Loss).
PURPA (Public Utility Regulatory Policy Act): Law requiring IOUs to purchase power from QFs at avoided costs of generation – Hirsh claims that this outcome was actually an unintended consequence of PURPA, which was part of a comprehensive set of energy policies pushed through during the Carter Administration.
QF: A power producer meeting certain criteria such as cogeneration, use of renewable fuels, or achieving a certain efficiency – were allowed to ignore government regulations affecting IOUs.
Avoided cost: basis used for determining the cost that QFs would be offered for their electricity. It was chosen as a politically neutral term, it included capital costs as well as fuel costs.
Market power: market failure which occurs when one or more of the participants has the ability to influence the price or other outcomes in some general or specialized market. The most commonly discussed form of market power is that of a monopoly, but other forms such as monopsony, and more moderate versions of these two extremes, exist.
Efficiency (economic): A term that refers to the optimal production and consumption of goods and services. This generally occurs when prices of products and services reflect their marginal costs. Economic efficiency gains can be achieved through cost reduction, but it is better to think of the concept as actions that promote an increase in overall net value (which includes, but is not limited to, cost reductions). Related to Pareto efficiency (also Pareto optimality or allocative efficiency) in which the market could not reallocate resources through trade, production or consumption to make at least one person better off without making anybody else worse off.

3. Bonus Problem

1. The field of energy has its share of crazy units. Take, for instance, the "ton," a unit used in reference to computer server rooms, which require a great deal of energy to operate and to keep cool. (In 2011, US data centers will consumed about 100 billion kWh.) One *ton* is the heat rate that would melt one short ton of ice in a day.

a. If the specific heat of fusion of water is 334 J/g, what is the total amount of energy (in Btus) required to melt a short ton of ice? What would be the average thermal output rate (in Watts) of a server room required to melt a ton of ice in 24 hours? (Assume that all thermal energy released serves to melt the ice.)

2000. lb. ice x $\frac{454\ g}{1\ lb}$ x $\frac{334\ J}{1\ g}$ x $\frac{1\ Btu}{1055\ J}$ = 2.87×10^5 Btu

$\frac{2000\ lb\ ice}{24\ hours}$ x $\frac{1\ hour}{3600\ sec}$ x $\frac{2.87E5\ Btu}{2000\ lb}$ x $\frac{1055\ J}{1\ Btu}$ = 3500 W

b. You operate a data center with cooling needs of 5.7 tons (a pretty average size). What if, instead of dumping it into the outside, the heat from the data center was used to provide water heating services for a neighboring apartment complex. Given that all the showerheads in the apartment building flow at an efficient 1.7 gpm (gallons per minute), how many showers worth of hot water could be hot water could be generated from the data center's waste heat? Assume that water comes into the building at 62 °F and that the average person showers with 81 °F water, and that no heat is lost between the data center and the hot water tank. *Before calculating the answer, what does your intuition say?*

$\Delta U = mc\Delta T$
ΔU = 5.7 x 3500 W = 19950 W
c = 4.184 J/g•°C
ΔT = (81°F – 62 °F) = (27.2 °C – 16.7 °C) = 10.6 °C
m = (19950 J/s)/(4.184 J/g•°C x 10.6 °C) = 450. g/s

450. g/s x $\frac{60\ sec}{1\ min}$ x $\frac{1\ L\ water}{1000\ g}$ x $\frac{1\ gal}{3.79\ L}$ x $\frac{1\ shower}{1.7\ gal/min}$ = 4.2 showers

AGENDA

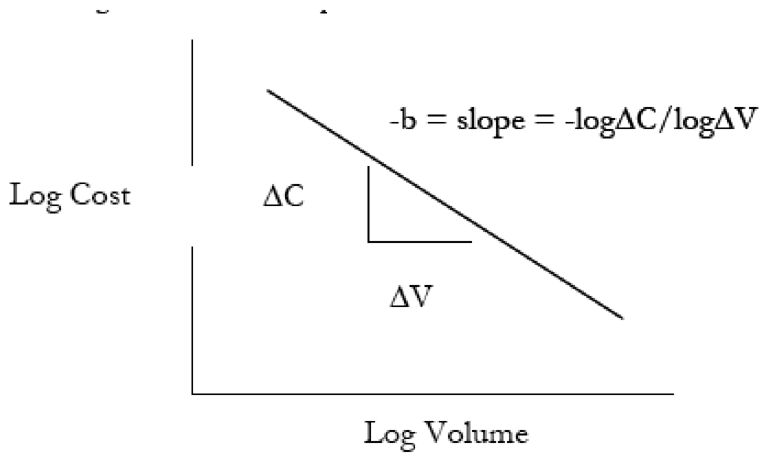
1. Learning curve
2. Energy efficiency
3. Mid-term questions

---

1. <u>Learning curve</u>

The theory of learning curve is that as a technology is disseminated more widely is adopted by more not only do costs fall, but they fall in a predictable pattern. (i.e. the cost of a wind turbine falls as more wind turbines installed). The relationship between the cost of a technology and the volume of it produced is liner on a logarithmic scale. In qualitative terms - this more or less translates to a given percentage increase in volume will lead to percentage decrease in price.

Learning curve derivation.
How do we get these relationships?



Note: Some people will account for the negative slope as part of the value of b, and thus will use b instead of –b

Learning Curve formula:

$$\frac{C}{C_0} = \left(\frac{V}{V_0}\right)^{-b}$$

<u>Progress Ratio</u>
Often, modelers use what is called a "progress ratio", based on a sometimes empirical, sometimes assumed relationship between cost and volume for a given technology. The progress ration is factor that indicates how much the cost will decline given a doubling in volume.
For example, if we expect there to be a 20% decline in cost for energy doubling in volume. Calculate b for such a case:
Doubling in volume means $V_2 = 2V_1$
20% decrease in price means $C_2 = (1 - 0.2)C_1$

$$\frac{C_2}{C_1} = \left(\frac{V_2}{V_1}\right)^{-b}$$

$$\frac{(1-0.2)C_1}{C_1} = \left(\frac{2V_1}{V_1}\right)^{-b}$$
$$\frac{0.8C_1}{C_1} = \left(\frac{2V_1}{V_1}\right)^{-b}$$
$$0.8 = 2^{-b}$$
$$\log 0.8 = \log(2^{-b}) = -\mathrm{b}\log 2$$
$$\mathrm{b} = \frac{-log0.8}{log2} = 0.32$$

From the above example we know that the progress ratio (R) is $R = 2^{-b}$, this is the same as saying

$$C(2V_1) = R \times C(V_1)$$

From this, we can calculate how much we expect cost to decline over time.

If the progress ratio is 0.8, this tells us that if volume double, the new cost $C_2 = 0.8C_1$ i.e. that costs declined by 20%.

Practice problem:

SOLAR energy currently provides only about a quarter of a percent of the world power supply, but the industry is growing at staggering speed. "Underlying this growth is a phenomenon that solar's supporters call Swanson's law, in imitation of Moore's law of transistor cost. Moore's law suggests that the size of transistors (and also their cost) halves every 18 months or so. Swanson's law, named after Richard Swanson, the founder of SunPower, suggests that the cost of the photovoltaic cells needed to generate solar power falls by 20% with each doubling of global manufacturing capacity." Let's calculate if Swanson's law is true or not?

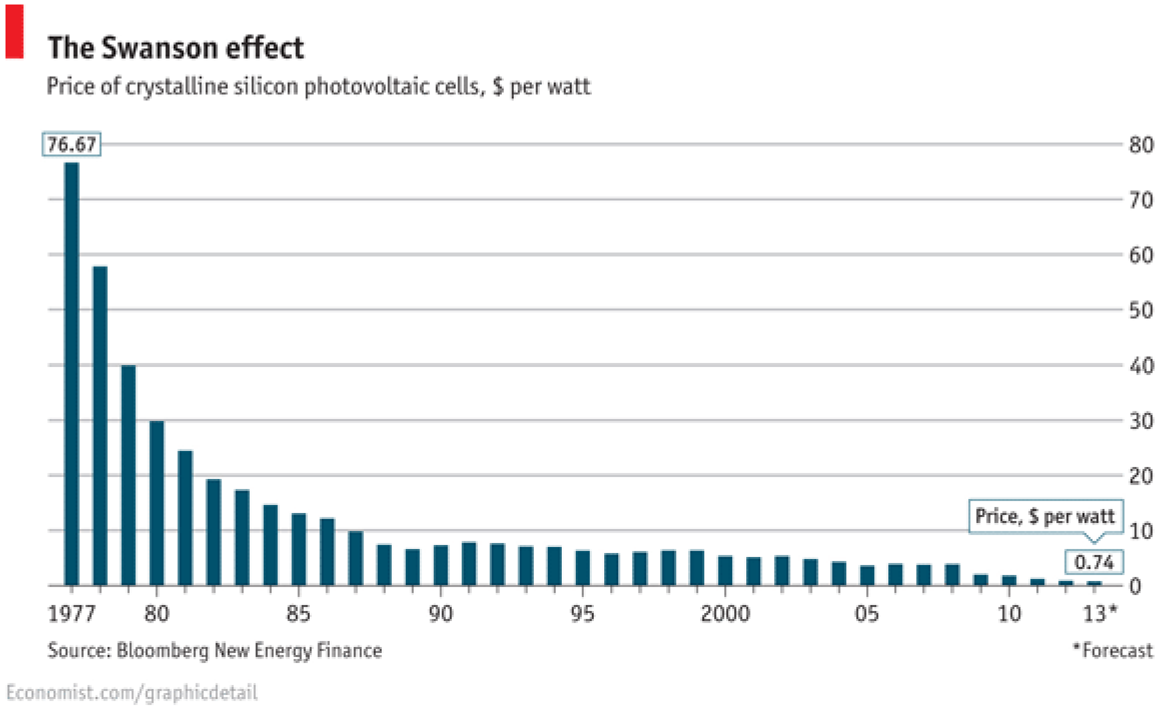
As a background, BP Energy Statistical Review 2013 shows global solar consumption is 400GWh in 1990, to 93TWh in 2012.

See the data for the question from the table:

Year	Installed capacity (GW)	Average cost ($/W)
2000	1.5	5
2011	70	1
2013 (projected)	100	0.74

Data from REN21 Global Status Report and read from the chart.

2011: b = 0.4188, R = 0.7480
2013: b = 0.4549, R = 0.7295   The progress rate is decreasing. And double volume brings down cost about 20% roughly holds, the actual learning rate is better than predicted.



Source: The Economist.

2. <u>Energy efficiency</u>

1) Why energy efficiency?

Energy efficiency (EE) is a significant piece to save energy and mitigate carbon emission. Changing utility economics made energy efficiency (EE) look attractive as a way to combat technological lock-in and stasis.

2) Megawatts versus Negawatts:

Negawatt is a cute term coined by Amory Lovins to describe the effect of very large-scale energy efficiency and stress that energy efficiency measures are equivalent to building new capacity. Of course, equating power not used to power produced is not always so straightforward – plus, not everyone agrees that negawatts and megawatts are equal.

3) If efficiency is such a good thing, why do people not just do it?

(Energy efficiency is) better than a free lunch, it's a lunch you get paid to eat.
-- Amory Lovins

…conservation may be a sign of personal virtue, but it is not a sufficient basis for a sound, comprehensive energy policy.
-- Dick Cheney, from a frequently cited speech made in Toronto in April, 2001

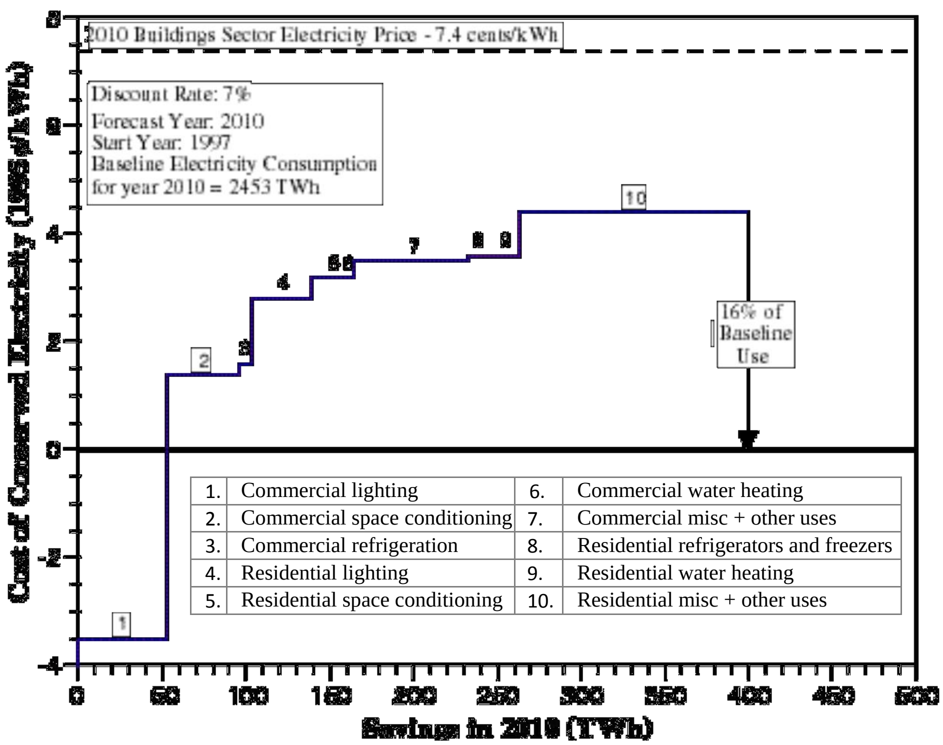
Main barriers for energy efficiency:

Barriers	Policy to address
Information failure	Energy labeling
Externalities	Standards
Economic failure	Building codes
Principle-agent problem	Technology improvement
Behavior failure	Decoupling
Rebound	Education
	Economic incentives
	Subsidies and tax credits
	Time of use price
	Dynamic pricing

4) Cost of conserved energy

We can define the cost of conserved energy (CCE) by looking at a ratio of the cost of the technology or intervention to the quantity of energy saved…

Dan's EE lecture has the following plot (slide. 57). There's a similar one in Hirsch (p. 152) – how do we interpret this?



Interpreting the figure:

This figure works like a supply curve for energy conservation. Drawing a horizontal line at a given cost of power production allows you to determine which energy efficiency measures are cost effective. Drawing a vertical line from the intersection of the horizontal line and the supply curve gives you the quantity of power saved by implementing those efficiency measures.

CCE calculation

$$CCE = \frac{\text{annualized energy cost (\$/yr)}}{\text{conserved energy (kWh/yr)}}$$

…gives you an answer in $/kWh

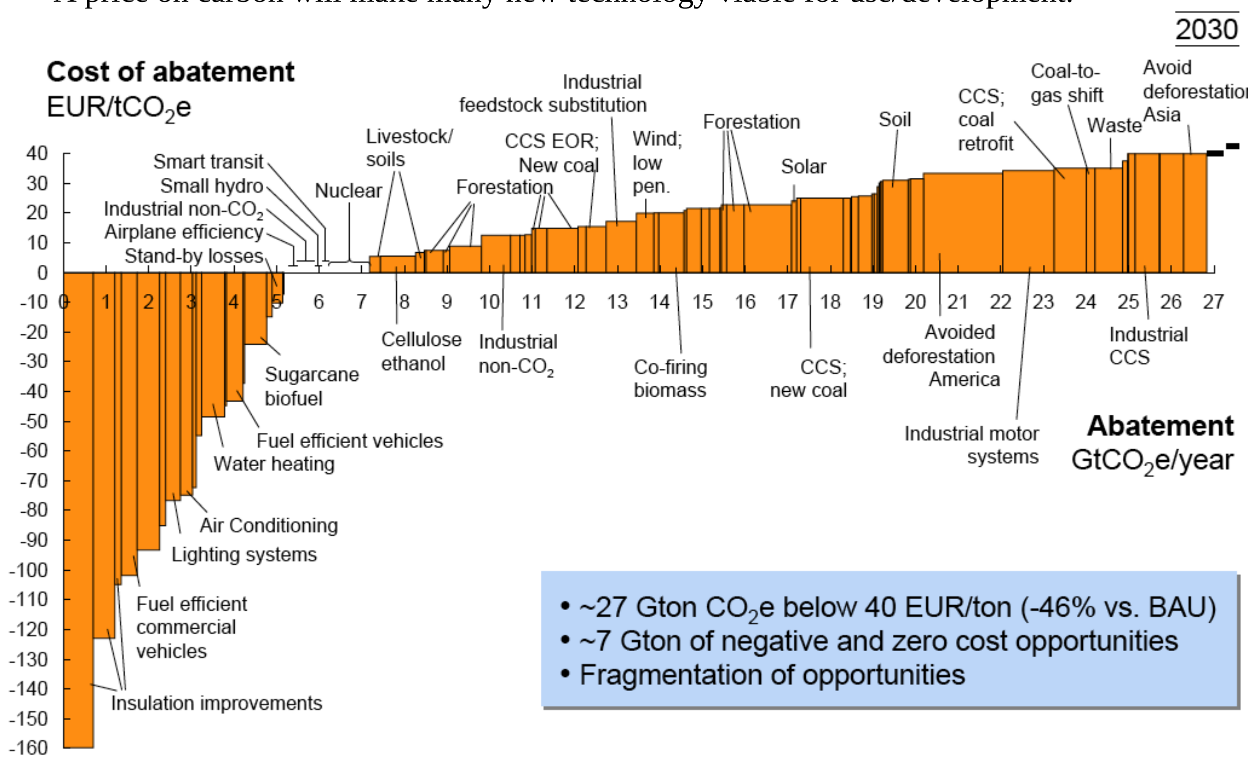
Example:
$100 additional cost for a more efficient refrigerator which saves 250 kWh/year
It lasts 10 years, if the discount rate is 5%, then the CRF = 0.13/year and the CCE is:

$$CCE = \frac{\$100 * 0.13\text{yr}^{-1}}{250 \text{ kWh/yr}} = \$0.05/\text{kWh}$$

Of course, the analysis changes if the old fridge isn't ready to be replaced…
…this is one of the big challenges of EE policies…

5) Carbon mitigation cost curve
Similar to the cost of conserved energy curve, the x-axis is the accumulated carbon/carbon dioxide abatement, and y-axis is the the cost of abatement.

Key messages:
There whole lot of policy/measures with negative cost, they are actually saving money to achieve carbon mitigation.
A price on carbon will make many new technology viable for use/development.



LCA, The Grid

Agenda:

1. **LCA**
2. **The Grid**

Topics: LCA, EIO-LCA; Electric Power Grid; Current, Voltage, and Resistance

Section I. LCA Discussion

- What is the purpose of LCA?
  - Uses of LCA
    - To compare two products (paper and plastic bags)
    - To inform design choices
    - To identify areas for impact reductions (for example, emissions)

  - What is the lifecycle? -- Supply Chain Stages

  1. Raw material extraction
  2. Raw material into products
  3. Manufacturing and assembly
  4. Use phase
  5. Disposal phase
  6. Distribution phases (between each stage)

- What are the differences and relative advantages of “process-based” LCA vs. a tool like EIO-LCA? Discuss briefly how one might go about using either to calculate the greenhouse gas emissions associated with an electric car.
  - Process is extremely difficult, but more exact. Need huge database of parts, precise sense of manufacturing process.
- General discussion of Input-Output Analysis and EIO-LCA

Section II. EIO-LCA Example

Suppose I want to know the $CO2_e$ emissions associated with the construction of a wind farm, using EIO-LCA. The wind farm needs to produce 20 GWh of electricity per year and has a capacity factor of 22.8%. Each 1 MW turbine costs $1M. How can I get an approximate answer?

I could use the "turbine and turbine generator set units manufacturing" sector. Or, to be more specific, I could break the turbine manufacturing into processes and components…. I know that for every 1 MW turbine, I need $100K of carbon fiber. Using the "plastics material and resin manufacturing" sector, I see that there are 1660 tonnes CO_2e emitted $1M of output from this sector. (Not surprisingly, while a quarter of this comes from the manufacturing sector itself, much of the rest comes from "power generation and supply," "oil and gas extraction," "petroleum refineries," and "organic chemical manufacturing.")

Here you start to see the web of interdependencies in the manufacturing sector. And now we can figure out the $CO2_e$ impact of our wind farm—let's use the turbine manufacturing sector for ease.

Specifically, for our problem, if we need to produce 20 GWh of electricity per year:

.228 (cap) x 8760 hours = 1997.28 hours

20 GWh/1997.28 hours = 10 MW capacity

10 MW x 1 M$/1 MW = $10 million dollars of products from the "turbine and turbine generator set units manufacturing" sector = 3980 tCo2e[1].

[1] Carnegie Mellon University Green Design Institute. (2013) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428 sectors) Producer model [Internet], Available from: <http://www.eiolca.net/> [Accessed 21 Oct, 2013]

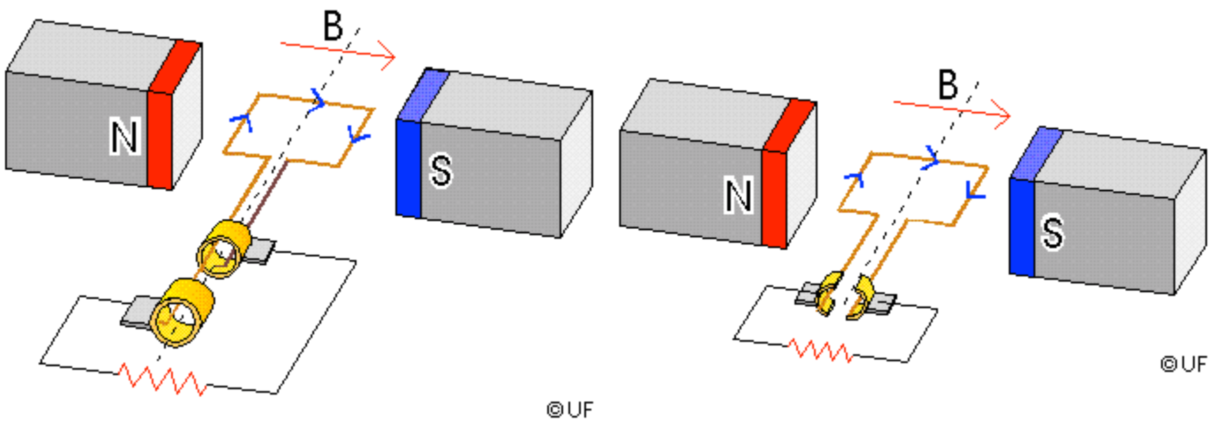
Section III. The Grid – Concepts and Definitions

Concept	**Definition**	**Identity**	**Units**
Charge	Quantitative property attached to an electron (-) or proton (+)	$q_e = -1.60\times10^{-19}$ *q stands for charge*	Coulombs (C)
Current	Net transfer of electrical charge through a given area in a given time	$I = \frac{dq}{dt}$	Ampere (A) 1 Amp = 1 C/second
Voltage	Change in potential energy of a charge. Voltage *rise* indicates an energy source (e.g. battery or generation station) and voltage *drop* indicates an energy sink or load (e.g. light bulb or households).	$V = \frac{dW}{dq}$ *where* *W stands for work or energy*	Volts (V) 1 Volt = 1 Joule/C
Power	Rate of change of energy	$P = \frac{dW}{dt} = VI$	Watts (W) or Volt-Amperes (VA) 1 W = 1 VA
Energy	Integration of power over time	$W = \int_0^t P dt$	Joules (J) or kWh 3.6×10^6J = 1 kWh
Resistance	Impedes the flow of current. Produces a voltage drop and conversion of electrical energy to heat. Proportionality constant describing the relationship between V and I **(Ohms Law)**. R increases with temperature.	$R = \frac{V}{I}$	Ohms (Ω) 1Ω = 1 V/A

Process	**Typical voltages**	**Equipment**
Generation	2-24 kV	Generator (AC, DC) – device that transforms mechanical energy (typically rotational) into electrical energy (more below)
Transmission and distribution	69-765 kV (trans) 23 kV (dist)	Transmission lines, substations, transformers, breakers, relays, reclosers,
Load (use/sales)	120-415 V	Households, commercial and industrial users

Other important terms:

AC – alternating current **DC** – direct current



In a generator a conductor rotated in a magnetic field generates a current. If the conductor is linked to separate but fully cylindrical slip rings, the current is AC (left). If the conductor is linked to broken half rings the current is DC (right).

Battery – a device that stores energy (typically chemical) and releases it as electrical energy in the form of DC current.

Measured in volts (potential difference that exists across the terminals)

Capacity can be measured in amp-hours (units of electrical *charge*) – this comes in handy for assessing energy storage needs… useful for intermittent renewables like PV.

Other important relationships:

Ohms Law: Voltage is proportional to current, and the proportionality constant is resistance R

$V = IR$

Combining Ohm's Law (V=IR) with P=IV gives us:

$P = I^2R$ or $P = V^2/R$

Kirchhoff's Current Law: The net sum of the currents into any node equals zero at each and every instant of time.

$$\sum_{node} I = 0$$

Kirchhoff's Voltage Law: The net sum of the voltages around any loop equals zero at each and every instant of time. $\sum_{\text{loop}}(V - IR) = 0$

Resistances in series and in parallel

You can use Kirchkoff's Laws and Ohm's Law to determine how the resistance changes when you put two equal resistors in series, or in parallel.

Practicalities

- For safety, we need low voltages at end use
- For efficiency, we need high transmission voltages (to minimize resistive losses in the transmission lines).
  $P = I^2 \cdot R = V^2/R$ no matter if P is power delivered to the load or *lost in the lines*.
- Therefore, we need to be able to change voltage

Discussion: Edison (DC) vs. Tesla (AC). Now we are talking about long distance high-voltage *DC* transmission lines. What has changed since the days of Tesla and Edison?

Details, Details: Time-dependence of AC current, reactive power. Regulation of the grid power to meet demand.

Section IV. Grid Example Problems

Example 1:

A typical 12 V car battery stores 5×10^6 J of energy, or slightly over 1 kWh. If the battery is connected to a 4 A headlight, the power delivered to the bulb will be:

P = 12 V x 4 A = 48 W

Example 2:

a) At 120 volts, how much current is needed to supply 10 houses, each with a load of 1,000W? What is the resistance of the load?

P_{Load} *= (10 homes) x (1 kW/house) = 10 kW*

Voltage = 120 V

P=IV, so I = P/V = 10kW /120 V = 83 Amps (8.3 A per household)

$P = I^2 \cdot R_{Load}$, so $R_{Load} = 1.4\ \Omega$

b) Given the resistance in the transmission line, how much power needs to be produced to deliver 10kW to these households? Assume $R_T = 0.5R_L$. What percent of the total power is lost?

$P_{loss} = I^2 \cdot R = (83A)^2 \cdot (0.7\ \Omega) = 4{,}822$ W, so a total of 14,822 W must be generated

Losses are ~33%

Typical system losses in U.S. = 9% (all T&D)

<u>Example 3</u>:

What if we stepped up the voltage to 1,200 volts with identical transmission lines (i.e., R_T = the answer in #2b). What are the power losses?

$I = P/V = 10{,}000/1200 = 8.3$ A (current needed to deliver same power is lower by a factor of 10)

$P_{loss} = I^2 R_T = (8.3A)^2 x(0.7\ \Omega) = 50.7$ W, so a total of 10,050 W must be generated - <u>losses <1%</u>

<u>Example 4</u>:
One AA battery contains 2500 mAh of charge and has an average voltage during discharge of 1.2 V. If a 4-pack of AA batteries costs $3.77, what is the cost per kWh?

2500 mAh x 1.2 V x 3600 s/h = 10,800 J → kWh/3.6 x 10^6 J * 10,800 J= .003 kWh/battery * 4 batteries = .012 kWh → $3.77/.012 kWh → $314 → $310/kWh

---

Section IV: More LCA example problems:

Example #1: Biofuels LCA
A typical yield for an acre of corn is 115 bushels, where each bushel is 56 pounds. 25 pounds are required to produce 1 gallons of ethanol.

(a) Assuming that the corn contains 4 Cal / g, and ethanol is 75,700 Btu/gallon, what is the energy conversion efficiency of the corn into ethanol? If the cornfield received a summertime average of 300 W / m2 of sunlight during its growing season, what is the overall efficiency for the conversion of sunlight striking the field into ethanol?

Energy in corn to make 1 gallon of ethanol:
*4 Cal / g corn * 4184 J/Cal * 25 lb. corn / 1 gallon EtOH*454 g corn/lb. corn = 190.0 MJ*

*Energy in 1 gallon of ethanol: 75,700 BTU / gallon * 1055 J / BTU = 79.9 MJ.*
Efficiency is 79.9 MJ / 190.0 MJ = 42%.

*Total ethanol energy per acre of corn: 115 bushels corn / acre * 56 lb. corn / bushel * 1 gallon EtOH / 25 lb. corn * 79.9 MJ / gallon EtoH = 20,582 MJ / acre.*

Solar energy input per acre of corn (assume a growing season of 4 months):
*300 W / m2 *4,047 m2 /acre*3600 sec/hr*24 hr / day*120 days =12,588,000 MJ / acre.*

Effective solar efficiency to produce ethanol is 20,582 / 12,588,000 = ***0.16%.***

(b) It takes 33,000 cubic feet of natural gas to produce one ton of nitrogen fertilizer, and corn requires about 2 lb. of fertilizer per bushel. Furthermore, the ethanol distillery uses about 28 billion cubic feet of natural gas for every one billion gallons of ethanol produced. Just from these two inputs (ignoring, for instance, diesel-fueled farm equipment), what are the fossil CO2 emissions per gallon of ethanol produced? If there are 121 MJ/gallon in gasoline, how does this compare to gasoline fuel on a percentage avoided CO2 basis?

*Fertilizer input: 33,000 ft3 NG / 2000 lb. fertilizer * 2 lb. fertilizer / bushel corn * 1 bushel corn / 56 lb. corn * 25 lb. corn / 1 gallon EtOH * 0.49 kg C / m3 NG [from bioenergy.ornl.gov; could also calculate based on ideal gas properties and molecular formula] * (1 m / 3.28 ft)^3 * 44 kg CO2 / 12 kg C = 0.750 kg CO2 / gal EtOH.*

*Distillery input: 28 billion ft3 NG / billion gal EtOH * 0.49 kg C / m3 NG * (1 m / 3.28 ft)^3 * 44 kg CO2 / 12 kg C = 1.425 kg CO2 / gal EtOH.*

The total is 2.175 kg CO2 / gal EtOH. Since one gallon of ethanol is worth 79.9/121 gallons of gasoline, this is equivalent to 3.294 kg CO2 / gallon of gasoline. One gallon of gasoline contains 2.42 kg carbon or 8.87 kg CO2. So this is a reduction of 63% of CO2 emissions.

(c) Suppose that the Midwestern farmer growing the corn had previously grown an acre of soybeans, and the global demand of soybeans remains constant. If a Brazilian farmer cuts down an acre of rainforest to replace the soybeans, and the emissions from this land use change are divided over 80 years, how does this revise the previous estimate? Assume the rainforest burning releases 18 kg C / m2.

First we have to figure out how many gallons of ethanol we'd get in 80 years from the acre of corn:

*115 bushels corn / acre (/yr)*56 lb. corn / bushel*1 gallon EtOH /25 lb. corn*80 yr = 20,608 gallons of ethanol.*

*Using this instead of 13,608 gallons of gasoline would save 13,608 gallons gasoline*63%*8.87 kg CO2 / gallon gas = 76,043 kg CO2.*

*In contrast, the rainforest destruction releases 18 kg C / m2 * 44 kg CO2 / 12 kg C * 4,047 m2 / acre = 267,000 kg CO2. We have increased the emissions by a factor of almost 4.*

Example #2: PHEV LCA

A typical PHEV might yield 3 miles per kWh of electrical energy delivered from the battery. Transmission / distribution is about 90% efficient, and battery charging / discharging is about 88% efficient.

(a) At a California electrical generation emission rate of 500 g CO2 / kWh, what are the CO2 emissions per mile traveled? How does this compare with an efficient conventional vehicle getting 40 mpg? (One gallon of gasoline contains 2.42 kg of carbon.)

*1 kWh / 3 mi * 500 g CO_2 / kWh * 1 kWh generated / (90%*88% kWh consumed) = 210 g CO_2 / mi.*

At 40 mpg, a conventional vehicle would generate:
*1 gal gas / 40 mi * 8,870 g CO_2 / gal = 220 g CO_2 / mi.*

(b) What about if we used an emission rate closer to the US electricity average, 1.2 kg CO2 / kWh?

At the US average, the value would increase by a factor of 1200 / 500 or 2.4, to 500 g CO_2/mi for the PHEV.

Note that these assumptions are probably relatively pessimistic for the PHEV energy requirements and generous to the conventional vehicle.

Energy and Society
Week 10 Section Handout

A Look Ahead: Current Events in Energy and Their Implications for the Future

In small groups (2-4 people), take 15 minutes to read one of the following articles and discuss it as a group. Be prepared to make a brief (3-5 minute) presentation of the article, highlighting answers to these questions:

1. What is the issue/topic highlighted by the article? How does it relate to Energy and Society?
2. What are the potential positive new developments highlighted in the article?
3. What are the (technical, political, economic) challenges associated with this topic/issue?
4. What are the uncertainties surrounding this topic? Do you have enough information to pick a side on the issue?
    a. If so, what is the most convincing facet of the issue?
    b. If not, what additional information would you need to have an informed opinion?

Renewables and grid integration
http://www.aps.org/policy/reports/popa-reports/upload/integratingelec-exsum.pdf

Utilities
http://www.midwestenergynews.com/2013/10/18/will-smart-meters-change-consumer-habits-early-indicators-say-yes/

http://www.sfgate.com/news/article/Solar-switch-forces-utilities-to-shift-priorities-4929363.php

Aviation fuel
http://www.scientificamerican.com/article.cfm?id=bio-jet-fuel-struggles-to

High-speed rail
http://innovations.coe.berkeley.edu/vol3-issue9-nov09/highspeedrail

eCommerce
http://latimesblogs.latimes.com/home_blog/2011/12/online-shopping-vs-traditional-shopping.html

Energy and development
http://newswatch.nationalgeographic.com/2012/04/17/pay-as-you-go-sunshine-how-solar-energy-and-mobile-phones-are-powering-the-developing-world/

http://www.smartplanet.com/blog/intelligent-energy/dial-a-photon-cell-phone-and-small-solar-panel-buy-african-power/13532

http://www.washingtonpost.com/blogs/wonkblog/wp/2013/07/17/the-world-bank-cuts-off-funding-for-coal-how-much-impact-will-that-have/

China

http://www.economist.com/news/briefing/21583245-china-worlds-worst-polluter-largest-investor-green-energy-its-rise-will-have

Water-Energy Nexus
http://www.ucsusa.org/assets/documents/clean_energy/10-Things.pdf?authToken=7b527426838bee6384338005a54045e5373b8137

Nuclear Power

What are the pros, cons, and uncertainties of using nuclear power?

Example Problem 1
Plutonium (Pu) is created by the decay of 239U into 239Pu and ultimately to other Pu isotopes.
239Pu has a half life of 24,000 years.
A large nuclear power plant produces 0.50 tons of reactor grade Pu per year, about 60% of which is 239P. How much of the 239Pu produced in 2009 will still be around in the year 10,000 CE?
This is an exponential decay problem. To solve these, you can apply the formula

$$C(t) = C0e^{-\lambda t}$$

where C is the concentration at time t, C0 is the concentration at time zero, t is the time measured from time zero (10,000 – 2009 = 7,991 in this case), and λ is equal to

$$\lambda = \frac{ln2}{t1/2}$$

t1/2 is the half life here.

Solving for λ gives you $\lambda = \frac{ln2}{24{,}000\ yrs} = \frac{2.9\times10-5}{yr}$

And plugging λ, t, and C0 back into the original equation gives you

$$C(t) = 0.30\ tons\ \times es^{\frac{-(2.9\times10-5)}{yr}\times7991\ yr} = 0.24\ tons$$

In other words, the Pu-239 will be our children's … (you get the point; this ends up being more than 250 generations) problem.

As mentioned in lecture, Pu is an alpha emitter, which means that it poses little risk if exposure is outside the body, but can be very dangerous if exposure is internal (e.g., through drinking water). See http://www.epa.gov/rpdweb00/radionuclides/plutonium.html.
The long lives of many radioactive byproducts of fission are what make longer-term waste storage such a challenge.

IV. Practice Problems or Discussion (25 minutes)

Practice Problem 2
What mass of uranium ore (in kg) enriched to 3% ^{235}U is required to produce 6132 GWh of electricity (equivalent to a 1 GW power plant running at 70% capacity factor)? Assume that each fission of ^{235}U produces 200 MeV (3.2 x 10^{-11} J), that all neutrons absorbed by ^{235}U cause fission, and that the nuclear power plant has a thermal efficiency of 33%.

Start with the energy requirement. Based on the efficiency, you know you'll need

$$\frac{6132\ \text{GWh}}{0.33} = 18582\ \text{GWh}$$

$$18582\ GWh \times \frac{3.6\ TJ}{GWh} = 66895\ TJ = 6.7 \times 10{\scriptstyle 16}\ J$$

The fission of each atom (nucleus) of ^{235}U generates 3.2 x 10^{-11}J, so we know that we'll need

$$6.7 \times 10^{16} J \times \frac{1\ atom U235}{3.2 \times 10^{-11} J} = 2.1 \times 10^{27}\ atoms\ U235$$

^{235}U accounts for 3% of the total U, so

$$\frac{2.1 \times 10^{27}\ atoms\ U235}{0.03} = 7.0 \times 10^{28}\ atoms\ U$$

Assuming that the uranium ore is ^{238}U (i.e., having a molecular weight of 238 g/mol), we can calculate the mass of uranium required.

$$7.0 \times 10^{28}\ atoms\ U \times \frac{1\ mol}{6.02 \times 10^{23}\ atoms} \times \frac{238\ g}{1\ mol} \times \frac{1\ kg}{1{,}000\ g} = 2.8 \times 104\ kg\ uranium$$

Practice Problem 3
We've heard about peak oil. Should we be worried about "peak uranium?" How long will US uranium reserves last?

1. What mass (in t) nuclear fuel is consumed by a 1.0 GW nuclear power plant (NPP) over the course of a year? Use an efficiency factor of 33% and a capacity factor of 0.90. Nuclear fuel has an energy content of 45,000 MWd_{th}/t.

22 t/y

2. If it costs $130 to mine and refine a kg of nuclear fuel, what is the fuel cost component ($/kWh) of nuclear electricity?

$\$3.7x10^{-4}$/kWh

3. Currently, there are 104 NPPs in the US, for a total nameplate capacity of about 106 GW. In 2008, 3.95x10^9 MWh of electricity was produced in the United States. What percentage of that total production was provided by nuclear plants? How many 1 GW NPPs would it take to provide all of the electricity consumed in the US?

21%, 501 NPPs

4. Assume that US electricity consumption stays steady at 2008 levels for the rest of history, and that nuclear power plants generate the entirety of this electricity. At this rate of electricity consumption, how long will US uranium reserves (0.32 million tons) last?

29 years

5. Now assume that electricity demand rises by 0.12x10^9 MWh/yr. In what year will US reserves be exhausted in this scenario?

2029 (starting from 2008)

<u>AGENDA</u>

I. Environmental Justice Definitions and Topics
II. Environmental Justice Group Work
III. Photovoltaics: Semiconductor Basics
IV. Grid Connected Photovoltaic Systems

I. Environmental Justice - Definintions

What is EJ? Here's the EPA's current definition:

Environmental Justice is the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. EPA has this goal for all communities and persons across this Nation. It will be achieved when everyone enjoys the same degree of protection from environmental and health hazards and equal access to the decision-making process to have a healthy environment in which to live, learn, and work.

This is not law, but guides the application of other laws like the Civil Rights Act (Title IV) to environmental issues and in the enforcement of environmental laws like the Clean Air Act.

In 1994, Executive Order 12898 (Clinton) required that achieving EJ must be part of every federal agency's mission, with respect to enforcement, allocating resources, and participation.

What might be missing from EPA definition, or why might its implementation be flawed?

- Only addresses environmental bads, not goods, like access to energy or fresh food.
- Doesn't acknowledge power, i.e. participation appears central but ability to participate effectively is assumed to be equal.
- Only addresses direct environmental harms in U.S., missing how to address when goods and bads are distributed globally through international pollution, trade, climate change…

Climate change has been a very active area of discussion relating to environmental justice concerns and greenhouse gas emissions. The preamble of the United Nations Framework Convention on Climate Change recognizes a need for global cooperation and response…"*in accordance with their common but differentiated <u>responsibilities</u> and respective <u>capabilities</u> and their social and economic conditions*"

What are some potential EJ implications of climate change?

- *Some nations have contributed very little to the problem, and who are least able to adapt will likely bear the greatest impacts of a changing climate e.g. flooding of low-lying areas.*
- *Should poorer countries have a right to develop along a similar path as wealthy ones*

What do you think are some of the main characteristics that make certain populations more "vulnerable" to environmental injustice?

Is EJ primarily an issue of race? Economics? Some other demographic trend? None or all of the above?

Do you think environmental injustice primarily arises from the energy industry or from other industries? What other industries do you think give rise to serious environmental justice concerns?

Is there a relationship between green jobs and environmental justice? Why or why not?

II. Group discussion:

Split up into groups. Each group will be tasked with discussing the environmental justice concerns relating to one of the following energy sectors: Oil, Nuclear, Coal, and large Hydroelectric. Consider the entire process of generating energy within your sector, including extracting and/or processing fuel, construction and operation of plants, end of life issues for the plant, dominant end uses of your energy, as well as waste and fuel byproducts as applicable.

Given your knowledge of the historical practices in your team's sector, answer the following questions and present your thoughts to the whole section:

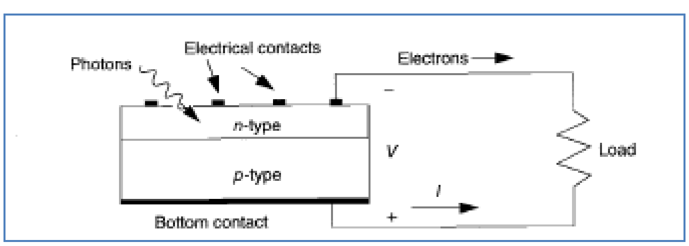
- *What are some of the major concerns for environmental justice in your sector?*
- *What kind of changes to your sector could lead to fewer sources of concern, or even greater environmental justice?*
- *Do the environmental justice concerns raised by climate change alter the environmental justice concerns in your sector? Do you expect your sector's response to an increasingly carbon constrained world to remedy past environmental justice concerns created by your sector?*

After presenting in teams, what sort of patterns, if any, seem to be arising?

What, if any, are the Environmental Justice concerns of solar and wind? What about efficiency?

III. Photovoltaics Basics: What is really going on in a Solar Cell?

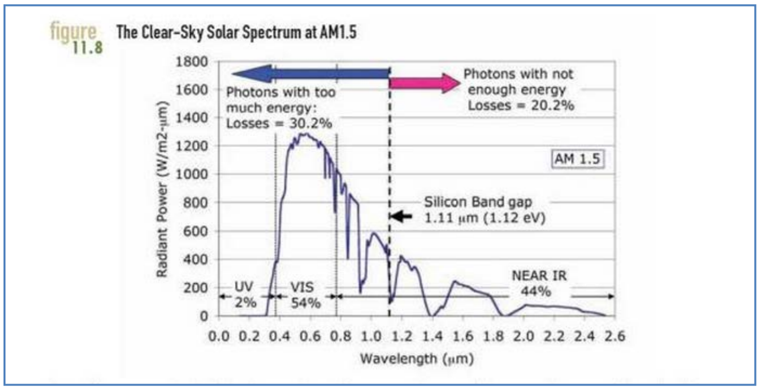
- A silicon atom has four outer electrons and naturally bonds covalently with four other silicon atoms to form stable crystalline silicon. At absolute zero silicon is a good insulator, because the electrons are tightly bound to the nuclei. For an electron to escape from its covalent bond it needs enough energy, called the band gap energy. Exposing Si to sunlight allows photons to provide that energy.
- The photons need to have as much energy as the band gap so the photons need to have an incoming wavelength of less than 1.11microns.
- When a negatively charged electron leaves its nucleus it also leaves behind a net positive charge, called a hole, associated with that nucleus. If an electron from an adjacent si atom slides into that hole the positive charge will appear to move. The trick is to get the electron to move away from the hole before the two have a chance to recombine. This is done by creating an electric field within the PV device that pushes the electrons in one direction and thus pushes holes in the other direction. The accumulating charge on opposite sides of the cell creates a voltage. The movement of electrons through the cell creates a current flow. Hook this up to a load and you have a solar powered source of electricity.
- To create the electric field two regions are established with a crystal by doping one side with Phosphorous which has 5 electrons in its outer shell so when it combines with Si it leaves an electron behind that can roam around the crystal (n-type Si). The other side is doped with Boron which has 3 electrons and thus the Si nuclei are quicker to grab extra electrons so there are positive 'holes' in abundance (p-type Si). Both n-type and p-type materials have charged mobile carriers so the electrical conductivity of Si increases. It's not as conductive as a metal, so called a semiconductor.
- When p-type and n-type semiconductors are brought together, electrons diffuse from the n-region into the p-region filling holes creating an immobile negative charge in the p-side and leaving behind immobile positive charge on the n-side. This region of charged atoms is called the depletion region and it creates a slight electric field the works against the continuous movement or diffusion of electrons across the junction.
- Exposure to sunlight creates hole-electron pairs. If the holes and electrons reach the vicinity of the depletion region, the electric field sweeps electrons into the n-region and the holes into the p-region. This creates a voltage across the cell. When a load is connected to the cell, the electrons flow through from the n-region through the load and return to the p-side creating the current needed to power the device (*see summary schematic diagram below*).



IV. What factors affect PV Performance?

Based on this understanding, what are the main factors that affect the efficiency of turning all that energy from the sun into electrical energy?

- Band-Gap Constraint (*see figure below*) - over half the incoming solar energy is wasted because photons either don't have enough energy or they have more than is needed to create hole-electron pairs.
- Photons that are not absorbed by the cell either because they are reflected off the face of the cell
- Recombination of holes and electrons before they can be separated by the electric field
- Internal resistance



Based on all of these factors, average efficiency of c-Si solar cells is around 20%, but in the lab cells are achieving +25%.

Some non-Silicon Solar Films such as CIGS, CdTe, Amorphous Si have higher band gaps. And these materials are cheaper and offer the promise of low cost printing production methods. But, they tend to be less efficient (10 – 15%), which means larger areas and area related costs.

PV modules are rated under standard laboratory test conditions (STC) that include a solar irradiance of $1kW/m^2$ (called 1-sun), a cell temperature of 25^oC. Modules are not always exposed to 1-sun of insolation (**in**coming **sol**ar rad**iation**). So an insolation of 5.4kWh/m2 is the same as 5.4 hours of 1kW/m2 sun for the day. Capturing insolation can be maximized by proper orientation (south facing panels), tilting panels to the latitude of their location, or using single/double axis tracking.

Together these factors affect the efficiency of the solar cell at converting the insolation it actually receives into DC electricity. Beyond this efficiency of the conversion process, there are a number of other external factors that create system losses which affect the amount of AC electricity produced by a solar cell.

- Temperature Sensitivity – Most modules lose 0.5% of their power for each degree Celsius of increased cell temperature.
- Dirt
- Electrical mismatch of modules
- DC-to-AC inverter inefficiencies

The **de-rating factor** is based on the sum of these losses. $\mathbf{P_{AC} = P_{DC} * (de\text{-}rating\ factor).}$ A typical PV system de-rating factor is about 75%, which means an array typically delivers only about three-fourths of the manufacturers DC_{STC} rated power.

Putting all these factors together we can estimate PV capacity given basic information:

SOLUTION BOX 11.3

The Total Potential for Rooftop PV in the United States

A study of the roof area in the United States potentially available for PVs estimates 3.5 billion square meters of residential rooftop area and 2.9 billion square meters of commercial roof area (Chaudhari, 2004). These estimates account for roof orientation, shading, and structural issues. Assuming 17%-efficient collectors, an average annual solar exposure of 5 kWh/m^2-day, and a de-rating factor of 0.75, find the annual energy that could be delivered if that entire available space is utilized.

Solution:

The total area of 6.4 billion square meters would allow an installed capacity of

$$P_{DC,STC} = 6.4 \times 10^9\ m^2 \times 1\ kW/m^2 \times 0.17 = 1088 \times 10^6\ kW$$

With 5 kWh/m^2-day of insolation (equivalent to 5 hrs of 1 kW/m^2 sun), and using the 0.75 de-rating factor, the energy that could be delivered would be

$$\text{Annual energy} = 1088 \times 10^6\ kW \times 0.75 \times 5\ hr/day \times 365\ day/yr = 1490\ \text{billion kWh/yr}$$

The total net output of all U.S. power plants in 2005 was 4340 billion kWh, so PVs could supply just over one-third of the entire demand. In fact, if we include transmission losses from traditional power plants to end users, which are avoided by on-site generation, this full build-out of PVs would be sufficient to supply half of the total electricity demand of all U.S. buildings.

Photovoltaics turn solar energy directly into electricity and this is only one way to use the sun's energy. Concentrated Solar Power and Solar Water Heating are also becoming more commercially important, and rely on the thermal energy of the sun.

AGENDA

I. Instantaneous and Average Power in the Wind
II. Extracting Wind Energy
III. Hydropower

I. Instantaneous and Average Power in the Wind

What is essentially taking place in a wind turbine?

The base holds up the wind turbine to a place that there is wind. The wind pushes on a turbine, which captures the energy by rotating. In the gear box the gear turns the big and slow rotation of the wind turbine into a small and fast rotation needed by the generator. The rotating gears will cause the generator to rotate, creating electricity.

But how much power is in the wind?

a. Instantaneous Power in the Wind:

Consider a ‘piece’ of air with mass m, moving at a speed v, its Kinetic Energy is given by the equation

$$\mathrm{K.E.} = \frac{1}{2}mv^2$$

Because energy is per unit of time, the power represented by a mass of air moving at velocity v though areas A will be:

$$\text{P through area A } = \frac{\text{Energy}}{\text{Time}} = \frac{1}{2} \times \frac{mass}{time} \times v^2$$

The mass flow rate through the area A is a product of air density, wind speed and cross sectional area A.

$$\text{m flow rate } = \frac{mass\ passing\ through\ A}{time} = \rho A v$$

where ρ = air density = 1.225 kg/m3 at 15°C and 1atm

Combining these two relationships gives $\mathrm{P_w} = \frac{1}{2}\rho A v^3$

Note from this equation that the power in the wind increases as the cube of wind speed. Doubling wind speed increases the power eight fold. Also note that power goes up as the swept area increases. Since Area is πr^2 then a doubling of the rotor blade diameter increases available power by a factor of four.

<u>Average Power in the Wind – Be careful!</u>

Suppose the wind blows for 10 hours at 8 m/s and 10 hours at 4 m/s. What would be the total energy and average power per square meter of area over those 20 hours?

Solution:

Applying wind power formula to each regime:

$$\text{Energy} = \frac{1}{2}\rho v^3 \left(\frac{W}{m^2}\right) \times \Delta t(hr)$$

$$\text{Energy}\left(10\text{hr@}8\frac{\text{m}}{\text{s}}\right) = 0.5 \times 1.225 \times 8^3 \times 10 = 3136\frac{Wh}{m^2}$$

$$\text{Energy}\left(10\text{hr@}4\frac{\text{m}}{\text{s}}\right) = 0.5 \times 1.225 \times 4^3 \times 10 = 392\frac{Wh}{m^2}$$

$$\text{Total} = 3136 + 392 = 3528\frac{\text{Wh}}{\text{m}^2}$$

Notice how insignificant the energy contributed by those low speed, 4 m/s winds is. The average power over those 20 hours is:

$$\frac{3528\,\frac{\mathrm{Wh}}{\mathrm{m}^2}}{20} = 176.4\,\frac{Wh}{m^2}$$

Suppose we had simply plugged the average wind speed of 6 m/s into the equation. What would we have gotten for average power?

$$\text{Average power} = \frac{1}{2}\rho v^3 = 0.5 \times 1.225 \times 6^3 = 132.3\,\frac{W}{m^2}$$

Our 132.3 W/m2 estimate using average wind speed is 25% lower than the correct answer of 176.4 W/m2.

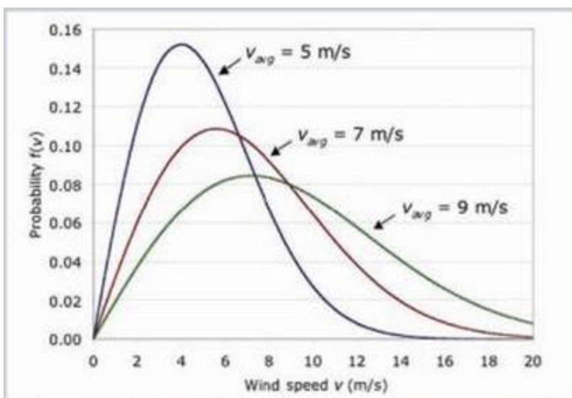
b. Average Power in the Wind

That example shows us the non-linear relationship between wind speed and power and reminds us that we need to be cautious in estimating average power in winds that have variable speeds. We thus need some distribution of wind speeds at a site if we want to estimate the average power or total energy that a wind turbine will produce.

The distribution of wind speeds is often assumed to follow what is known as a Rayleigh probability density function, described by a complicated equation. The bulk of wind energy will be found at wind speeds above the mean (average) wind speed at the site. The equation describing the distribution looks like:

$$p(v) = \frac{b}{v_c}\left(\frac{v}{v_c}\right)^{b-1} \exp\left(-\frac{v}{v_c}\right)^{b} \text{ where } b > 1, v \geq 0, \text{and } v_c > 0$$

where b is a “shape” parameter that affects the spread of the distribution. For b close to 1, the distribution is broad, indicating a wide range of wind speeds. For b > 2 the distribution becomes sharper indicating more consistent wind speeds. Most wind sites with appropriate wind distributions for wind turbine installations have shape parameters approximately equal to 2. A Weibull distribution with shape parameter equal to 2 is called a Rayleigh distribution, and is a common assumption for the wind speed distribution if the true distribution is unknown. v_c is a scale parameter that approximates the mean wind speed..



A wind regime that has Rayleigh statistics has the nice property that $avg(v^3) = 1.91\,(v_{avg})^3$. If we assume Rayleigh statistics then the average of the cube of wind speed is 6/π=1.91 times the average wind speed cubed.

$$P_{avg} = 1.91 \times \frac{1}{2} \times \rho \times (v_{avg})^3$$

So that if we just plug in the average wind speed for a site into the equation for power we derived earlier and multiply by the correction factor 1.91, we find the average power in the wind if the wind distribution follows Rayleigh statistics. This variability of wind speeds is why they are often grouped in Classes, where Class 2 winds are called marginal (5.6 – 6.4 m/s) and Class 7 winds are called superb (greater than 8.8m/s). Most wind turbines installed today are in Class4 and Class 5 sites.

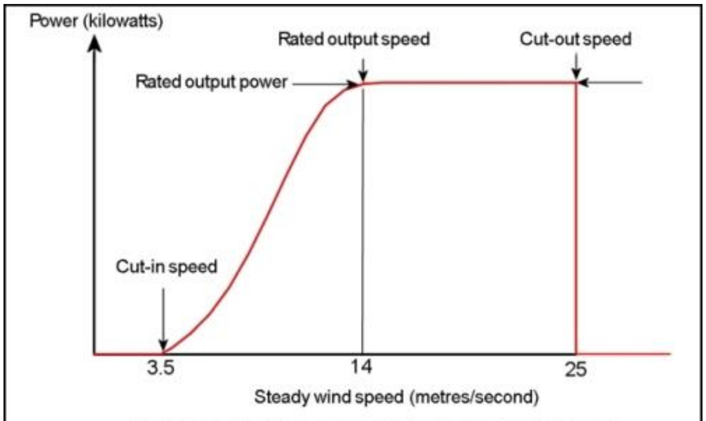
II. Extracting Wind Energy

Power Curve, Capacity Factor and Efficiency

Based on the above theory and operating constraints, what can we say about the relationship between Power Output and Wind Speed?

Wind turbine CF's are affected by both the wind regime and the turbines power curve. The power curve is a graph of power output as a function of wind speed.

- Cut in Wind Speed – Below this speed the turbine is not turned on because the power that would be generated is not enough to offset the generator losses.
- Above the cut-in speed the power output climbs rapidly as the cube of wind speed
- Rated wind Speed – At this speed the generator is delivering as much power as it can. Above this wind speed the pitch of the turbines is adjusted to shed some of the wind to keep from overpowering the generator.
- Cut-out wind speed – Above this wind speed the winds are just too high and too dangerous so the turbine shuts down.



Typical wind turbine power output with steady wind speed.

Estimating annual energy production in the wind:

$$\text{AEP} = \text{P}_\text{R} \times 8760hr \times CF$$

where for wind follows Rayleigh distribution

$$\text{CF} \approx 0.087\text{v}_{\text{avg}} - \frac{P_R}{D^2}$$

v_{avg} is average wind speed in m/s, P_R is the rated power output (kW) in of the turbine and D (m) is the diameter

QUESTION: Consider a 2MW, 80m wind turbine in Rayleigh winds with average wind speed of 7m/s. What is its capacity factor and annual electricity production?

$$\mathrm{CF} = 0.087 \times \frac{7m}{s} - \frac{2000}{80^2} = 0.2965$$
$$\mathrm{AEP} = \mathrm{P_R} \times 8760hr \times CF = 2000\mathrm{kW} \times 8760\mathrm{hr} \times 0.2965 = 5 \times 10^6 kWh$$

What is the Theoretical Efficiency Limit of a Wind Turbine?

Betz Limit: There is a limit to how much of this power from the wind can be extracted by a rotor. The rotor efficiency depends on the *number of blades* and the *tip-speed-ratio* (the speed at which the outer tip of the blade is rotating divided by the wind speed). The theoretical maximum rotor efficiency is called the *Betz limit*, and is 59.3%. The law can be simply explained by considering that if all of the energy coming from wind movement into the turbine were converted into useful energy then the wind speed afterwards would be zero. But, if the wind stopped moving at the exit of the turbine, then no more fresh wind could get in - it would be blocked. In order to keep the wind moving through the turbine, to keep getting energy, there has to be some wind movement on the outside with energy left in it.

$$P_{avg} = \eta_{turbine} \times A_{rotor}(m^2) \times P_{wind}(W/m^2)$$

Although turbine efficiencies vary depending on the wind regime, in good winds they tend to operate with an overall efficiency of somewhere between 25 – 35% efficiency.

III. Hydropower

Currently about 16% [BP Energy Statistical Review 2013: 3,673TWh out of 22,504TWh total electricity generation in 2012] of world electricity production (6% in US and 17% in CA including imports). Hydropower converts gravitational potential energy and/or kinetic energy in flowing water into electric energy by forcing falling or flowing water through turbines.

For big dams that rely on falling water fed by reservoirs, the amount of work ΔE done by an object of mass m falling height h (called the *head* in hydropower systems) in a gravitational field is:

$\Delta E = mgh$ where g is the acceleration due to gravity (9.8 m/s^2 at sea level).

Power is related to the rate of mass flow: $P = \frac{\Delta E}{\Delta t} = \frac{\Delta m}{\Delta t} gh$

Substituting P for $\Delta E/\Delta t$ and expressing $\Delta m/\Delta t$ in terms of the volume of liquid moved per unit time (the rate of fluid flow φ) and the density of water ρ, gives a useful expression: $P = \rho\varphi gh$

For P in watts, ρ is measured in kg/m^3, φ is measured in m^3/s, g is measured in m/s^2, and h is in meters.

Example

Hoover Dam has an installed capacity of 2.08 GW and an effective head of 576 ft (175m). When running at full capacity, what is the rate of water flowing through the turbines?

Solve for φ in the equation for Power: $\varphi = \frac{P}{\rho gh} = \frac{2.08\,GW}{1000\frac{kg}{m^3} * 9.8\frac{m}{s^2} * 175m} = 1213\frac{m^3}{s}$.

Hydro facts and figures

- As of 2012 installed global capacity was ~990 GW
- Top five installer: China, Canada, Brazil, U.S, Russia.
- Big (> 30 MW), small (1-30 MW), mini (0.1-1MW), micro (< 0.1 MW), and even “pico” hydro (ITDG’s term for 20 kW systems they’ve installed)
- 45,000 big dams worldwide
- Total investment > $2 trillion
- Estimated 40-80 million people displaced

- Flow in 60% of world's rivers affected
- Can be very land intensive: installed hydropower in Brazil ranges from 1-2,000 kW/ha

Other issues around hydro:

- Reservoirs provide other "services": flood control; irrigation; recreation; fisheries
- Massive impacts on ecosystems and possible seismic effects
- Population displacements and human rights abuses
- Public health concerns (changes in disease vectors: newly formed wetlands, infrastructure, etc).

Resources

- World Commission on Dams http://www.dams.org/
- International Rivers Network (based in Berkeley) http://www.irn.org/
- US National Hydropower Association http://www.hydro.org/
- Intermediate Technology Development Group (ITDG) http://www.itdg.org/

AGENDA

I. Consequences of oil as the primary transportation fuel (Oil resources vs. reserves; risks of the oil transition) – 20 mins

II. Transport alternatives, alternative vehicle technologies and needs for scale-up (Innovation) – 30 mins

---

I. Consequences of oil as the primary transportation fuel

- Transportation, particularly light trucks and cars, dominates U.S. oil consumption.
- The transportation system is very important for the U.S. and global economy, so this sector of the economy will continue to demand fuel into the foreseeable future.
- Unlike other energy sectors, such as power generation, there is very little inter-fuel competition. Substitutions for gasoline or diesel have been very rare, and only lately, with the advent of hybrid and electric vehicles, has much changed in the fuel system over 100 years.

Two major consequences of maintaining the status quo and continuing to rely on oil as the primary transportation fuel are: **oil dependence** and **climate change**.

- Oil dependence - this leads to economic vulnerability, national security risks, and ultimate resource depletion.
- Climate change - if we continue to burn oil for transportation fuel as we do today, it is likely that we will saturate the atmosphere with CO_2 ("run out of atmosphere") before we actually run out of oil to burn.

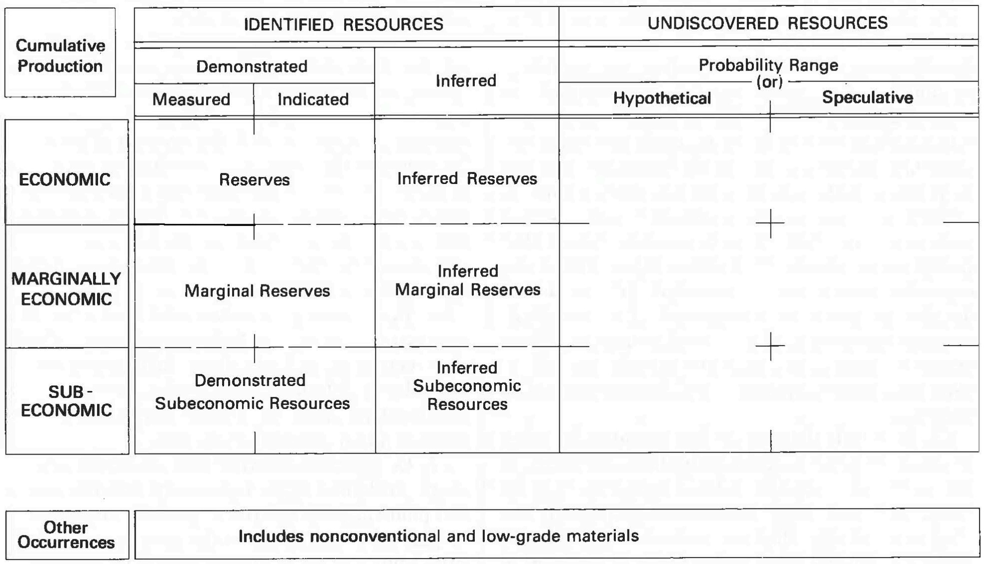
(*This is the point of Farrell, 2006 – "Risks of the Oil Transition" – there are perhaps lots of substitutes out there, but how much can we actually afford climatically to burn?.)*

There has been much speculation over the years as to how much oil remains to be discovered, developed, and produced. Some argue that the stock of oil worldwide is dwindling, while others contend that there are vast amounts yet to be discovered and developed. Key concepts often misconstrued in these arguments include the concepts of oil **resources** versus oil **reserves**.

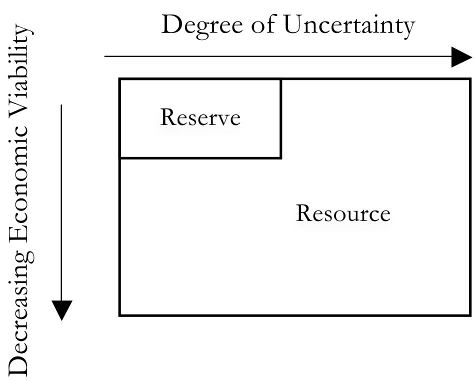
- o Resources: refer to the total quantity of fossil fuel resources, including identified and undiscovered resources.
- o Reserves: refer to the quantity of resources that are proved, probable, and possible, given current technology, economic viability, oil prices, etc.

- One way to depict these two concepts is with a "McKelvey Diagram," (appeared on lecture slides and can also be found in the Section Handout).

Full McKelvey Diagram:



We can conceptualize this as follows. *(May want to draw this on the board.)*



Exercise 1:

Consider how the above diagram would change if:

a. The price of oil increases.

Reserves box expands downward

b. Additional oil exploration.

Reserves box expands to the right

c. A new technology, such as horizontal drilling, allows for aggregation of previously sub-economic resource.

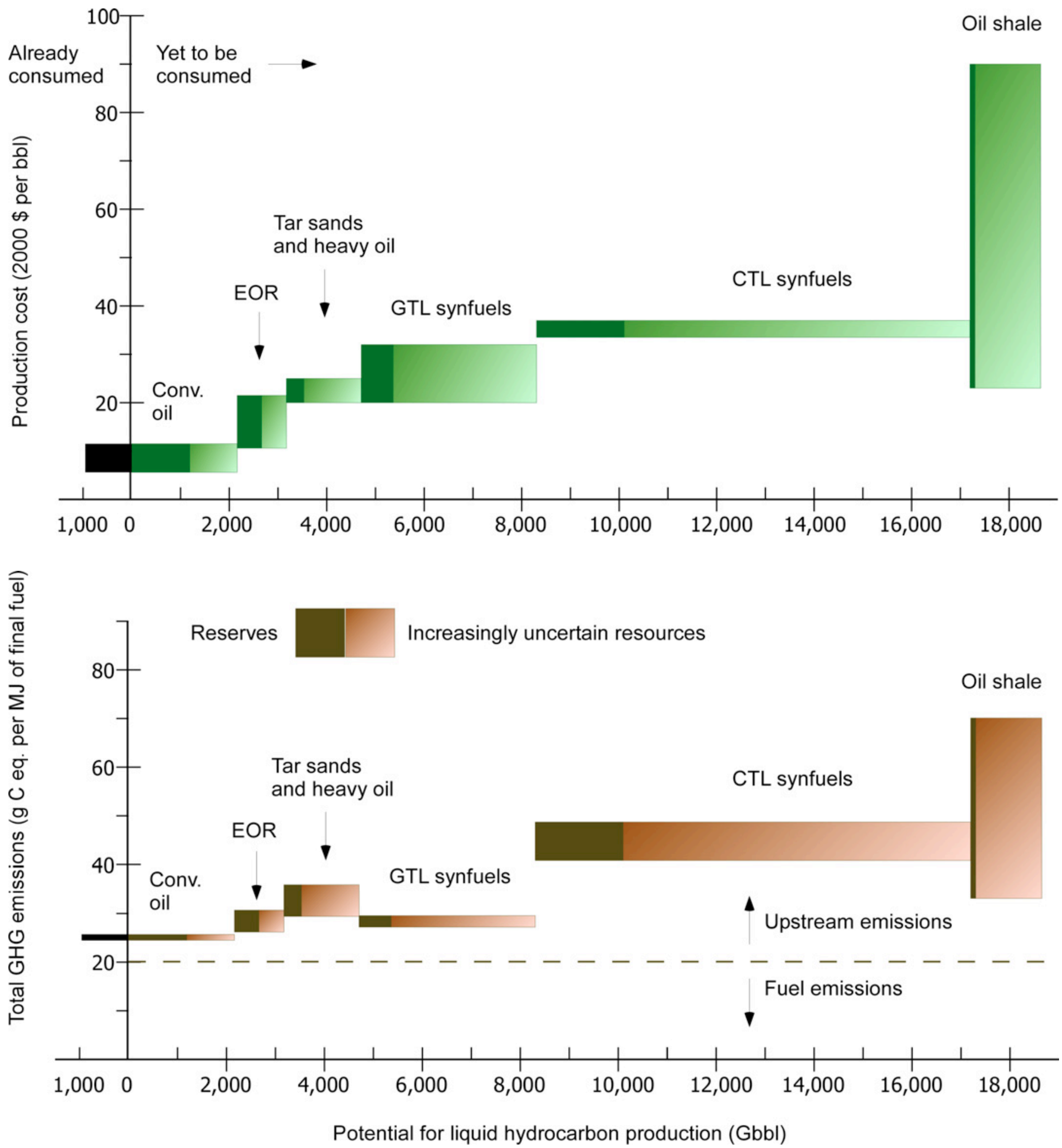
Reserves box expands downward

c. New policy includes the price of externalities (i.e. carbon emissions) in the oil price?

Depends on the mechanism that imposes this additional price on the cost of oil; may be the case that this law limits certain types of exploration that would otherwise expand the box downward, such as tar sands development, etc.

Yet no matter how much oil is "down there," in the end we're facing an additional constraint.

Describe or draw an idealized version of the graph(s) below. Point out how Farrell is embedding some "McKelvey diagrams" in this graph.



(Graphs from Farrell and Brandt, 2006.)

II. Alternative vehicle technologies and what's necessary for scale-up (Innovation)

We can also break down (decompose) per capita emissions for car and truck (light-duty vehicle) transport in the following way (Sager et al. 2011):

$$\bar{C} = \underbrace{(C/E \times E/V)}_{\substack{\text{LDV propulsion} \\ \text{GHG intensity}}} \times \underbrace{(V/D \times D/T \times T)}_{\text{Per capita LDV transport use}} .$$

What this does is give a number of "policy handles" to work on…explain each one.

Technology	**C/E**	**Carbon intensity of fuel**	**gCO2-e/MJ**	
	E/V	**Energy intensity/efficiency of propulsion**	**MJ/VKT**	**VKT = vehicle kilometer traveled**
Behavior/urban and social system design	**V/D**	**Inverse occupancy ratio**	**VKT/PKT**	**PKT = passenger kilometers traveled**
	D/T	**Average passenger trip distance**	**PKT/trip**	
	T	**Number of annual car trips**	**Trips/yr/person**	

Example Problem 1: In the US, the average carbon intensity of fuel is about 96 gCO2-e/MJ, while the energy intensity of propulsion is roughly 3.2 MJ/km. Each car on the road averages 1.2 occupants, while the average passenger makes an average of 200 trips per year, with each trip averaging 65 kilometers. What's the per capita emissions in kg, per person per year, to two sig figs? If the US annual per capita emissions of carbon dioxide is about 19 tCO2-e per person, what percentage comes from travel in light-duty vehicles?

96 gCO2-e/MJ * 3.2 MJ/VKT * .833 (VKT/PKT) * 65 PKT/trip * 275 trips/person/yr = 4,576 → 4,600 kg CO2-e/person/yr ------- 4,576 kg CO2-e /19,000 kg CO2-e = 24%

Exercise 2:
What are some different strategies for reducing the amount of oil that we use for transportation and/or for reducing the amount of CO_2 emissions that come from transportation? Try to think across the various terms in the decomposition above. Ie., how can we "change this equation"?

Possible responses should generally fall into these three categories (which you can highlight at the end).

1.Change vehicle efficiency.	*2. Change transport behavior or urban fabric /social need for auto (reduce driving).*	*3. Change carbon intensity of fuels.*
- Increase CAFE (Corporate Average Fuel Economy) Standards - Decrease the size/weight of vehicles - Decrease horsepower in exchange for better fuel economy	- Encourage more transit, biking, walking generally. - Improve transit systems quality, coverage, and frequency. - Invest in bike and pedestrian infrastructure. -Improve transportation planning to facilitate travel via transit and non-motorized modes.	- Increase use of electricity as transportation fuel (But only where C-intensity of the electricity grid is lower than the C-intensity of gasoline). - Blending of lower carbon fuels, such as ethanol, with gasoline. - Increase use of biodiesel (waste oil). - Transition to compressed natural gas as an alternative fuel.

Dislike "behavior" in some ways because it obscures the urban design and lifestyle choices that have brought us to this point. All the responsibility is put on the individual and his or her "behavior"—however, if you live in a city such as Houston or some other place with a really poor transit system, your "behavior" is very hard to change.

The following table provides a quick summary of some of the key characteristics for different types of vehicle technologies. There is some confusion today about the differences between ICE, hybrid, plug-in hybrid, and battery electric vehicles; this table provides some of this information at a very basic level.

Vehicle Characteristics	**Internal Combustion Engine/Conventional Vehicle**	**Hybrid Vehicle**	**Plug-in Hybrid Vehicle**	**Battery Electric/All Electric Vehicle**
Examples	Honda Civic	Honda Insight	Prius PHEV	Nissan Leaf
Fuel	Gasoline	Gasoline	Gasoline and Electricity	Electricity
Means of Propulsion	Internal combustion engine (ICE)	ICE and battery/electric drive system	ICE and battery/electric drive system	Battery/electric drive system
Battery	Lead-acid	Nickel metal hydride	Lithium ion	Lithium ion
Vehicle Range	~300 mi./fill	~300 mi./gas fill	~300 mi./ gas fill	50-105 mi./charge
All-Electric Range	N/A	N/A	10-50 mi.	50-105 mi.
Fueling Infrastructure/Options	Gasoline pumps	Gasoline pumps	Gasoline pumps; Electricity outlet (at home, 120V or 240V outlet); Battery swap	Electricity outlet (at home, 120V or 240V outlet); Battery swap
Time to Fuel	Minutes	Minutes	Gasoline: Minutes Charge at home: 4-8 hours Fast Charge: 30 min.	Charge at home: 4-8 hours Fast Charge: 30 min.

Tailpipe Emissions	CO_2, NO_x, SO_2, PM	CO_2, NO_x, SO_2, PM	CO_2, NO_x, SO_2, PM (when operating with ICE).	No tailpipe emissions.

Discussion/Exercise 3:
Take a look at the two last columns, for PHEVs and BEVs, and think about what would be necessary to scale this technology up. What would be necessary to support these vehicles in the transportation system? What are some features that automakers and policymakers should focus on to make these vehicles more "adoptable"? How might policymakers accelerate transportation innovation?

What's needed to bring PHEVs and EVs to scale/possible responses:

- *Major challenge for all-electric vehicles: think how annoying it is when your phone runs out of batteries and then multiply that by …..*
- Charging infrastructure for charging at home: separate meters to distinguish vehicle charging from other electricity use because of tracking for the Low Carbon Fuel Standard and charging lower rates for PEV charging.
- Public charging infrastructure (i.e. charging at work, shopping, etc.): who will provide charging stations and how will people pay for the electricity "fuel" that they acquire in public.
- Battery swapping may be another option, but consider what this may mean for vehicle battery ownership (i.e., it's likely that the automaker or another entity would have to own the battery and lease it to EV owners).
- Vehicle range limitations are a major concern for adoption; might be necessary for automakers to facilitate easy charging or to develop better batteries that are capable of holding a charge for longer.
- What would happen to the electricity distribution system if several EV owners lived in the same neighborhood? It's expected that this may require some upgrades to the distribution system (i.e., new transformers), but who should pay for that? EV owners? Ratepayers?
- While battery technology is improving, its not quite where it needs to be to overcome some barriers to EV adoption (i.e., limited ranges, etc.), but to improve batteries, will likely require larger scale production (to facilitate learning), but who will adopt before superior batteries are developed (a classic chicken and egg problem).
- And many, many more! ☺

Applied and Basic research

Quest for fundamental understanding?	**Yes**	Pure basic research (**Bohr**)	Use-inspired basic research (**Pasteur**)
	No	–	Pure applied research (**Edison**)
		No	**Yes**
		Considerations of use?	

Section Notes

Energy and Society (ER/PP 100/184; ER/PP 200/284) Fall 2013
Week 15

Section Objective: familiarity with the terminology and mechanics of hydrogen fuel cells

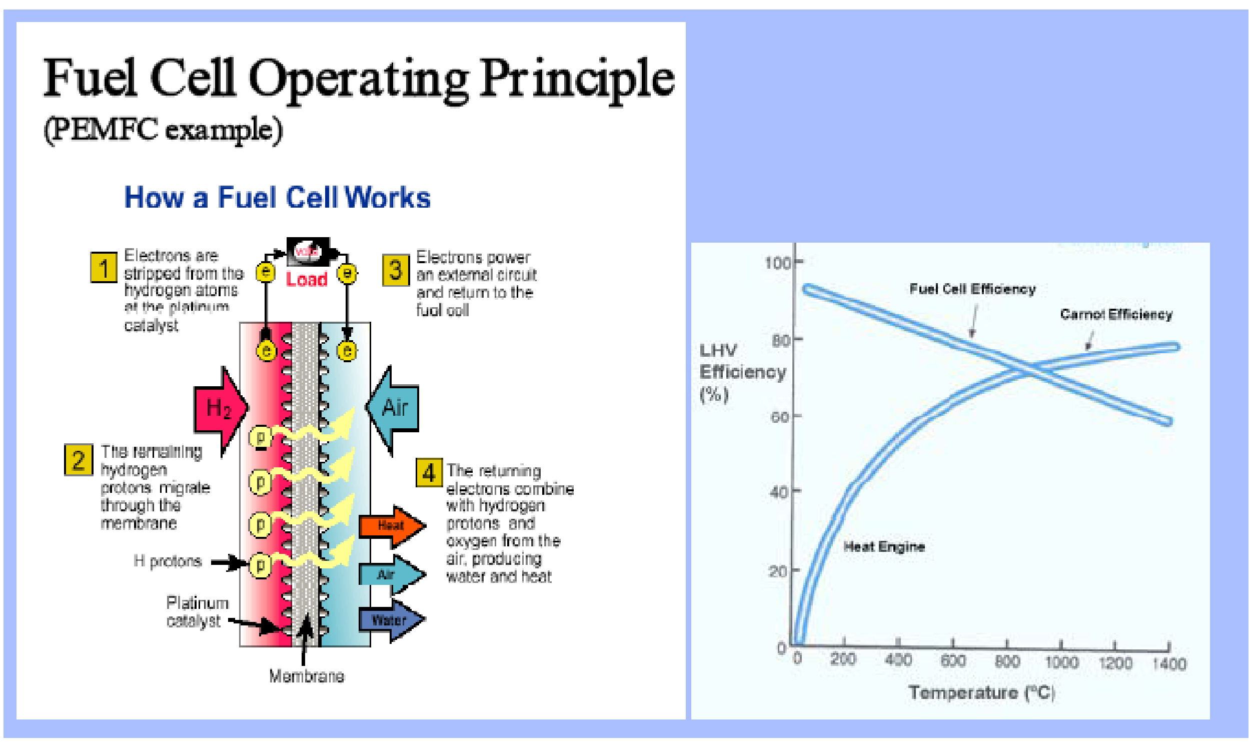
Agenda:

1. Questions/Announcements/Housekeeping (5 minutes)
2. Hydrogen fuel cell operation (10 minutes)
3. Fuel cell efficiency (15 minutes)
4. Section semester wrap-up and evaluation (20 minutes)

1. Q&A

2. Hydrogen and Fuel Cells – how it works

Fuel cells (FC) make electricity through a chemical reaction between H_2 and O_2. H_2 is supplied to the negative electrode of an FC, where a catalyst (e.g., platinum) strips electrons from the H atoms. To generate electricity, the electrons move from the FC's negative to positive electrode. Rather than circling around like the electrons, the H atoms that have shed their electrons become H ions (H^+) and travel straight through a polymer electrolyte membrane (PEM) to reach the positive electrode. On the positive side, with the help of a catalyst, the H^+, electrons, and oxygen (from air) re-combine to form water (see fig below). A single FC generates ~0.6V, so hundreds of cells are stacked in series connection to raise the voltage to 12V, 24V, 48V, etc.



Questions:

1. What are the advantages of using hydrogen fuel? Disadvantages?
Advantages: renewable and abundant, non-toxic reaction products
Disadvantages: hard to store/transport, little infrastructure in place, potentially carbon-intensive to make

2. Why do we refer to hydrogen as a "fuel" or "energy carrier" and not an "energy source?"
We don't mine hydrogen; we have to make it. This involves an input of energy, a fraction of which is turned into useful work by the fuel cell. Thus, hydrogen "carries" the input energy to the fuel cell.

Thermodynamics of Fuel Cells (and LHV/HHV in combustion)

- **Entropy (S)**
    - *Simple definition* - a thermodynamic quantity representing the amount of energy in a system that is no longer available for doing mechanical work without adding additional work to the system.
    - *Advanced definition* – Entropy is defined by quantifying the probability of every possible microscopic state that the constituents of a macroscopic system can occupy: i.e. $S = -k_B \Sigma p_i \ln(p_i)$
- **Enthalpy (H)** – thermodynamic state function that is the sum of both internal energy (U) and the product of pressure and volume, P·V so that $H = U + P \cdot V$.
    - H is a measure of the energy required to form a substance out of its constituent parts. It is useful to define changes in energy for processes that occur at near constant pressure like combustion and it quantifies the amount of energy in a system capable of doing mechanical work.
- **Gibbs Free Energy (G)** – A thermodynamic state function that defines the criteria for a process to proceed spontaneously. It is defined as the difference of enthalpy and entropy x temp.
    - $G = H – T \cdot S$
    - A natural process occurs spontaneously if and only if the associated change $\Delta G < 0$. A system reaches equilibrium when ΔG = zero, and no spontaneous process will occur if $\Delta G > 0$.
- **Fuel Cell Efficiency**
    - The ideal efficiency of a fuel cell is defined as the ratio of ΔG to ΔH. In other words it is the maximum possible energy that is available for work (ie. the energy not lost through entropy) divided by the total heat of reaction.
    - Fuel cell maximum efficiency, $\eta_{max} = \Delta G / \Delta H$. The theoretical H_2 FC efficiency versus Carnot efficiency for a heat engine is shown in the figure above.
- **Higher Heating Value (HHV) vs Lower Heating Value (LHV) of a Fuel**
    - "We need these two ways of expressing the heating value of fuels because the combustion of some hydrogen-rich fuels releases water that is subsequently evaporated in the combustion chamber. In other words, the process of evaporating water "soaks up" some of the heat released by fuel combustion. That heat, known as the "latent heat of vaporization," is temporarily lost and therefore does not contribute to the work done by the combustion process. As a result, the formation and vaporization of water in the combustion chamber reduces the amount of thermal energy available to do work, whether it be driving a piston, spinning a turbine, or superheating steam."
    -

"If the water vapor released by fuel combustion simply passes out of the chamber into the environment via the exhaust stream, the latent heat of vaporization is irreversibly and irretrievably lost. That is the case, for example, with most internal-combustion engines, such as diesel and gasoline engines. On the other hand, some advanced boilers have a secondary condensation process, downstream of the combustion step, which condenses the water vapor in the exhaust stream and recovers most of the latent heat being carried with it. The recovered heat can then be used productively." (quoted from http://www.extension.org/faq/27554)

- Summary: The HHV assumes that any water vapor has been condensed to a liquid. The LHV assumes any water produced during combustion/reactions remains in gaseous form and thus the latent heat of vaporization (i.e., the heat energy that is absorbed when water evaporates or is released when water condenses) is lost. These terms apply not just to fuel cells, but also to the combustion of other fuels.

3. Fuel Cell Vehicle Efficiency

The conventional way to compare the efficiency of vehicles is by the distance they can travel per unit of fuel (km/liter or mpg). However, this method is difficult for cars running on different fuels. An alternative metric measures not only how efficiently the car itself uses energy ("tank to wheel") but also how efficiently the energy is obtained and transported to the car's tank ("well to tank"). Combined, this measure of efficiency is called "well to wheel."

Problems
The amount of electrical energy input needed to electrolyze water (separate it into hydrogen and oxygen gases) in an ideal reaction is 237 kJ/mol of H2 produced.

1. How many kWh of electricity are needed to produce 1 kg of H2 (to three sig figs)?

*1 kg H2 * mol H2/ 2 g H2 * 1000 g / kg* 237 kJ/mol H2 * 1 kWh/ 3600 KJ = 32.9 kWh*

2. The enthalpy of 1 mol of hydrogen gas is 285.8 kJ, 48.7 kJ of which must be released in a reaction as heat transferred to the environment (increase of entropy). What remains is the Gibbs free energy, capable of doing useful work in a fuel cell. Julian's Fully Fultonic Fuel Cell can convert the Gibbs into electricity with an efficiency of 80%. A household Fultonic has a nameplate capacity of 1000 W.

a) A what rate (g/hr) will the household Fultonic consume hydrogen fuel when it's operating at full capacity?

$1000\ W \times (.001\ kJ/s/1\ W) \times (3600\ s/hr) \times (mol\ H_2/189.7\ kJ_{elec}) \times (2\ g/1\ mol) = 38\ g/hr$

b) 285.8 kJ/mol is the higher heating value of hydrogen, meaning that we expect all the reactants (water) to be liquid. If we collected all the water created by a Fultonic operating at full capacity, how long would it take to fill a 750 mL Kleen Kanteen? Assume a density of water of 1 g/mL.

$H_2 + 0.5O_2 \text{->} H_2O$

$1000\ W \times (.001\ kJ/s/1\ W) \times (3600\ s/hr) \times (mol\ H_2/189.7\ kJ_{elec}) \times (1\ mol\ H_2O/mol\ H_2) \times (18\ g/mol) \times (1\ mL/g) = 342$ *mL/hr, so 2.2 hours.*

c) Imagine the Fultonic is installed in a poorly ventilated basement (or a normal Barrows Hall classroom) that is 2.5 m by 4 m by 4 m. If all the waste energy from the hydrogen combustion process stayed in the basement, by how much would the basement temperature be raised by the Fultonic operating at full capacity for 12 hours? (The density of air is 1.2 kg/m^3, and its specific heat is 1 J/g-K.)

$\Delta Q = mC\Delta T$

$\Delta Q = 12\ hr \times 1000\ W \times (.001\ kJ/s/1\ W) \times (3600\ s/hr) \times (96.1\ kJ_{heat}/189.7\ kJ_{elec}) = 2.19 \times 10^7\ J$

$m = 40\ m^3 \times 1200\ g/m^3 = 48,000\ g$

$\Delta T = 2.19 \times 10^7/(48,000 \times 1) = 459\ K$. Hydrogen fuel cells have been marked as a good candidate technology for cogeneration.

4. Discussion/wrap-up on semester