Energy Systems

Prof. Keith Goossen

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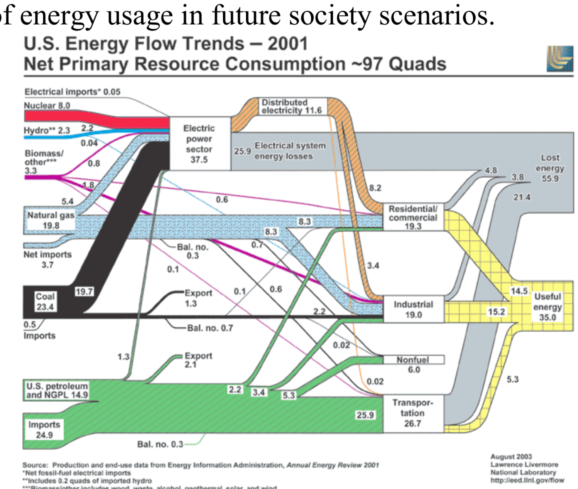
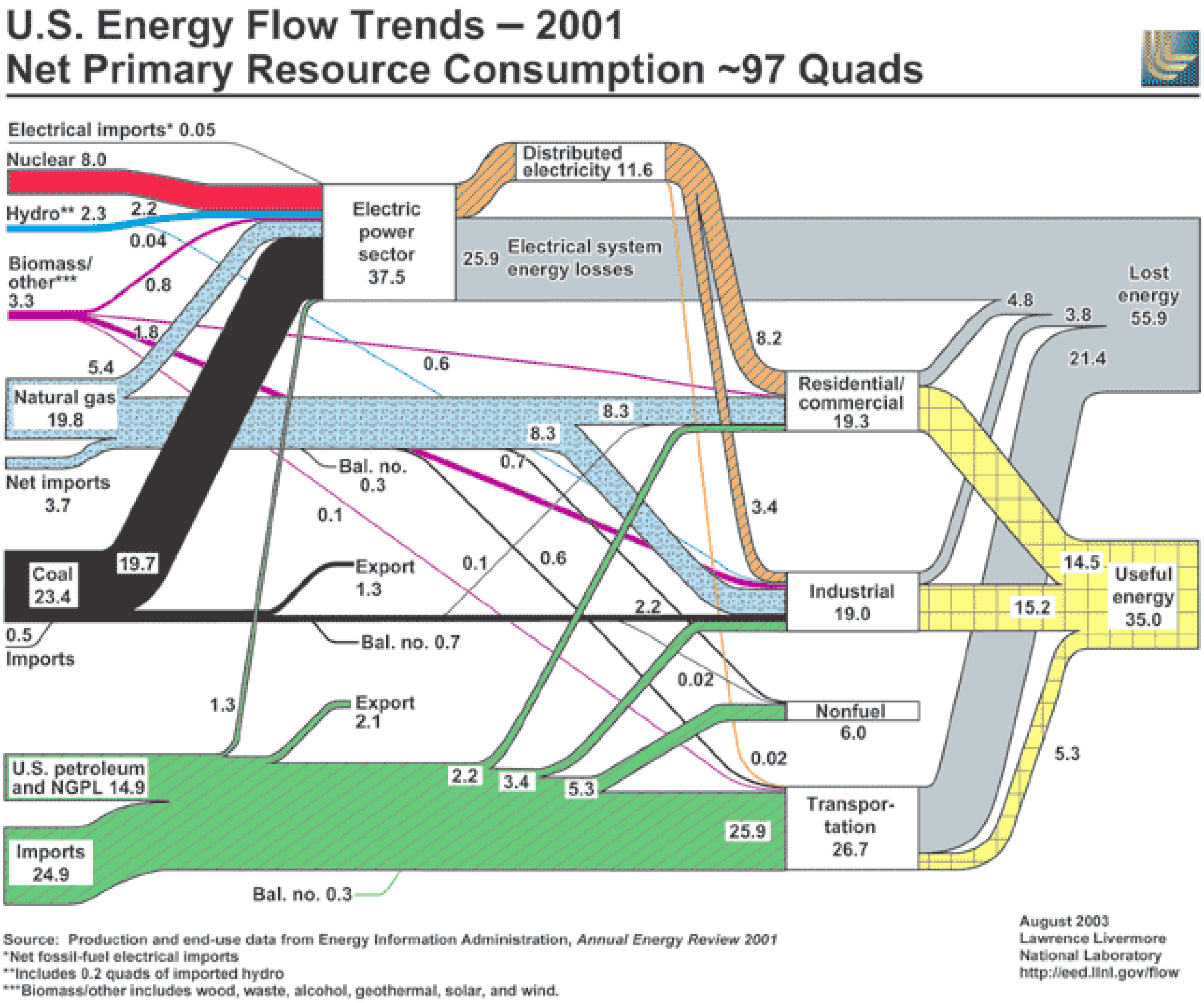


PREFACE

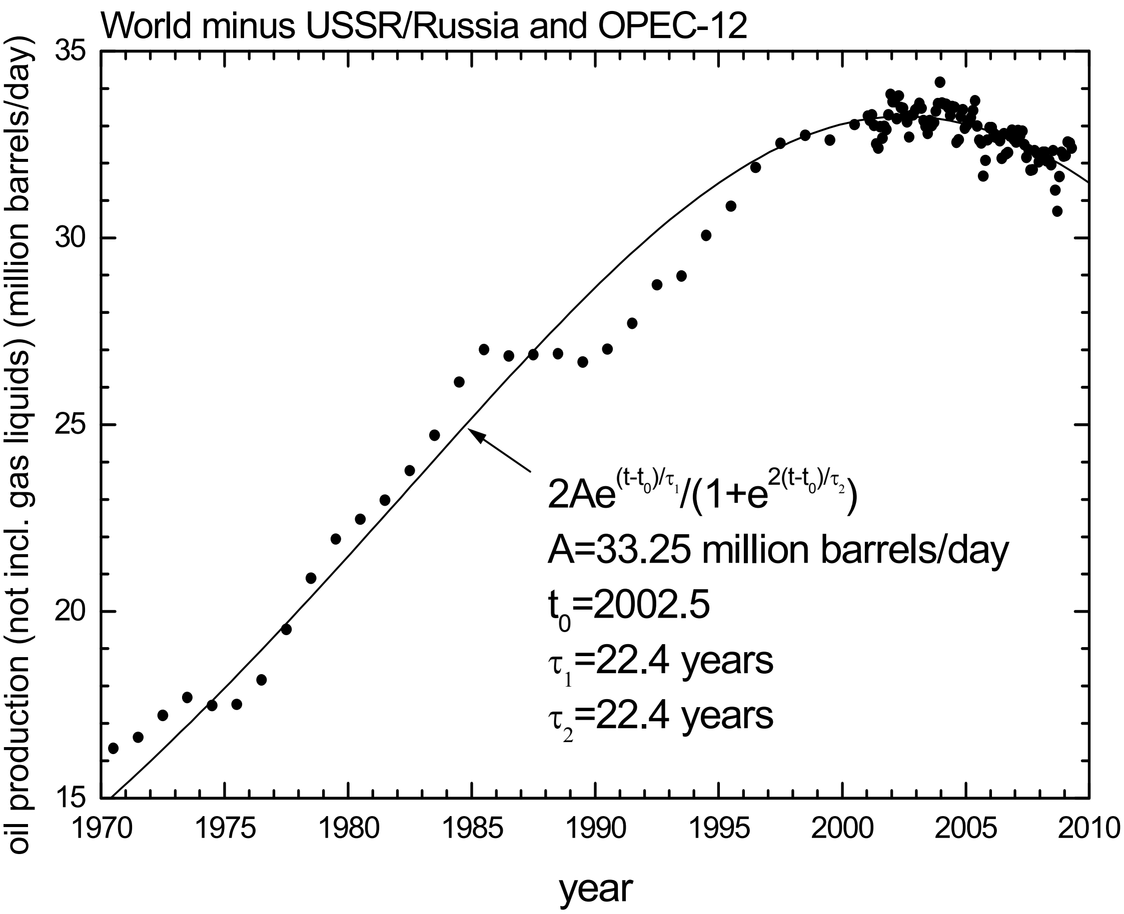
Shown here is the energy use chart for the United States in the year 2001:



It shows on the left, energy sources, and on the right energy uses. In the middle, sources are converted to useful forms and there are losses (rejected energy).

This chart is what this course is about; we will follow it from left to right chronologically in the semester. The quantities in the chart are in quads, or, quadrillion (10^{15}) BTU. This unit may seem odd to many of you, but you'll learn how to convert it to other energy units such as joules or kilowatt-hours. In fact, becoming fluent with the magnitudes of energy involved in running this country (and the world, although I don't have a similar chart for it), is part of what this course is to provide you.

Nicely, the total energy use (inputted, before losses) of the US is about 100 quads, so, the other numbers on the chart are nearly percentages as well. Examining it, we see that petroleum (pretty much oil), supplies about 38 % of our needs, followed by coal at 23 %, natural gas at about 19 %, nuclear about 8 %, then "other". Right away you should see that "other" is not much, and so all the talk you might have heard about running out of oil, etc., could be worrisome if true. We will apply some of the reasoning to the arguments that oil, coal, and natural gas are "running out"; the reality is that we don't know, but have something of an idea that is based upon production rates. For example, while production of oil in OPEC countries is affected by politics, generally in non-OPEC countries, production is based upon the oil that is left and how hard (expensive) it is to get it. Thus, we have the following graph, which shows that non-OPEC (and subtracting the USSR and Russia, which went through its own political gyrations), peaked in 2002:



The concept that oil production "peaks" is very suggestive from this plot. Interestingly, it appears to fall at the same rate that it climbed, although there is no hard theory that necessarily predicts this. Also, one sees that the time constant is on the order of decades, not centuries. While including the rest of the world's production in this plot makes it more complicated, as we will see later in the course, it is again suggestive that if production can peak in one section of the world, it can do so in the world as a whole.

In the "other" section of energy sources, we have all the alternate forms, hydroelectric, biomass which includes wood and ethanol, wind, solar, etc. For each of these the total resource availability will be examined, to see if they can take the place of our mined chemical energy sources.

The chart also shows how the sources are used, for example, half our electric generation is from coal, and nearly all our transportation is petroleum based. It also shows the efficiency of these conversions from sources to useful forms. This course will examine how our society's energy use could be made more efficient. Finally, it shows the breakdown of end uses of the energy.

Living "green" is touted as a way to reduce our energy consumption and thus deal with reduced energy availability. However, to a certain extent we've seen the effects of reduced energy consumption in the last couple of years- while the causal connections are not certain, the fact of the matter is that after energy consumption peaked in this country about the year 2007, the economy went into recession. In the last part of the course, the correlations between economic output and energy consumption will be examined, with the concept of predicting energy requirements going forward into the future.

That leads to the crux of the course and your final assignment (in lieu of a final exam): you will each be asked to reproduce the energy flow chart for the year 2030. While no one knows the answer to this, the goal of this course is to provide you each with the necessary knowledge to make a prediction. Your grade will be based upon the thoughtful arguments you provide to support your choices.

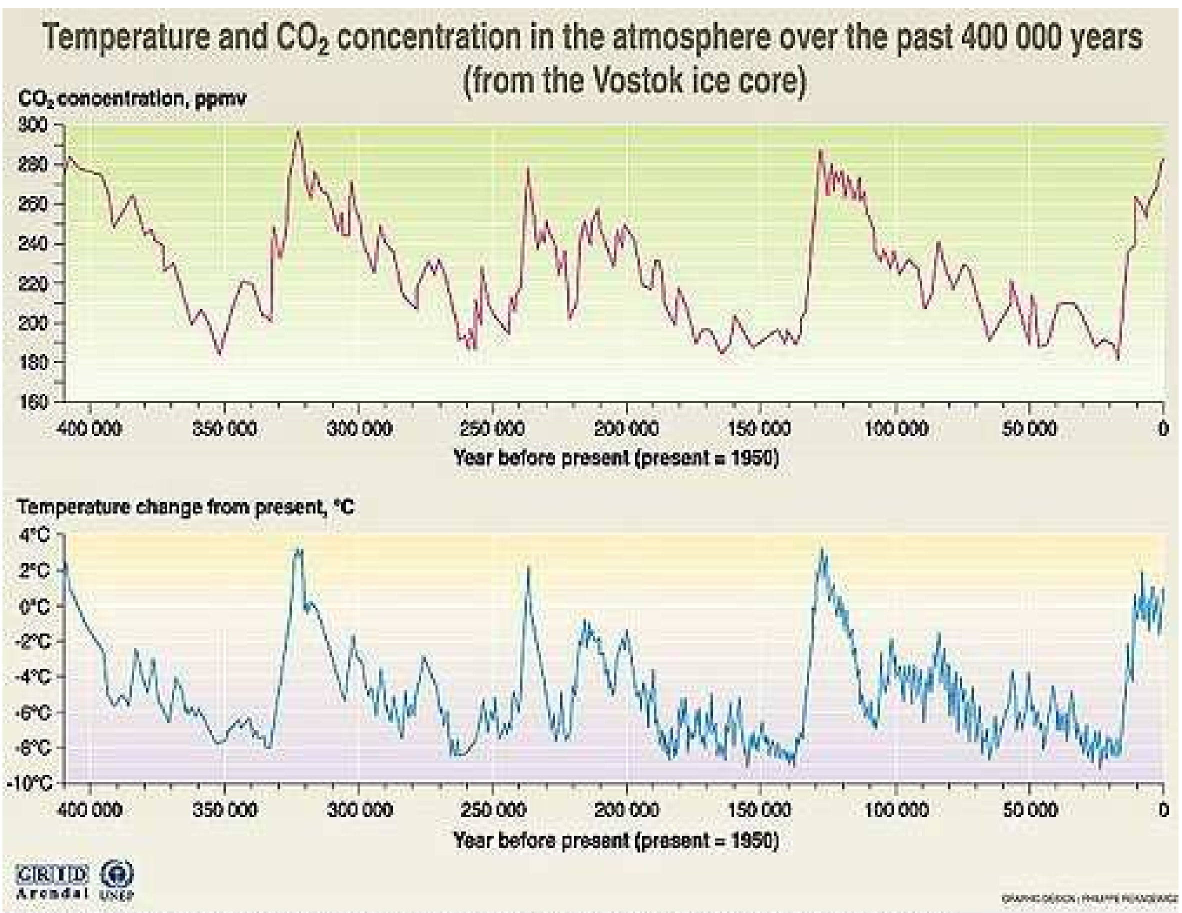
QUALIFICATION

This course is not about global warming. Of course, we all know the arguments that increased emission of greenhouse gases is affecting our climate. But, these issues create an additional element of complication to your final assignment that we wish to avoid. Catastrophe may loom due to ignoring this, but I think you will find your final assignment difficult enough without the additional restriction of avoiding greenhouse gas emission. So, you are NOT to take that into account.

Of course, in real life we may not be able to do this.

That being said, let's step away from the course for a moment (since this course is not about global warming, the following will not be on any assignment or test), and you can just sit back and watch.

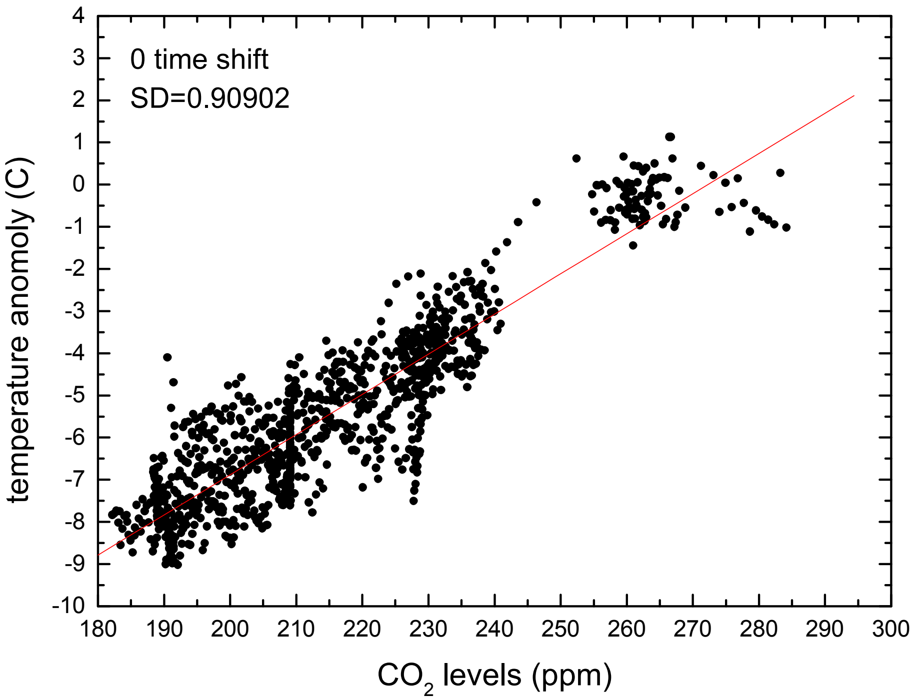
Most arguments of the folly of greenhouse gas emission, primarily CO2, are based upon the following correlation seen in the paleoclimatic record:



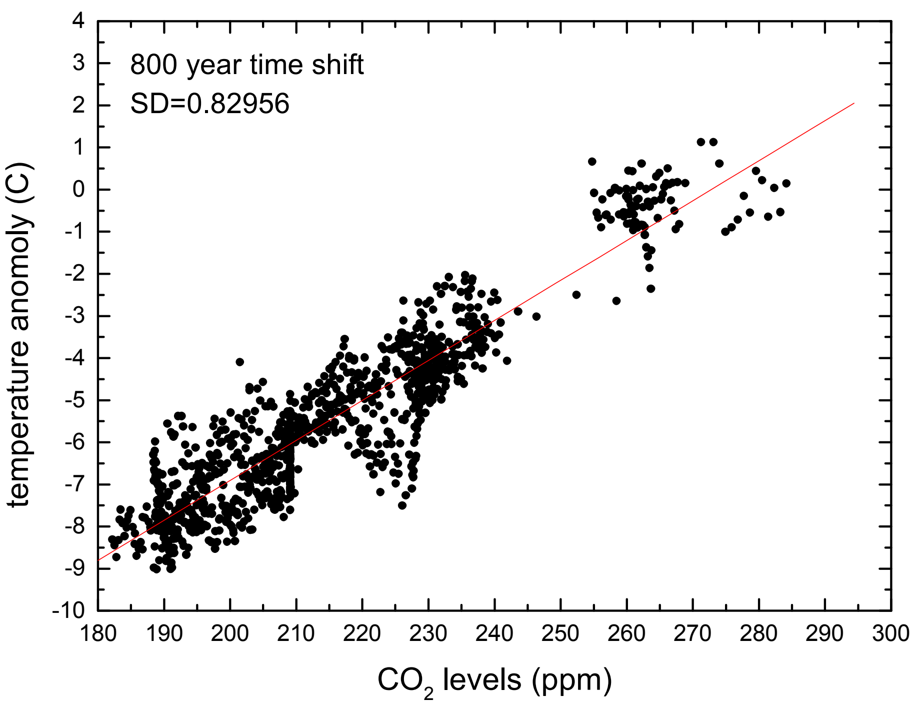
Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

As can be seen, when the level of CO2 in the atmosphere is high, the temperature is high. Since we've now emitted enough CO2 to reach ~ 385 ppm, we are well beyond any level seen in the recent prehistoric record.

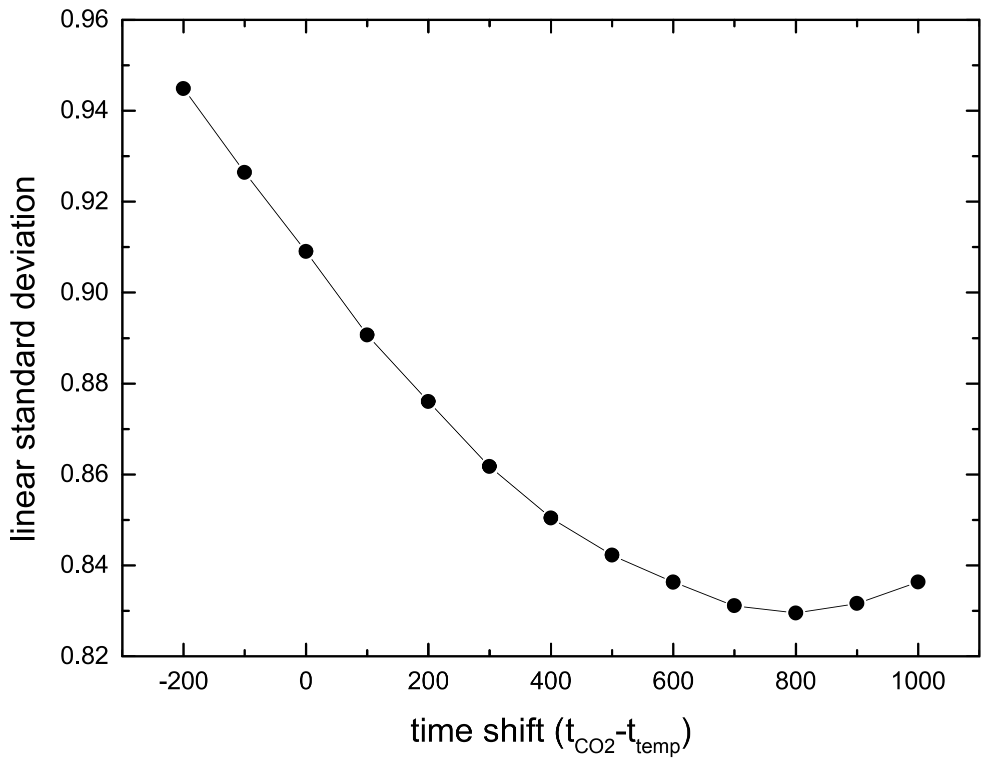
While the correlation seems clear, I find it actually helpful to plot temperature vs. CO2, plotting one vs. the other for each point in time:



Now, the level of correlation can be seen a little more clearly. It appears quite linear. Note that I have written “0 time shift”. In fact, if one shifts the time records relative to each other, the linearity is improved:



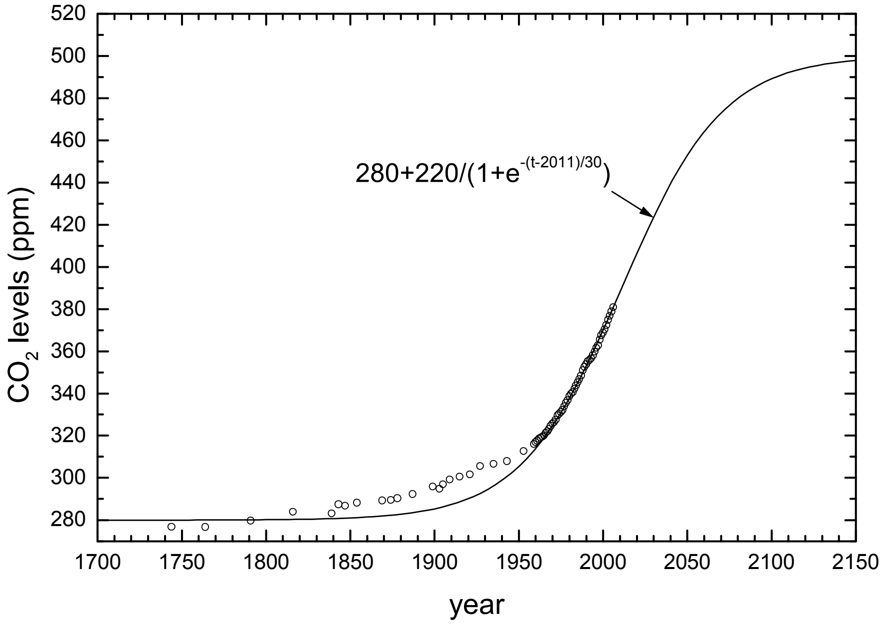
It may not seem so much improved, but the magic of plotting programs with statistical analysis shows that the standard deviation from a linear fit has gone down. We can plot this standard deviation vs. time shift:



Note, it is minimized at a shift of 800 years. Note, this time shift is in the direction, that the change in temperature occurred **first**. That is, in the paleoclimatic record, the temperature went up first, then the CO2 went up. This fact has been observed before.

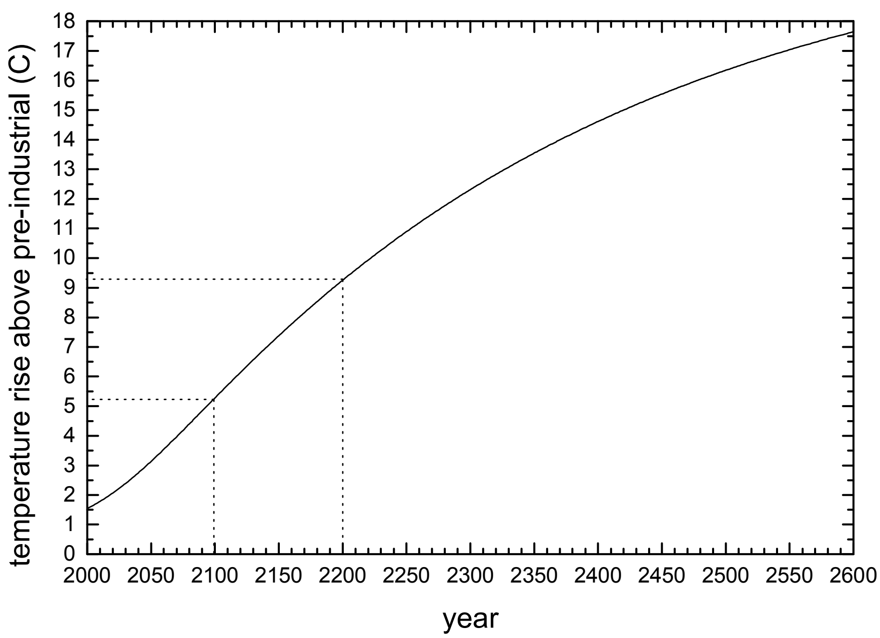
Now, the question is, in modern times when we have increased CO2 levels, will temperature follow? This is the real question of global warming, are they connected in such a way, that while in prehistoric times CO2 followed temperature, now, with CO2 rise occurring first, will they achieve the same equilibrium value anyway? Furthermore, is the time lag to reaching that equilibrium value the same if CO2 rise occurs first?

If we accept that as true, we can simply extrapolate the straight line in the above plot to read the equilibrium value. Now, the timing of the change is a little more complicated as the CO2 levels are themselves changing. This is the modern CO2 record, with the (perhaps optimistic) projection that levels will stabilize at 500 ppm:



The circles are recorded data, and the solid line a fit and projection. The temperature is then given by the convolution of this input data to the impulse response function that results in a 800 year time lag for each instantaneous increase (those of you not familiar with signal processing methods, just accept this):

$T(t) = \int_{1800}^{t} \frac{dC(t')}{dt'} h(t-t')dt'$. Then, we have



This is, of course, while not so worrisome for me (being near 50) and somewhat worrisome for you students (near 20), is downright scary for our later descendants. Incidentally the 5 C rise by 2100 is within the predictions of atmospheric models, so this "black box" approach seems to have merit. What this is showing is that even if CO2 rise stops and is stabilized at 500 ppm, which based upon the curve fit shown appears to be the most optimistic scenario, climate change is pretty much catastrophic; it will just take several hundred years. This can be thought of as the time constant related to the heat capacity of the planet; big things take a while to warm up. This also shows why current arguments that climate change is not happening may be spurious; by the graph current temperatures are rising only 0.1-0.2 C per decade, and it is just not so noticeable.

Okay! Now that we've scared the * out of us about CO2 and climate change, we're going to ignore it (apart from pointing out the physics of why, coal emits more than natural gas as we go through the chemistry of fuels). It will not be part of your final assignment. Obviously, from the above it's not something we should ignore, it's just that the final assignment is complicated enough without including it in the analysis.

I. Introduction

1. Forms of energy, and energy units.

The energy of things in motion, or kinetic energy

Energy is the ability to do work. And work it does! In the United States, each of us has on average the equivalent energy of 40 humans doing work for us every day, in the form of electricity, fuel to move us around, etc. We'll go through those numbers later, but first we need to understand some basic things about energy.

This section may be a review for some of you going back several years. Engineers will basically recognize it as the science of dynamic mechanics, or of things in motion, taught in a fashion summarizing the field in terms of the energy of things in motion, called kinetic energy. Understanding kinetic energy is the starting point to understanding energy in general, and of course has many relevant examples in energy systems. In this section the energy in a flywheel will be derived, as well as the power per unit area in wind.

One could argue that the most basic law of physics is

$$\text{energy} = \text{force} \times \text{distance} \quad , \qquad \text{(I.1.1)}$$

that is, the energy (E) that is expended by the thing doing the forcing equals the force applied times the distance over which the force is applied. Stated more mathematically, and taking into account that the force (F) may change over distance (x),

$$E = \int \mathrm{F}d\mathrm{x} \quad , \qquad \text{(I.1.2)}$$

and if we want to get really picky, we need to take into account that force and movement are vectors, and the force may not be in the same direction as the movement, a complete mathematical description would be

$$E = \int \mathbf{F} \bullet \mathbf{dl} \quad . \qquad \text{(I.1.3)}$$

For those of you who have not had vector calculus, in the words of the Hitchhiker's Guide to the Galaxy, DON'T PANIC. We're not going to do anything much more complicated that this. In equation I.1.3, **F** the force can point in one direction, and **dl** the differential or very small section of the path what is being pushed, can be in different directions. We need to be able to analyze when this happens. The simplest example is a ball rolling down a hill. The force of gravity is down, but the motion is at an angle. As a reminder, the dot product represents product of the projection of one vector onto the other, and is just the same as any other right triangle, given by the products of the magnitude of the vectors times the cosine of the angle between them. In what follows we'll keep the force and the motion in the same direction, so won't need to know this, but I.1.3 is written for completeness at this point.

When the thing doing the forcing expends energy, it transfers that energy to something else (not always the thing being forced as we will see). If a ball is pushed with constant force F, it acquires energy

$$E = \mathrm{Fx} \quad . \qquad \text{(I.1.4)}$$

Another important law of physics is

$$\mathrm{F} = m\mathrm{a} \quad , \qquad \text{(I.1.5)}$$

where m is the mass of the thing being pushed, and a is its acceleration. Acceleration is the rate of change of velocity over time,

$$\mathrm{a} = \frac{d\mathrm{v}}{dt} \quad , \tag{I.1.6}$$

and with constant acceleration, then,

$$\mathrm{v} = \mathrm{a}t = \frac{\mathrm{F}}{m}t \ . \tag{I.1.7}$$

But the velocity is the rate of change of distance with time,

$$\mathrm{v} = \frac{d\mathrm{x}}{dt} \quad , \tag{I.1.8}$$

so we can write

$$\frac{d\mathrm{x}}{dt} = \frac{\mathrm{F}}{m}t \quad , \tag{I.1.9}$$

and integrating, we have

$$\mathrm{x} = \frac{\mathrm{F}}{2m}t^2 \quad . \tag{I.1.10}$$

Using (I.1.10) to substitute for time in equation (I.1.7), we obtain

$$\mathrm{v}^2 = \frac{\mathrm{F}^2}{m^2}t^2 = \frac{\mathrm{F}^2}{m^2}(\frac{2\mathrm{x}m}{\mathrm{F}}) = \frac{2\mathrm{Fx}}{m} \quad , \tag{I.1.11}$$

and then using (I.1.4) to substitute for force, we have

$$\mathrm{v}^2 = \frac{2\mathrm{Fx}}{m} = \frac{2E}{m} \ , \tag{I.1.12}$$

and solving,

$$E = \frac{1}{2}m\mathrm{v}^2 \ . \tag{I.1.13}$$

This *kinetic energy* has been transferred from the forcer to the thing being forced. It is equal to the energy expended by the forcer. This is the principle of *conservation of energy*, that if one expends energy it must be transferred to something else.

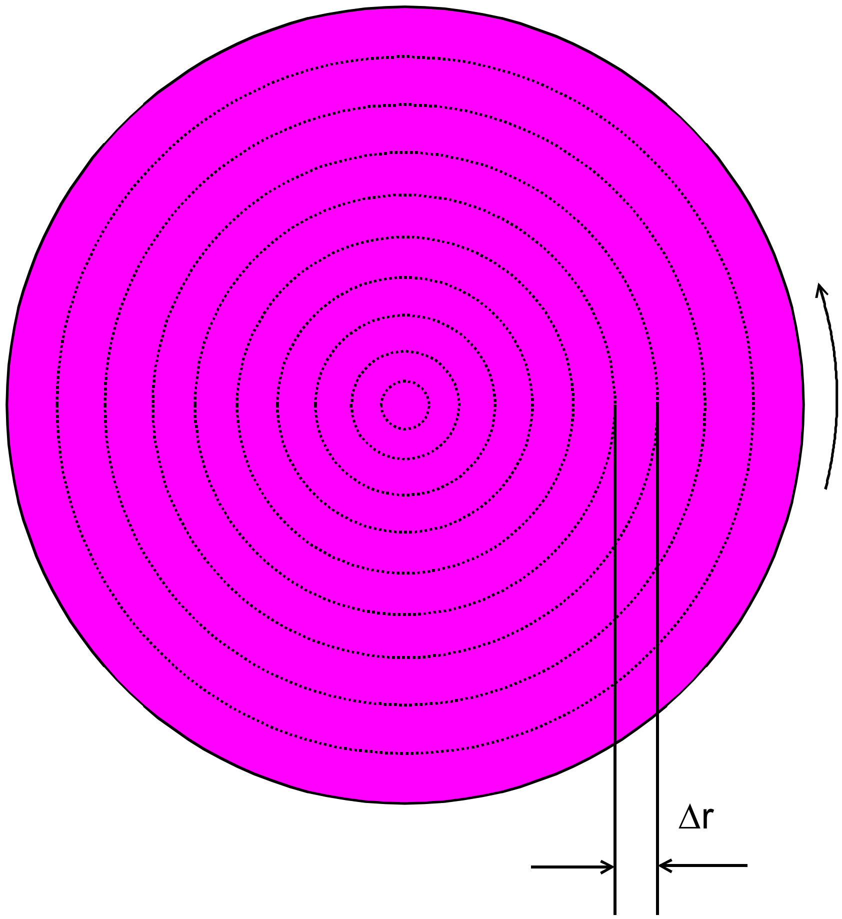


Figure I.1.1: A spinning flywheel, divided mathematically into sections.

When the object acquires kinetic energy, it acquires the ability to do work. This is of course, simple to understand, since if it strikes another object it can cause that object to move, and so it does work on it.

EXAMPLE- ENERGY IN FLYWHEEL

A flywheel is a spinning wheel, where the term flywheel refers to the fact that the wheel can be engaged by a gear or other such mechanism, so that its motion can be transferred elsewhere. Thus, a flywheel stores energy. We can analyze how much using equation I.1.13 if we divide it up into concentric sections as shown in figure I.1.1. If the flywheel completes a revolution in time *T*, the velocity of a section at radius r is given by

$$\mathrm{v}(\mathrm{r}) = \frac{2\pi \mathrm{r}}{T} \quad . \qquad \text{(I.1.14)}$$

Simple, right? Velocity is just distance traveled (the circumference of the section) over the time it takes. If the total mass of the flywheel is m_{tot}, then the mass of each section is given by

$$m(\mathrm{r}) = m_{tot} \frac{2\pi \mathrm{r}(\Delta \mathrm{r})}{\pi R^2} \quad , \qquad \text{(I.1.15)}$$

where R is the radius of the flywheel. Again, simple. The mass in each section is given by the fractional area of the section times the total mass. As a reminder, the area of a circular shell is the circumference times the thickness of the shell. So, the energy in each section is given by

$$E(\mathrm{r}) = \frac{1}{2} m(\mathrm{r}) \mathrm{v}(\mathrm{r})^2 = \frac{1}{2} \{ m_{tot} \frac{2\pi \mathrm{r}(\Delta \mathrm{r})}{\pi R^2} \} \{ \frac{2\pi \mathrm{r}}{T} \}^2 = m_{tot} \frac{4\pi^2 \mathrm{r}^3 (\Delta \mathrm{r})}{R^2 T^2} . \qquad \text{(I.1.16)}$$

Now, to get the total energy, we sum all the sections. We turn $\Delta \mathrm{r}$ into the differential $d\mathrm{r}$, and get

$$E_{tot} = \int_0^R E(\mathrm{r}) d\mathrm{r} = \int_0^R m_{tot} \frac{4\pi^2 \mathrm{r}^3}{R^2 T^2} d\mathrm{r} = m_{tot} \frac{\pi^2 \mathrm{r}^4}{R^2 T^2} \Big|_0^R = m_{tot} \frac{\pi^2 R^2}{T^2} . \qquad \text{(I.1.17)}$$

EXAMPLE-POWER IN WIND

We can't say how much energy is in wind, because we would need to know how much of it there is. To understand the energy properties of wind, we need to introduce *power* (W), which most of you know is the rate of change of energy with time. That is to say,

$$W = \frac{dE}{dt} . \qquad \text{(I.1.18)}$$

We're not getting to units yet, but since electricity consumption is universal and most or you are somewhat familiar with your electric bill, we can say that if you consume 1 kilowatt of power, for 1 hour, you have consumed 1 kilowatt-hour of energy.

For wind, it is even a little more complicated, since an area (for example, the area defined by the blades of a windmill) must be defined. If we count how many wind molecules cross the plane of this area over a given time, and count all their forward energy, and divide this forward energy by the time, that would be the power in the wind. Since the area could be different depending on the situation, we define a *power flux* as the power that has crossed a plane of unit area:

$$P = \frac{W}{A} . \qquad \text{(I.1.19)}$$

Flux is a general physical property that can apply to many different things. For example, the flux of the wind molecules themselves would be the number of them crossing a plane per unit time, per unit area. Imagine a plane of a certain area, take a stopwatch, and if you could, count the number of molecules crossing that plane in a certain time, divide by the area and the time, and you get the flux. While this measurement may be difficult, a simple equation can give flux, which is density of those things per unit volume (N) times their velocity perpendicular to the plane:

$$flux \quad of \quad things = (volume \quad density \quad of \quad things) \quad x \quad velocity \qquad \text{(I.1.20)}$$

Note that this has the dimensions of "things" per unit area per unit time. To see this relation, just imagine a very thin box of thickness dx with x being the direction of flow. The number of molecules in this box is given by their volume density N times the area A times dx. If the velocity is $d\mathrm{x}/dt$, all of the molecules leave this box in a time dt. So we have that the

$$things \;\; leaving \;\; thin \;\; box \;\; in \;\; time \;\; dt = NA(dx) \;, \qquad \text{(I.1.21)}$$

where the velocity is dx/dt. Thus, the flux is given by

$$things \;\; leaving \;\; thin \;\; box \;\; in \;\; time \;\; per \;\; unit \;\; time \;\; per \;\; unit \;\; area =$$

$$N\frac{dx}{dt} = N\text{v} \qquad \text{(I.1.22)}$$

Note that in this equation, we have been calling the velocity the forward velocity. Sometimes it is called the average velocity. For air molecules, they have a lot of random thermal velocity, that averages out to zero. For v to be non-zero, their must be an average flow.

Now, equation I.1.22 is a great relationship, since we can use it to calculate the flux of *anything*, including energy, if we know the volume density of energy. For wind, this is simple, since each molecule has a certain amount of kinetic energy given by equation I.1.13, and if we know the mass density, or mass of air per unit volume ρ, the kinetic energy density per unit volume U is just

$$U_{wind} = \frac{1}{2}\rho \text{v}^2 \quad . \qquad \text{(I.1.23)}$$

Just think about this for a moment. All we've done is take every air molecule in a certain volume, added up all their energies $m_{molecule}\text{v}^2/2$, and divided by the volume.

Having the kinetic energy density in wind, we just multiply by the velocity to get

$$P_{wind} = U_{wind}\text{v} = \frac{1}{2}\rho \text{v}^3 \quad . \qquad \text{(I.1.24)}$$

Those of you who have investigated windmills will recognize this formula, from the v^3 dependence of the power one obtains from a windmill. This is one of the problems using a windmill, that an area with half the wind velocity gets an eighth of the power.

Frictional power losses of things in motion

While later in the course we will examine conversion efficiencies, or lack thereof, caused sometimes by friction in moving systems, I wanted to correct a possible misconception, that the frictional power losses are somehow proportional to the energy of the thing in motion. They are not. Frictional power losses are determined by that which is causing the friction, and are different depending upon whether it is air, rubbing of surfaces, etc., and even then depends upon the exact situation. So, for example, the power required to keep a flywheel spinning is not a fraction of the energy in the spinning flywheel. A little more on that below.

First, we can easily calculate how much power I must exert to push a table across the floor (at constant velocity). This depends upon the friction between the table legs and the floor. While the physics of this friction are quite complicated, having to do with the binding forces between the atoms of table and floor, the end result is a simple formula for the force impeding forward motion of the table:

$$\mathrm{F}_{friction} = -\mu \mathrm{N} . \qquad \text{(I.1.25)}$$

Here the negative sign denotes that the frictional force is opposite to my pushing force. Here μ is a dimensionless (i.e., it is just a number, since $F_{friction}$ and N are both forces) fudge factor incorporating all those interatomic forces, and N is the force of the table pushing down on the floor, due to gravity. Near the earth, gravitational forces are simply proportional to the mass of the object (in this case the table), given by

$$\mathrm{N} = mg , \qquad \text{(I.1.26)}$$

where *g* is the gravitational constant for objects near the earth. (As an aside, note that since acceleration equals force divided by mass, all things fall at the same acceleration, *g*, when there is no air resistance).

Now, since if the table is moving at a constant velocity, my pushing force must equal the frictional force, the energy I am providing to the system is given by

$$E_{\mathrm{suppliedbypushing}} = \mathrm{F}_{friction} x = \mu m g x . \qquad \text{(I.1.27)}$$

Then, since power is the time derivative of energy, we have that

$$W_{pushing} = \frac{dE}{dt} = \mu m g \frac{dx}{dt} = \mu m g \mathrm{v} , \qquad \text{(I.1.28)}$$

and we see that the power supplied to keep the table in motion is proportional to its velocity. Of course, the kinetic energy of the table is still given by

$$E_{kinetic} = \frac{1}{2} m \mathrm{v}^2 ,$$

proportional to velocity squared. So the power required to keep the table in motion is not a fraction of the kinetic energy of the table.

Incidentally, this came up since someone was interested in the power required to keep a computer disc drive in motion. For that case, it turns out that the frictional losses are due to air resistance. This has been studied, and an author has found that

"Experiments using a single 3.5-in. disk in enclosure show that aerodynamic power loss is proportional to the second power of rotational speed and the fourth power of disk radius,"

so, for air resistance, power loss does go as the velocity squared. We will talk about this later when discussing the miles per gallon of your car on the highway.

Thermal energy of matter, or heat

If when I push the table, it does not go faster, where does the energy I have expended go? Of course, the answer is that the table legs and floor are heated by the friction between them. Everyone knows that when you rub your hands together they get warm. The heat content of material is proportional to its temperature, and it is a measure of the kinetic energy of the atoms and molecules of the material. So, while I pushed the table, its kinetic energy did not increase, the kinetic energy of the atoms and molecules of the table and floor did.

Heat is sometimes regarded as "wasted" energy, and indeed, it is difficult to imagine deriving work from a heated table leg. However, it can!, by heating something colder, and thus transferring its energy to a colder object. Heated air of course do work, since it goes in motion, and can turn for example a turbine. We'll discuss this more when we talk about energy conversion of burning fuels.

Potential energy, or energy stored against an elastic force

In the earlier example of a ball rolling down the hill, somehow it had to get on the hill, and that which lifted it expended energy against gravity to do so, and that energy was stored in the ball as potential energy, since gravity is an elastic force, and things that go up also go down (without energy loss unless there is air resistance, etc.).

Gravity is not the only elastic force, and a simple example is a spring. When a spring is compressed, potential energy is developed in it, and if it is released, that potential energy is converted into kinetic energy. One can calculate the potential energy in a spring using the same force time distance formula, noting that the force required to compress a spring is given by

$$\mathrm{F}_{spring} = -K\mathrm{x}\,, \qquad \text{(I.1.29)}$$

where the negative signs just means the spring force is working against that which is compressing it, and x is the distance it has been compressed. Here everyone knows that the more you compress a spring, the harder it gets to do so, so the force goes up with x. Then, the potential energy in the spring is given by

$$E = \int -\mathrm{F}_{\mathrm{spring}} d\mathrm{x} = \int K\mathrm{x}d\mathrm{x} = \frac{1}{2}K\mathrm{x}^2\,. \qquad \text{(I.1.30)}$$

There are many examples of elastic forces, and the energy stored when working against one is always given by force time distance. For example, the potential energy stored in an object lifted against gravity a height h is mgh .

Energy stored in a compressed gas

If you walk into almost any industrial plant (or even look around our university), you will see pipes marked "compressed air". Later, we will discussed compressed air more, and the devices called air compressors that pressurize the air, but the reason these pipes are there is that when air is compressed, energy is stored that can be released anywhere along the pipe, which is convenient. Just take an air gun located on the line and blow it on something; it will move, so the compressed air has done work. In this sense, compressed gases are like springs since they can store energy. In industrial plants compressed air lines are used as an energy source for everything from opening and closing valves to moving containers along an assembly line.

Compressing a gas, by for example reducing the volume of a container of gas, leads to higher pressure in the gas, so if it is released it can blow on something and do work. Note that the increased pressure of the gas is not due to repulsion of the molecules of the gas against each other. Rather, it is due to the fact that when the volume of the container is reduced, the gas molecules moving about do to thermal motion will strike the sides of the container more often. That is, if the temperature of the gas has not changed, and the volume is reduced, the velocity of the gas molecules is unchanged, and the number of times the molecules strike the container per unit time goes up, so the pressure against the sides of the container goes up. So, we can write that the pressure of the gas p is proportional to one over the volume of the container V, at constant temperature:

$$p \propto \frac{1}{V}\text{, at constant temperature.} \qquad \text{(I.1.31)}$$

Now, if the volume is unchanged, but the temperature (T) of the gas increases, then the velocity of the gas molecules increases, so we can write that

$$p \propto T\text{ , at constant volume.} \qquad \text{(I.1.32)}$$

Now, if the number of gas molecules (n) in the container goes up, the number of times the molecules strike the chamber per unit time also goes up, so

$$p \propto n\text{, at constant volume and temperature.} \qquad \text{(I.1.33)}$$

These three equations are summarized in the Ideal Gas Law,

$$p \propto \frac{nT}{V}. \qquad \text{(I.1.34)}$$

We see that when a gas is worked against, that is, the volume is changed, pressure and temperature can both changed. If a gas is compressed a certain way, its temperature goes up, that is, it absorbs heat from the surroundings. If this gas is then moved to another location, and allowed to expand, its temperature goes down, that is, it delivers heat to the surroundings. This is the basis for air conditioning. Much of thermodynamics is concerned with, when a gas is compressed, how much energy goes into added pressure (an elastic force that stores energy) and how much goes into added temperature (heat). How this happens affects the efficiency of things from engines to refrigerators, and we'll discuss it in detail later.

Power in electrical current

Electrons in a wire move with an average velocity because there is a force do to an electric field, present in the wire. While electromagnetics and all the associated formulas are a complicated subject, here, we just will note that the force on an object is proportional to its charge and the electric field present:

$$\mathrm{F}_{electric} = q\mathrm{E}\,. \qquad \text{(I.1.35)}$$

This is sensible, since it seems that if either the charge or the electric field goes up, so should the force. For an electron, its charge is denoted as *e*. But, what is an electric field?

When it comes right down to it, that is a question about the fundamental nature of physics, but we can side step it by just saying that two charges interact, repelling if of the same sign and attracting if opposite. So an electric field is set up when charge is present. How the electric field is developed in the wire is something we don't have to worry about here, but we do have to understand its relationship with voltage.

While electric field is not something we deal with in our everyday life, voltage is. We talk about a battery being a 9 volt battery, for example, meaning that there is 9 volts across the terminals. If I placed an electron between the terminals of a 9 volt battery, it would be drawn to the positive terminal. So, there must be an electric field between the terminals. That electric field is given by

$$\mathrm{E} = \frac{V}{L}, \qquad \text{(I.1.36)}$$

where V is the voltage and L is the distance between the terminals. This make sense: if the voltage is lower, the force on the electron is lower, and if the distance between the battery terminals is greater, the force is also lower.

A difficulty does arise that the electric field can vary between the terminals. To account for this we write that

$$V = \int \mathrm{E}(\mathrm{x})d\mathrm{x}\,. \qquad \text{(I.1.37)}$$

Note that is E is constant, I.1.36 is recovered. Now, a further complication is that electric field is a vector; this is taken into account by writing

$$V = \int \mathbf{E} \bullet \mathbf{dl}\,. \qquad \text{(I.1.38)}$$

Note that this is as we did in computing energy from force and distance in equation I.1.3. In fact, comparing I.1.3 and I.1.38, and noting I.1.35, we can write that the energy an electron gains when moving through an electric field is

$$E = \int e\mathbf{E} \bullet \mathbf{dl} = eV\,. \qquad \text{(I.1.39)}$$

Now, current is the movement of electrons through the wire, and is defined as the amount of charge that passes a plane perpendicular through the wire per unit time. So it is the number of electrons passing the plane per unit time, multiplied by their charge *e*. It is the same at every point along the wire, which makes sense, as otherwise the electrons would bunch up. So, if there is a wire with a voltage V across it, by the time the electrons reach the end of the wire, they have each acquired an energy eV. The number of them reaching the end of the wire is given by the current divided by the electron charge, or I/e. So the energy per unit time, or the power, that goes through the plane at the end of the wire is given by

$$W = eV\frac{I}{e} = IV \; . \qquad \text{(I.1.40)}$$

Thus, getting back to our battery example, if a wire, or any device for that matter, is hooked up to the battery, and draws a current *I*, the battery supplies a power *IV*. Later, when we discuss AC electric power systems, this formula will be modified since if the current and voltage are varying in time, so does the power, and we then must talk of average power. That will introduce a factor into the formula, but basically, we can remember that electric power is proportional to voltage times current.

Energy in light

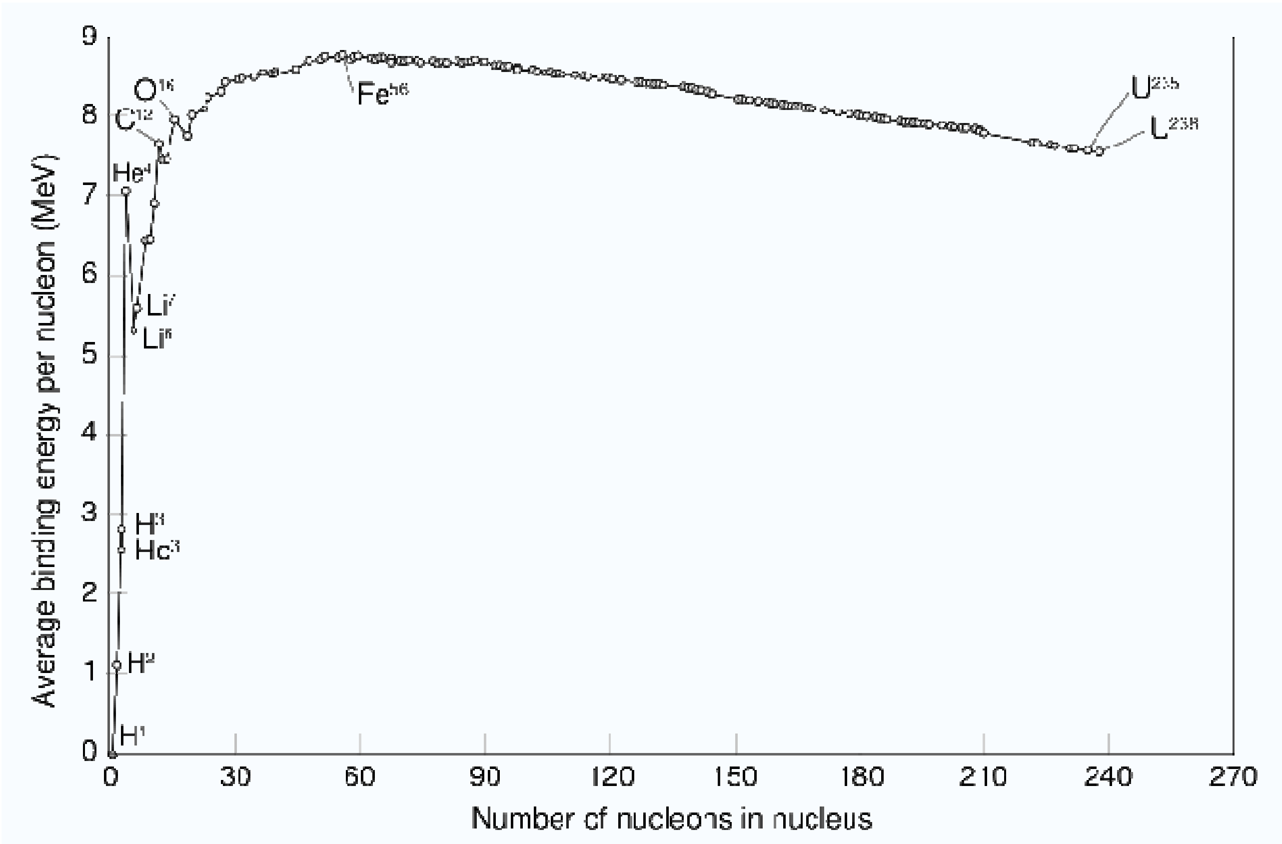
We've all felt sunlight warming our skin, but how does it do it? We don't think of light as having kinetic energy (and indeed photons have no mass), and yet it clearly conveys energy. The answer lies in the fact that light is electromagnetic radiation, which means that it is composed of electric and magnetic fields moving through space. We're not going to go through Maxwell's equations here and derive how this happens, but simply will note that, as we've seen in the last section, electric (and magnetic, but a little more complicated) fields induce forces on electrons. So, when light is absorbed in a material, it imparts its energy to the electrons in the material. In a solar cell, this induces average forward motion of the electrons, or current, and the solar cell can supply electric power. In your skin, it causes the electrons to go to excited states in the atoms and molecules of your skin, and then generally the electrons lose this energy when the atoms and molecules bounce off of other atoms and molecules, and thus is transferred to a general rise in the kinetic energy of the atoms and molecules of your skin (heat), and it gets warm. One sees that generally light can cause useful motion of electrons, or heat. Solar cells are not 100 % efficient since much of the absorption leads to heat.

Energy stored in chemicals

When light causes electrons to go into excited states about atoms and molecules, they usually lose this energy in the form of heating the system as discussed in the last section. However, if the right molecules are around, the electrons in these excited states can precipitate a chemical reaction, where the products of the reaction have more energy that the reactants. Of course, this is what photosynthesis is, and the resulting sugars have stored chemical energy, since they can react with other chemicals later (oxygen) to release energy. There are other means to induce electrons about atoms into excited states, so that they may react to produce chemicals with stored energy, for example for plants at the bottom of the ocean near volcanic vents, but most plant life, which supports all other life, produces chemical with stored energy via light absorption. Chemistry and the formation and burning of chemical energy will be discussed more in the section on hydrocarbons.

Nuclear energy

Nuclear energy is the energy stored in either heavy or very light nuclei. It can be understood from the following diagram of the nuclear binding energy as a function of atomic number:



One sees that heavy nuclei, such as uranium, have less binding energy than atoms of iron, for example. In nuclear fission, which powers all nuclear power plants today, nuclei of uranium (particularly isotope 235) split into lighter nuclei, typically barium and krypton and barium in a controlled chain reaction. When this happens, it's like the barium and krypton nuclei are bound together tighter, like they've dropped down a well, and potential energy is converted into kinetic energy. In other words, the uranium atoms have stored nuclear energy, just as hydrocarbons have stored chemical energy. These reactions are initiated by spontaneous splitting of uranium nuclei that has a certain low probability of happening, releasing neutrons. These neutrons can then be absorbed by other uranium nuclei, making them unstable and resulting in them splitting, releasing more neutrons, causing more reactions, etc.: chain reaction. If a critical mass of uranium 235 is present, you get an uncontrollable chain reaction and a bomb. With a sub-critical mass, or with moderators that absorb neutrons to slow the chain reaction, you get a heat source that can power a reactor. Clearly, you have to know what you are doing.

The reaction of uranium is then

$$n + U_{235} \rightarrow U_{236}(unstable) \rightarrow Kr_{92} + Ba_{141} + 3n \qquad \text{(I.1.41)}$$

Note that the number of nucleons (protons and neutrons) is the same on each side, 236. However, even though the number of nucleons has not changed, the total mass of the system has reduced, by about $3\text{x}10^{-28}$ kilograms. The reduced mass has been converted into energy via the formula

$$E = mc^2, \qquad \text{(I.1.42)}$$

where c is the speed of light.

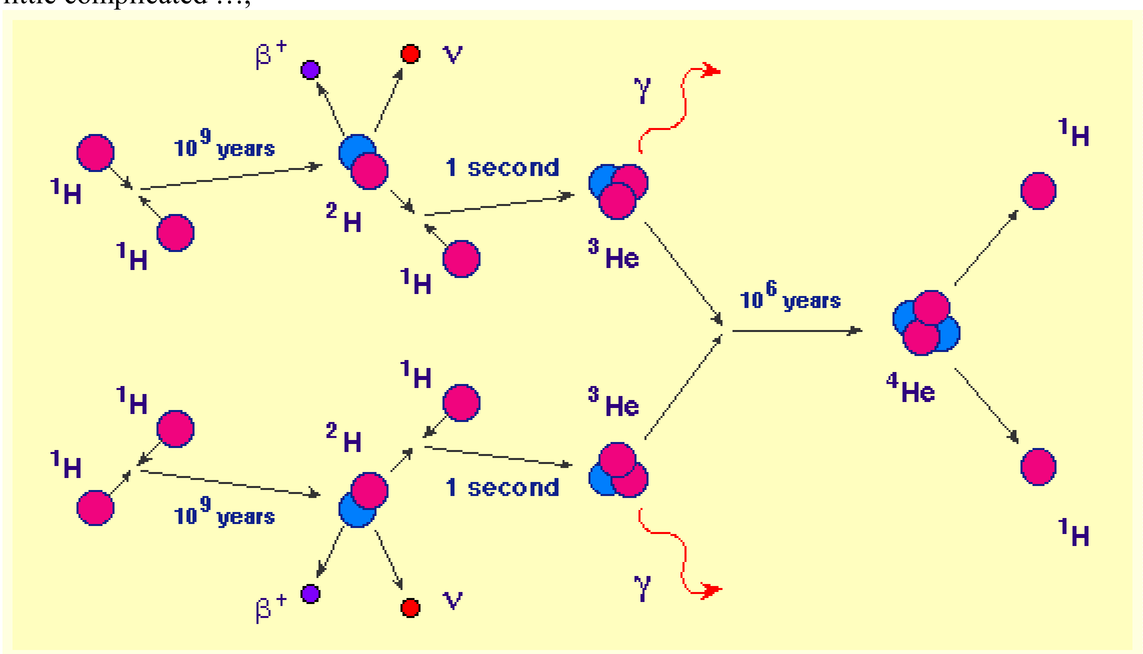
As an aside, an interesting question is whether in chemical reactions that release energy, such as burning of hydrocarbons, the products of the reaction have less mass than the reactants. There actually seems to be some debate about this. We can calculate what it would be though. The nuclear reaction in I.1.41 releases 180,000,000 electron-volts (we'll convert this later, for now just think of it as a number) of energy. The chemical reaction

$$2H_2 + O_2 \rightarrow 2H_2O + 5.7 \text{ eV} \qquad \text{(I.1.43)}$$

releases as shown 5.7 electron-volts. So the mass change is about 30 million times smaller, if it occurs. I don't think anyone has measured this.

Okay, so where did the stored energy in the uranium come from? To understand this, one must realize that our Sun formed from the remnants of earlier stars which underwent supernova. In those explosions, higher weight nuclei were formed, including uranium, so the energy stored in uranium nuclei came from those massive stellar events.

On the light element side of the above chart, we note that very light nuclei such as hydrogen can combine to produce nuclei with higher binding energy, so energy can be released in those nuclear reactions. Of course, this is what powers the sun. The overall reaction in the sun is a little complicated …,



Main branch of the proton-proton chain.

but basically, hydrogen is converted into helium, and mass is converted into energy in the process.

Can nuclear fusion reactors be built? Of course, one can see that getting a hunk of uranium-235 (which is difficult, thankfully), and adjusting it's shape and size in the presence of moderators, is a bit easier than getting two positively charged nuclei close enough together to fuse. The sun does this trick by have the force of its gravity to compress the nuclei together at great temperature. Experimental fusion reactors attempt this by confining the nuclei with magnetic fields, and heating the confined plasma, or hot gas with dissociated electrons, until fusion occurs. So far, no one has succeeded in getting more energy out via fusion that put in to heat the gas.

Energy Units, absolute measures

It may seem mundane to devote a section to units, but working in the energy field, there is a mixture of English and Metric units and being able to fluidly convert, accurately or estimating in your head, will help analysis. We will use as our basis point the Metric system. In part this is because of the prevalence of the watt as an electrical power measurement, that everyone can relate to as a power unit. Think of a 100 watt light bulb, and you have a feeling for how much power a watt is. One watt equals one joule expended per second:

$$1 \text{ watt}=\frac{\text{joule}}{\text{second}} \quad . \qquad \text{(I.1.44)}$$

A joule of energy, for example, is the energy of a mass of 2 kilograms moving at 1 meter per second:

$$1 \text{ joule}=\frac{1}{2}\text{(2 kilograms)}(1 \ \frac{\text{meter}}{\text{second}})^2, \qquad \text{(I.1.45)}$$

using equation I.1.13. Note, as many of you are familiar with, that we are using the MKS system of units here (meters, kilograms, seconds), of which joules and watts are part of. As mentioned, watts are used in the electrical industry, and one watt of power is the power conveyed in a current of 1 ampere after passing through a voltage of one volt:

$$1 \text{ watt=(1 ampere)x(1 volt).} \qquad \text{(I.1.46)}$$

Of course, electrical power is also typically measured in kilowatts (1000 watts), and electrical energy measured in kilowatt-hours (1000 watts x 3600 seconds = 3,600,000 joules).

Note that in our discussion of nuclear energy, we talked about the energy release of a nuclear reaction in terms of electron-volts, or eV. They are easy to convert, since it is the energy gained by an electron when passing through a voltage of 1 volt. Since the charge of an electron is $1.6\text{x}10^{-19}$ coulombs, by the equation energy=charge x voltage we have that

$$1 \text{ electron-volt} = 1.6\text{x}10^{-19} \text{ joules} . \qquad \text{(I.1.47)}$$

Okay, now it gets fun, since we have to introduce English units that, somewhat by legacy, have stuck around in the energy world. Particularly, we have the energy unit of a British Thermal Unit, or BTU, which is defined as the energy it takes to raise 1 pound of water by 1 degree Fahrenheit. Do not worry about this definition, just focus on the conversion,

$$1 \text{ BTU=1055 joules.} \qquad \text{(I.1.48)}$$

One can get a feeling for this by thinking of a 1000 watt source, that it could probably heat a pound of water by 1 degree Fahrenheit in about a second. Now we get to power, which in English units is typically BTU's/hour (as opposed to joules/second in Metric), and somewhat nicely have about the same amount as a watt:

$$1 \ \frac{\text{BTU}}{\text{hour}}=\frac{1055\text{joules}}{3600\text{seconds}}=0.29 \text{ watts.} \qquad \text{(I.1.49)}$$

One typically sees heating and air conditioning equipment rated in terms of the BTU/hour of heating or cooling capability.

Another place BTU's are, somewhat strangely, used, is when describing very large amounts of energy, such as the total yearly energy consumption of the United States. These large amounts of energy are typically described in Quads, or quadrillion BTU's:

$$1 \text{ Quad} = 10^{15} \text{ BTU's} \tag{I.1.50}$$

For example, the United State consumed 99.9 Quads of energy in the year 2006 from all sources. A somewhat useful conversion is

$$1\,\frac{\text{Quad}}{\text{year}} = \frac{10^{15}\text{x}1055\text{joules}}{365.25\text{x}24\text{x}3600\text{seconds}} = 3.3\text{x}10^{10} \text{ watts} = 33 \text{ gigawatts.} \tag{I.1.51}$$

So, the average total power consumption in the United States in 2006 was 3340 gigawatts (3.34 terawatts.)

Another very common unit of power, that everyone is familiar with from the automotive industry, is horsepower. And it really was invented by testing the lifting power (pounds per hour) of a horse (actually the story is that it was a pony, then they multiplied by 1.5 to get a "horse" power. I guess "ponypower" sounded dumb.) Actually there are two energy units called horsepower, one for mechanical and electric motors (even those are very slightly different) and one for boilers. We'll discuss boilers later in the course. For now, for motors, use

$$1 \text{ horsepower} = 746 \text{ watts.} \tag{I.1.52}$$

Although not usually relevant to the energy industry, it is interesting to note that the unit of energy on food labels, the food calorie, is actually defined as 1000 "physics" calories:

$$1 \text{ calorie} = \text{energy required to raise 1 gram of water 1 degree centigrade.} \tag{I.1.53}$$

$$1 \text{ food-calorie} = 1000 \text{ calories.} \tag{I.1.54}$$

Converting to joules,

$$1 \text{ calorie} = 4.19 \text{ joules.} \tag{I.1.55}$$

Note that for the average human

$$\text{Human power consumption} = \frac{2000\text{food-calories}}{\text{day}} = 97 \text{ watts}, \tag{I.1.56}$$

$$\text{US "foodpower" consumption} = 97 \text{ x } 300{,}000{,}000 = 29 \text{ gigawatts.} \tag{I.1.57}$$

Note that the power output of a human (for example when using a pedal generator to charge a battery), is about 65 watts (www.windstreampower.com). Since a horse is about 10 times the weight of a human, and so maybe we can say can produce 10 times the power, the above definition of a horsepower is perhaps on the mark.

Energy units in terms of quantities of source materials

Often energy usage is quoted in terms of the amount of, for example, fuel. This chart lists those conversions:

BTU Content of Common Energy Units

1 barrel(42 gallons) of crude oil = 5,800,000 Btu

1 gallon of gasoline = 124,000 Btu

1 gallon of heating oil or diesel fuel = 139,000 Btu

1 cubic foot of natural gas = 1,026 Btu

1 gallon of propane = 91,000 Btu

1 short ton of coal = 20,681,000 Btu

1 kilowatthour of electricity = 3,412 Btu

One can use these conversions to come up with some interesting comparisons of energy sources. For example, since 1 kilowatt-hour of electricity typically cost $0.10, by the above, the same amount of electrical energy as in a gallon of gasoline is (124/3.4) x $0.10 = $3.65. That may make electric cars look unattractive with current gasoline prices, but in the later sections we'll show that the efficiency of an electrical motor is about 3 times that of an internal combustion motor, so the resulting cost per equivalent gasoline gallon is $1.22.

Note that although cheaper to the end user, electric cars use the same amount of original energy, as one must take into account the efficiency of the electric power plant in converting fuels into electricity, so it works about the same as converting those fuels directly at the car.

Along these lines, it is interesting to note that as the United States consumes about 9 million barrels of gasoline a day, or 378 million gallons, that is the equivalent power of (378,000,000 x 124,000)/24 = 1953000000000 BTU/hour, or 566 gigawatts. In 2004, the United States consumed 3.55 trillion kilowatt-hours (that was what was sold at all meters). This is equivalent to an average electric power consumption for the country of 3.55×10^{15} / (365.25 x 24) = 405 gigawatts. Thus to run all our cars on electric power requires more than a doubling of consumption.

I. **Introduction**

2. Energy scales in the universe.

Solar power

Energy is all around us! But, that's like saying nitrogen is all around us (it is 78 % of the atmosphere); yet getting pure nitrogen costs a lot. In a like sense, energy exists in vast quantities in our universe; getting it in a useful form is the problem.

Let's start with our sun. We can calculate its power output through a variety of means. The most direct is actually to measure its surface temperature, and use the theory of electromagnetic radiation from thermal sources (Blackbody radiation theory) to calculate it. I will do that as an aside here, but it is more complicated than expected for this course. [If the sun's temperature is 5800 K, using the Stephens-Boltzmann's equation $P = \sigma T^4$, we get 64,000,000 watts/meter^2. Given the sun's radius of 700,000,000 meters, it has a surface area of 6.2x10^{18} meter^2. Thus the power output of the sun is 4x10^{26} watts.] We can calculate the power output with what has been presented in the course, if we look up that the sun converts 4.5x10^9 kilograms of hydrogen mass into energy each second. Actually, we could figure this out by noting the current mass of the sun, and its expected lifetime. But given $E = mc^2$, this means that the sun has a power output of (4.5x10^9)(3x10^8)^2 = 4x10^{26} watts, yielding the same result.

Power output of Sun = 4x10^{26} watts. (I.2.1)

How much of this reaches Earth? We can calculate how much impacts our atmosphere by considering the fraction of area subtended by the Earth's diameter. Given our orbit at 145,000,000 kilometers, the sphere concentric with the Sun at our orbit has a surface area of 2.6x10^{17} kilometer^2. Given the radius of the Earth of 6,400 kilometers, its cross-sectional area is 5.1x10^8 kilometer^2. Thus the power output of the Sun that strikes the Earth is 4x10^{26}x(5.1x10^8/2.6x10^{17}) = 7.8x10^{17} watts. Note that this means that in space, the solar irradiance is 7.8x10^{17}/5.1x10^{14} = 1500 watts/meter^2. This has actually been estimated to be 1400 watts/meter^2. So 6-7 % is lost on its journey through space.

Sun's power output reaching Earth = 7.3x10^{17} watts. (I.2.2)

Solar irradiance in space above Earth = 1400 watts/meter^2. (I.2.3)

Note that as in the homework problem of the last section, the amount that reaches Earth through the atmosphere is 1000 watts/meter^2.

Solar power is the most obvious "universe" power possibly available to us; also sources of energy such as hydroelectric, wind, and biomass are really derivatives of solar power generally. What are other "universe" sources?

Tidal power

One is tidal power, or the movement of the oceans caused by the gravitational pull of the Moon (and Sun, really, but we'll just consider the Moon here). What follows is a very loose calculation, taking the kinetic energy of the Moon, and assuming this energy is converted into tides over the Moon's lifetime, which we will take as 1 billion years, just to get an order of magnitude. The mass of the Moon is 7.4×10^{22} kilograms. It has an orbital radius of 380,000 kilometers, so its velocity is about $2\pi\, 3.8 \times 10^{8}/(28 \times 24 \times 3600) = 990$ meters/second. So the kinetic energy of the Moon is $0.5 \times 7.4 \times 10^{22} \times (990)^2 = 3.6 \times 10^{28}$ joules. If we assume this energy is converted into tidal energy over the 1 billion year (3.2×10^{16} seconds), this gives the available tidal power as

"rough" calculation of available tidal power = 1.1×10^{12} watts. (I.2.4)

Of course, only a very small fraction of this is really available. One can think of this power as being the power contained in the Earth's ocean's "bulge" as it rotates about the earth each day. It is probably optimistic to consider tapping a percent of this, or perhaps tens of gigawatts.

Power in Earth's rotation

[Insert homework 1 solution here]

Geothermal energy

The heat developed within the earth comes from several sources, including tidal forces, but more than half comes from radioactive decay of heavy elements, particularly uranium and thorium. Nearly all uranium is isotope 238, which decays with a half life of 4.5 billion years, by the reaction

$$U_{238} \rightarrow Th_{234} + He_4 + 4.2 \text{ MeV}. \qquad \text{(I.2.5)}$$

Uranium's abundance in meteroites is about 0.008 parts per million (on a weight basis); it is somewhat more concentrated in Earth, so if we use 0.01 parts per million, and the weight of the earth of $6x10^{24}$ kilograms, there is about $6x10^{16}$ kilograms of uranium in the earth. Given the mass of a uranium atom of about 238 times the mass of a proton (neutrons have about the same mass), or $238x(1.7x10^{-28}) = 4x10^{-26}$ kilograms. Thus there are approximately $6x10^{16}/4x10^{-26} = 1.5 \text{ x } 10^{42}$ uranium atoms in the earth. If half decay in 4.5 billion years, that is about $5.3x10^{24}$ that decay each second (not really, decay is an exponential phenomena, but this gives an order of magnitude result). Since 4.2 MeV = $6.7x10^{-13}$ joules, we have a power of

Geothermal power (uranium decay) $\cong (6.7x10^{-13})(5.3x10^{24}) = 3.6x10^{12}$ watts (I.2.6)

Actually, total geothermal power is estimated to be 44 terawatts, including all sources, which fits with this calculation. Unfortunately, it is distributed across the surface of the earth. It is unlikely more than 0.001 (?) of this could ever be used, or as in tidal power, a few tens of gigawatts.

I. Introduction
3. Energy scales in human endeavor.

As previously mentioned, in the United States we are currently consuming about 100 Quads of energy per year (before efficiency losses). Converting this to average power in watts, and dividing by the 300 million people in the country, that is

Average US power consumption per person = 11,000 watts. (I.3.1)

That is, every day, 24 hours a day, what we consume, sometimes higher, sometimes lower, but on average, this. Given our earlier calculation that a human is capable of an energy output of about 65 watts, we have that

Average US power consumption per person = 169 "humanpower", (I.3.2)

or, each of us has on the average the equivalent of 169 humans doing work for us (note correction to earlier text).

The ways in which this energy is being expended can be examined with the energy flow diagram chart. 34.4 Quads/year is consumed to generate electricity, or 1.1 terawatts (before system losses). Dividing by 300 million, we have that

Average US electricity consumption per person (before losses) = 3,800 watts. (I.3.3)

Note that after systems losses this is 11.1 Quads/year, so that

Average US electricity consumption per person (after losses) = 1,200 watts. (I.3.4)

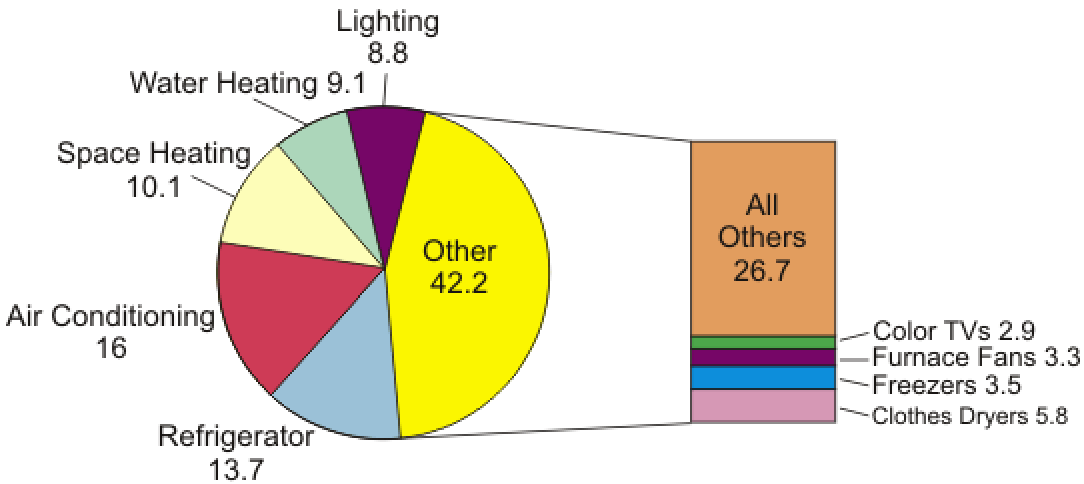
If we subtract off the 3.6 Quads/year of electrical energy that go to our factories, we have that

Average residential/commercial US electricity consumption per person (after losses)
= 830 watts (I.3.5)

The US Department of Energy states that 1 trillion kilowatt-hours of electricity was sold to residences in 2004. This translates to

Average residential US electricity consumption per person (after losses)
= 380 watts (I.3.6)

Here is how that electricity consumption is broken down:



Source: Energy Information Administration, Form EIA-457A, B, C, E, and H of the 2001 Residential Energy Consumption Survey.

One sees that air conditioning is the major single user of electricity.

Part of the reason we've gone through this exercise is to help you create your projected energy flow diagram charts; part of the reason is to explain how each of you is consuming 3800 watts of primary energy to produce electricity, when it seems like it is not that much from your daily life. First, 2/3 of that is lost as heat in the production of electricity. Then, 1/3 of the useful electrical energy goes to our factories (we still do manufacture things in the US). Then, 2/3 of what's left goes into our commercial spaces like offices, restaurants, hair salons, etc. This leaves 1/10 of the primary electrical energy that winds up being used by us in our homes. For every electrical watt you use in your home, 9 watts goes into making that energy and powering our factories and commercial spaces.

We can use our energy flow chart to examine how much we use for transportation, which is 25.9 Quads/year of primary energy, or on average 855 gigawatts. Note that a whopping 80 % is lost or not converted into useful motion. I imagine that is heat loss in the engines and frictional forces impeding motion. In any event we have that

Average US transportation consumption per person (before losses) = 2,900 watts. (I.3.7)

Average US transportation consumption per person (after losses) = 570 watts. (I.3.8)

The largest component of this is us driving around in our personal vehicles, generally using gasoline. If at 75 miles per hour, your car gets 25 miles per gallon, you are consuming 3 gallons per hour. Using our earlier figure for energy content per gallon, that works out to 372,000 BTU/hour, or

Power to drive down highway at 75 mph and 25 mpg (before losses)
= 108,000 watts. (I.3.9)

In other words, driving down the highway like this takes the equivalent of

Power to drive down highway at 75 mph and 25 mpg (before losses)
= 1,660 "humanpower", (I.3.10)

meaning it would take 1,660 people to push you in your car down the highway at those speeds. Fortunately we are not in our car continuously; on average we consume 380,000,000 gallons of gasoline a day. We can use that to calculate an equivalent average gasoline power consumption of 570 gigawatts, or

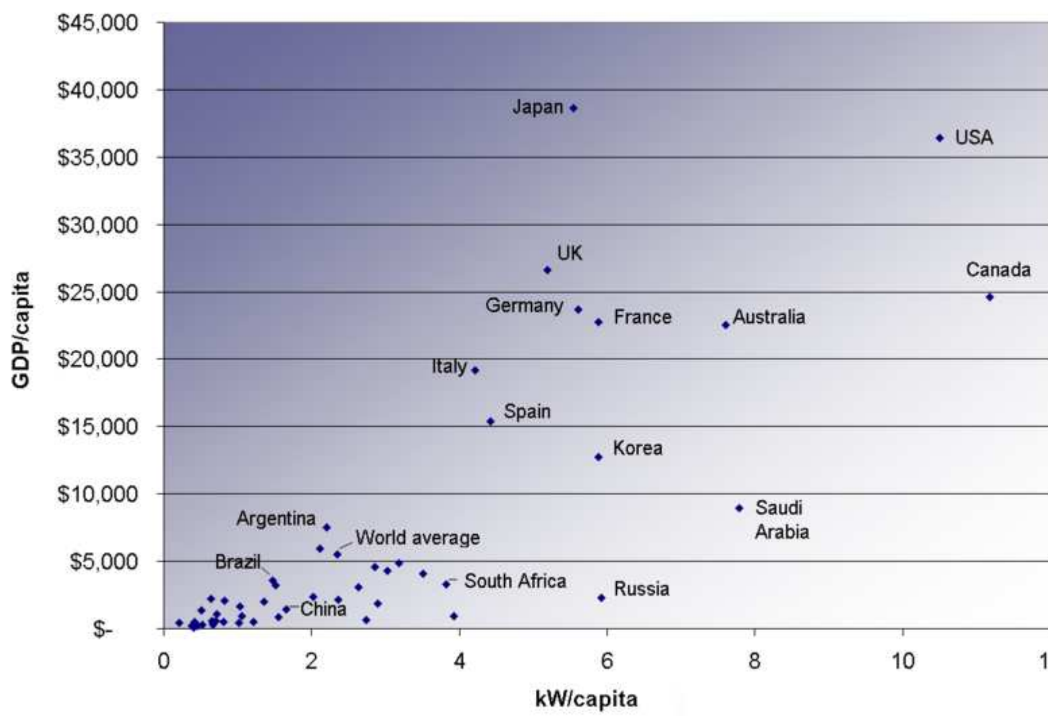
Average US gasoline power consumption per person (before losses)
= 1900 watts (I.3.11)

Average US gasoline power consumption per person (after losses)
= 380 watts (I.3.11)

It is interesting to note that the average gasoline power consumption after losses equals the average residential electrical power consumption after losses.

We could go on generating these analyses, and you will in making your charts. Now, a stated goal of your charts is to not reduce useful energy per person. That is to say, you are presented with an engineering problem of coming up with sources and changes of methodologies and efficiencies to enable us to live pretty much as we are now, in the US. I for one value air conditioning and don't want to give it up, especially if it's getting hotter.

As an aside to the course, though, we can examine energy use per person in other countries and in previous times. First, in other countries, the following is a great graph for illustrating energy use and quality of life:



Note the 11,000 watts per person in the US previously stated. GDP, or Gross Domestic Product, is the total sum of goods and services sold in a country, which we will talk about in the economics part of the course later. If money equals happiness, then GDP/capita (GDP per person) is an indicator of that. One sees that generally that rises with energy consumption per person, with the US roughly 5-7 times greater than the world average in both quantities. Lots of observations, some supportable, can be made looking at this chart. However, if one looks at countries which we roughly perceive have the same quality of life, that is, US, Canada, Japan, and various European countries, one sees that Canada has a lower GDP/kW rating (less efficient), while the European countries are higher, and Japan is twice as high. While some moral conclusions could be drawn from this, my personal observation is that: smaller countries with higher population densities have greater efficiencies. This is the “dense is better” argument that a living model with concentrated population centers linked with high efficiency rail systems for transportation, is generally more efficient for producing a good lifestyle with less energy.

However, your chart is for the US, and for the lifestyles/living arrangements that exist. You are not allowed to assume something else in your charts. For that, go to another course.

II. Energy Sources.

1. Chemical energy mined from the earth.

Introduction, and the fossil fuel vs. non-biological origin debate.

Earlier we discussed briefly chemical energy and how it is produced by having a chemical reaction with energy inputted, resulting in chemical products with higher potential energy. Those resulting chemicals then basically reside in the earth until we dig them up and then we can burn them and release the energy. The three main chemicals we use for fuel are oil (petroleum), coal, and natural gas. Basically, though, they are hydrocarbons, or compounds containing both hydrogen and carbon, that when reacted with oxygen, result in carbon dioxide and water which are more stable compounds, and so energy is released in the process.

We'll talk more about the specific reactions and chemicals later, but now we want to understand where this chemical energy came from. Oil, coal, and natural gas are called fossil fuels, from the theory that they resulted from living matter that over millions of years transformed into these products. There is a very small but vocal minority that insists they have non-biological origins. Here it must be stressed that we really don't know for sure. This is a very important issue for energy sustainability, since if oil, coal and natural gas are not fossil fuels but somehow, "renewable," that would change the equation of future energy supply significantly. Here are what I think are the best laid out facts for examining this issue.

First, we can probably dismiss coal from having a non-biological origin. The lineage of coal from peat, which is definitely biological matter, can be traced quite well as we will see in that section, and no one seems to dispute its biological origin.

That leaves oil and natural gas (mostly methane, or CH_4). Oil and natural gas are basically compounds containing various numbers of carbon and hydrogen atoms, with generally more atoms resulting in a liquid (oil), and less a gas.

First, methane clearly exists outside of biology. There is a lot of it in the outer planets and almost certainly not sufficient life (or any) to have produced it. The composition of the outer planets is shown in this table:

	Jupiter	Saturn	Uranus	Neptune
hydrogen	~ 90 %	~ 96 %	83 %	80 %
helium	~ 10 %	~ 3 %	15 %	19 %
methane	~ 0.3 %	~ 0.4 %	2.3 %	1.5 %
other	< 0.1 %	< 0.05 %	< 0.05 %	< 0.05 %

After hydrogen and helium, which apparently have existed since the early universe (not chemical hydrogen, and not a hydrocarbon but certainly a source of chemical energy that existed even before the solar system), methane is the most common compound.

That methane exists outside biology is not really that difficult to understand as with carbon and hydrogen, and lots of energy, present, it's likely that methane would form. Carbon is the fourth most abundant element in the Sun:

Composition of the Sun

Element	Abundance (percentage of total number of atoms)	Abundance (percentage of total mass)
Hydrogen	91.2	71.0

The table of elements at left was constructed from analysis of the solar spectrum, which comes from the photosphere and chromosphere of the Sun. But it is thought to be representative of the entire Sun with the exception of the solar core because of the degree of mixing which takes place between the layers of the Sun's interior.

Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

About 67 elements have been detected in the solar spectrum.

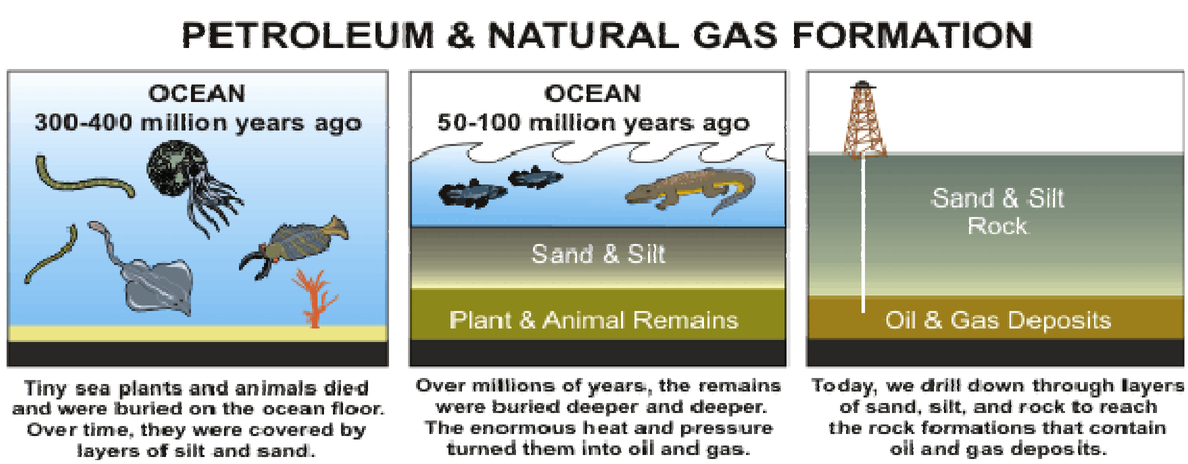
Oxygen is present in greater quantities in the Sun, but very little of it appears in the outer planets. I'm not sure what exactly to make of this, except that in compounds oxygen tends to occur in water and carbon dioxide, and with their higher evaporation temperature they tend to occur in solid or liquid form in the outer solar system.

Even higher atom count hydrocarbons have been detected on other planets. So the question is not whether they can be produced non-biologically, but whether that which we mine on earth has been.

For the US government's opinion, check out the DOE Energy Information Administration's "Kid Page" (http://www.eia.doe.gov/kids/energyfacts/sources/non-renewable/oil.html) (!):

HOW OIL WAS FORMED

Oil was formed from the remains of animals and plants that lived millions of years ago in a marine (water) environment before the dinosaurs. Over the years, the remains were covered by layers of mud. Heat and pressure from these layers helped the remains turn into what we today call crude oil . The word "petroleum" means "rock oil" or "oil from the earth."



So the government is clearly on the side of biological origin.

The question of biological or non-biological (abiotic) origins can roughly be summarized as follows:

Biological: living matter resulting from solar energy and photosynthesis produces hydrocarbon chains, which decayed and reformed into oil and natural gas.

Abiotic: methane trapped in the planet from the formation of the solar system percolates upward into the crust where it can cool and form higher chain hydrocarbons.

There is not a question that either may be a source. Shale rock, which we will discuss later, contains kerogen, which is clearly organic, and when heated in the lab will produce oil. On the other side, methane has also been converted to oil in the lab. There are many points to argue upon from both sides. It is true that oil contains microbes that indicate its biological origin, but the abiotic side argues that those microbes were absorbed by the oil as it percolated upward.

One of the main arguments from the abiotic side is that there has not been enough biological matter to account for all of the oil found. This is a difficult argument to debate as one has to agree on what fraction of biological matter can be converted, and since not all biological matter is converted (much of it decays on the surface and does not convert), mathematics is challenged.

However, one can analyze this question of whether enough biological matter existed to form all the oil we have found, if the above is written differently:

Biological: The source of carbon in hydrocarbons is carbon dioxide in the earth's atmosphere, which photosynthesis converts into hydrocarbons.

Abiotic: The source of carbon in hydrocarbons is methane trapped in the earth in its formation.

So, on either side, simply count all the carbon atoms and see if it equals.

On the biological side, we must first understand the early atmosphere on Earth. It is generally agreed that the first atmosphere (probably hydrogen and helium) was blown off the earth by solar winds. Then, an atmosphere formed from outgassing from the interior of the Earth, by volcanoes and such. Note that immediately, we see that from either argument, the origin of all carbon on earth is from gasses trapped in the Earth during its formation, either methane (which from the abiotic argument, must have stayed trapped), or carbon dioxide, which was released.

It is generally agreed that the atmosphere a billion years ago or so had about 100 times the carbon dioxide as today, and that has been reduced by photosynthesis. The weight of today's atmosphere can be calculated from noting its surface pressure, and is 5×10^{18} kilograms. The atmosphere (before industrial times) had 280 parts per million of carbon dioxide, or 0.028 %. Note that number that is quoted is a volume percentage. In mass percentage, carbon dioxide (pre-industrial) was 0.043 % of the atmosphere, or 2.2×10^{15} kilograms. So if there was 100 times the carbon dioxide in the atmosphere before plants got going, 2.2×10^{17} kilograms of carbon dioxide has been converted into hydrocarbons. Much of it is recycled during the life process, but that which has been reduced from the atmosphere, has had to be stored someplace, and that must be in either oil, coal or natural gas.

It is unclear how much oil is left (we'll get to that later when depletion is discussed), but we know that about 1 trillion barrels have been consumed. A barrel of oil is 42 gallons or 0.16 cubic meters. The density of petroleum is about (it varies) 920 kilograms per cubic meter, so a barrel weighs 150 kilograms. Thus, all the oil consumed is 1.5×10^{14} kilograms. This is not the final calculation, though, as we have to match carbon for carbon in carbon dioxide and oil.

Carbon dioxide contains 1 atom of carbon for 2 of oxygen, so the mass fraction of carbon is roughly 12/38, or from above then we have that

Mass of carbon consumed from carbon dioxide by all plant life since life began on Earth = 7×10^{16} kilograms.

In long chain hydrocarbons, we have two hydrogen atoms at each point on the carbon train, so the mass fraction of carbon in the train is 12/14. Note that in methane, which has four hydrogen atoms per carbon atom, it is 12/16. We will use 12/15. Then the

Mass of carbon in all oil consumed = 1.2×10^{14} kilograms.

Thus the mass of all carbon so far consumed in oil is ~1/500 of all the carbon consumed by plant life from the atmosphere. While there has been a lot of coal and natural gas consumed also, and we could go through that calculation, it is roughly resulted in the same amount of energy consumed, which is roughly proportional to the carbon, so the mass of all carbon consumed in hydrocarbon energy is perhaps 1/250 of all carbon consumed by plants.

Thus it would seem there was quite sufficient biological material to have produced all the hydrocarbons mined on earth.

On the abiotic side, one would have to assume there was sufficient methane trapped in the early earth to have supplied all the carbon. We could try to calculate the volume of the earth involved in this trapping, but of course it would be small, as we have seen that the volume of the earth's early atmosphere was sufficient. So it seems that methane could have been trapped in sufficient quantities.

The answer, seems to be, that both are possible, but that biological far outweighs abiotic. The one diagnostic that makes sense is to check the age of the hydrocarbon sample through isotopic analysis. This has been done (http://www.agiweb.org/geotimes/oct05/feature_abiogenicoil.html):

Abiogenic gas in the crust, however, has been discovered. Working at the Kidd Creek Mine in Ontario, Sherwood Lollar and colleagues analyzed gases found there and determined they were inorganic. Using both carbon and hydrogen isotopes, they identified a unique inorganic chemical signature that differs from the signatures of gases in economic accumulations, as published in *Nature* in 2002. "To date, nobody's been able to show that same signature in any of the economic deposits," Sherwood Lollar says. "That would argue that any of the economic deposits we've found to date are in fact quite consistent with biological origins." Still, she says, the work shows that inorganic gas is "a real phenomenon."

So, trapped methane during the formation of the Earth is real, but apparently not responsible for any of the hydrocarbons mined so far. Based on the isotope testing, they are all biological. And therefore, non-renewable on human time scales.

Chemical reaction analysis, or how much energy is in different sources

In order to analyze the chemical energy contained in the various materials, oil, coal, natural gas, we need to quantify how much energy is stored when a chemical reaction that has energy input proceeds. This is done by having a table of chemical bond energies:

Bond	Energy (kJ/mol)	Bond	Energy (kJ/mol)
H - H	436	N - N	160
C - H	413	N = O	631
N - H	393	N triple N	941
P - H	297	N - O	201
C - C	347	N - P	297
C - O	358	O - H	464
C - N	305	O - S	265
C - Cl	397	O - Cl	269
C = C	607	O - O	204
C = O	805	C - F	552
O = O	498	C - S	259

Table of energies in chemical bonds. Unfortunately, they are listed in kilojoules per mole (chemists). A mole is $6.02\text{x}10^{23}$ of something. So, the $H-H$ bond energy is listed for a mole of them. Dividing, we get that the energy for a single $H-H$ bond is $436{,}000/6.02\text{x}10^{23}$ = $7.24\text{x}10^{-19}$ joules. Since 1 eV = $1.6\text{x}10^{-19}$ joules, the energy in a single $H-H$ bond is 4.53 eV.

For example, in the earlier chemical reaction we noted,

$$2H_2 + O_2 \rightarrow 2H_2O + 5.7 \text{ eV} \qquad \text{(II.0.1)}$$

the reactants on the left absorb energy to break the bonds, and energy is released when the bonds form in the products on the right. If more energy is released than has been absorbed, the reactants are a chemical fuel source. If more energy is absorbed than has been released, the products are a chemical fuel storage medium. To proceed with this analysis, we need to understand what bonds are present in the various molecules of the reaction. To do this, we need to know the number of valance atoms about each atom in the molecules, which is equal to the group number the atom. So, the periodic chart is our friend:

Group**

Period	1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 ------- ----	9 VIII	10 ---	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 vIIIA 8A
								------- 8 -------										
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.47	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57 La* 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 190.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.5	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac~ (227)	104 Rf (257)	105 Db (260)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 --- ()	111 --- ()	112 --- ()		114 --- ()		116 --- ()		118 --- ()

Lanthanide Series*	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (147)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
Actinide Series~	90 Th 232.0	91 Pa (231)	92 U (238)	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

Each bond consists of 2 valance electrons. So, H_2 has a single bond:

$$H_2 : H - H \quad . \qquad \text{(II.0.2)}$$

Oxygen has six valence electrons. For atoms other than hydrogen and helium, we need to understand the **principle of 8 valence electrons** that applies to most molecules. That is, due to quantum mechanics and the formation of electron energy states about atoms, each atom in the molecule would like to have eight valence electrons. This is why the noble gases do not bond with other atoms, since they already have eight. Oxygen only has six. The oxygen atoms in the oxygen molecule "pretend" they have eight each, by either one counting the ones in the bond as their own. In order to do so, each oxygen atom must give up enough to the bond so that when either one counts the ones they have left, and the ones in the bond, they each have eight. Thus, in O_2, each oxygen atom gives up 2 to the bond, so there are 4 total in the bond. Each oxygen atom has 4 remaining to itself, so that when each oxygen atom counts its own and the ones in the bond, they count eight. Since there are 2 electrons per bond, O_2 has two bonds:

$$O_2 : O = O \quad . \tag{II.0.3}$$

For water, the hydrogen atoms each supply one valence electron, and the oxygen atom supplies 2 (one to each bond). Therefore the hydrogens (which wants 2, not 8), are happy, and the oxygen, which kept 4 and pretends it can count the 2 in each bond as its own, has 8 and is happy:

$$H_2O : H - O - H \quad . \tag{II.0.4}$$

Now, we can proceed with the energy analysis of II.0.1. Doing the conversion noted in the table caption, $O = O$ has a bond energy of 5.17 eV, and $H - O$ has a bond energy of 4.82 eV. So, we have that

$$\begin{array}{l} 2H_2 + O_2 \rightarrow 2H_2O \\ -[2(4.53) + 5.17] \rightarrow 4(4.82) \end{array} \quad , \tag{II.0.5}$$

or, 14.23 eV of energy was put in the break the bonds, and then 19.28 of energy was released when the water formed, for a net relese of 5.05 eV.

But, above we listed that 5.7 eV was released in the reaction. The difference comes from the fact that in just using the bond energies, we have implicitly assumed that the water is in gaseous state on the right. Of course, it is not, it forms water. When water condenses into liquid, it releases energy (makes sense, to go from liquid to gas, you must add energy). This energy is called the heat of vaporization, and for water it is 40.7 kilojoules/mole (note it is an order of magnitude less than bond formation energies), or 0.42 eV per water molecule. This would yield 5.9 eV for the above reaction with liquid water as the product; I'm not sure if the 5.7 eV quoted previously is a mistake or assumes some of the water is in vapor form.

To help us out, since I can't find the table in terms of eV/bond, I'll do the calculation:

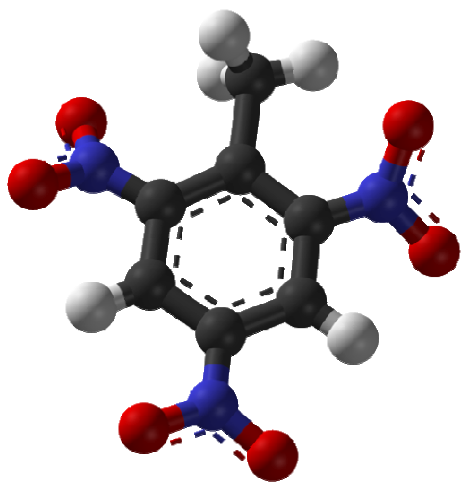
Bond	Energy (eV/bond)	Bond	Energy (eV/bond)
H - H	4.52658	N - N	1.66113
C - H	4.28779	N = O	6.55108
N - H	4.08015	N triple N	9.76952
P - H	3.08347	N - O	2.08679
C - C	3.60257	N - P	3.08347

C - O	3.71678	O - H	4.81728
C - N	3.16653	O - S	2.75125
C - Cl	4.12168	O - Cl	2.79277
C = C	6.30191	O - O	2.11794
C = O	8.35756	C - F	5.7309
O = O	5.17027	C - S	2.68895

For fun, TNT (Trinitrotoluene) is the chemical compound $C_6H_2(NO_2)_3CH_3$, and it decomposes according to the reaction

$$2\ C_7H_5N_3O_6 \rightarrow 3\ N_2 + 5\ H_2 + 12\ CO + 2\ C \qquad \text{(II.0.6)}$$

To compute the bond energies, we have to look at a 3D model of TNT:



Here the black atoms are carbon, the blue atoms are nitrogen, the red atoms are oxygen, and the white are hydrogen. The ring is like half single bonds and half double bonds, so there are 3 C=C bonds, 4 C-C bonds, 3 C-N bonds, 6 N-O bonds, and 5 C-H bonds, which add up to 76.8 eV per molecule, or 153.6 eV on the left. On the right, there are 3 N-N bonds, 5 H-H bonds, and 12 $C \equiv O$ bonds (11.2 eV each), or 162.0 eV on the right, not counting the carbon, which is in solid form. Here I'm not sure, but I think that that is graphite, which is formed using C-C bonds, so I'll count one of them, or 165.63 eV total, for a net energy release of 12 eV. The weight of the 2 TNT molecules is 7.54×10^{-25} kg, so there are 1.33x1024 pairs in a kg, or 2.5×10^{6} joules released per kg that explodes. A common unit of measure of energy (in atomic bomb parlance) is the energy released when a ton of TNT explodes. There are 907 kg in a ton, so 2.3 gigajoules is released per ton. I looked up this number, it is quoted as 4.2 gigajoules; not sure where the calculation went wrong. Since a BTU is 1055 joules, this equals about 4 million BTU. From before, a ton of coal has 20.7 million BTU of energy. So, coal has more energy than TNT! But, it does not explode.

Most chemical energy mined from the earth is in the form of hydrocarbons. This table lists the physical properties of the simplest hydrocarbons:

The Saturated Hydrocarbons, or Alkanes

Name	*Molecular Formula*	*Melting Point (^oC)*	*Boiling Point (^oC)*	*State at 25^oC*
methane	CH_4	-182.5	-164	gas
ethane	C_2H_6	-183.3	-88.6	gas
propane	C_3H_8	-189.7	-42.1	gas
butane	C_4H_{10}	-138.4	-0.5	gas
pentane	C_5H_{12}	-129.7	36.1	liquid
hexane	C_6H_{14}	-95	68.9	liquid
heptane	C_7H_{16}	-90.6	98.4	liquid
octane	C_8H_{18}	-56.8	124.7	liquid
nonane	C_9H_{20}	-51	150.8	liquid
decane	$C_{10}H_{22}$	-29.7	174.1	liquid
undecane	$C_{11}H_{24}$	-24.6	195.9	liquid
dodecane	$C_{12}H_{26}$	-9.6	216.3	liquid
eicosane	$C_{20}H_{42}$	36.8	343	solid
triacontane	$C_{30}H_{62}$	65.8	449.7	solid

II. Energy Sources.

1. Chemical energy mined from the earth.

a. Oil

Oil is a word we hear on the news just about every day now, and the definition for that word is "any of a large class of substances typically unctuous, viscous, combustible, liquid at ordinary temperatures, and soluble in ether or alcohol but not in water: used for anointing, perfuming, lubricating, illuminating, heating, etc.," but of course we are generally referring to petroleum. Petroleum literally means "rock oil," and was referred to as such because of the remarkable fact that oil could be gotten from a rock and not from some other source such as a whale.

Petroleum then is oil mined from the earth, and of the chemical energy mined from the earth accounts for most of our energy needs, in part due to the fact that it is a liquid and thus can be shipped through a pipeline (which a solid like coal cannot), or easily on a boat (which natural gas cannot unless cryogenic).

Repeating our chart of energy content of various materials,

BTU Content of Common Energy Units

1 barrel(42 gallons) of crude oil = 5,800,000 Btu

1 gallon of gasoline = 124,000 Btu

1 gallon of heating oil or diesel fuel = 139,000 Btu

1 cubic foot of natural gas = 1,026 Btu

1 gallon of propane = 91,000 Btu

1 short ton of coal = 20,681,000 Btu

1 kilowatthour of electricity = 3,412 Btu

and noting that a barrel of crude oil weighs roughly 150 kg and is 0.159 cubic meter, and the density of coal is about 1300 kg/m3, we can use this to generate the following table:

	BTU per kilogram	BTU per cubic meter
Crude oil	38,700	36,500,000
Coal	22,800	29,600,000

we see that on both a weight and volume basis oil has more energy than coal (making comparisons to natural gas is difficult without allowing compression or cryogenic liquefaction).

Giving a complete description of an energy source like petroleum could fill an entire volume. Here, we'll use a categorization to simplify the discussion. That is, <u>what</u> is it, <u>where</u> is it found, <u>who</u> has it and who uses it, and <u>how</u> is it found and used. We could ask "why," but then this would not be an engineering course.

<u>What</u> is petroleum:

Petroleum is a hydrocarbon substance found in or on the earth whose origins we have discussed. It is usually a liquid, which can vary from black and viscous to clear and thin, although to complete our discussion the solid forms of "tar" sands and shale must be considered. It consists primarily of alkanes with 5 to 12 carbon atoms, which as has been shown in the previous table are liquids at room temperatures and pressures. Mostly, it is obtained by drilling a deep hole in the ground where it flows up due to the pressure of the underground petroleum reservoir. Currently approximately 69,000,000 barrels are mined each day by this method. More about where it is found will be in the where section. After getting it out of the ground, it is separated (discussed in the how section) into products with various boiling points (and therefore various carbon numbers):

Petroleum Products Yielded from One Barrel of Crude, 2005

Product	Gallons
Finished Motor Gasoline	19.40
Distillate Fuel Oil	10.50
Kero-Type Jet Fuel	4.12
Petroleum Coke	2.23
Still Gas	1.81
Residual Fuel Oil	1.68
Liquefied Refinery Gas	1.51
Asphalt and Road Oil	1.34
Naptha for Feedstocks	0.59
Other Oils for Feedstocks	0.46
Lubricants	0.46
Kerosene	0.17
Miscellaneous Products	0.17
Special Naphthas	0.08
Finished Aviation Gasoline	0.04
Waxes	0.04
Total	**44.60**

Note the largest fraction is gasoline, which has 7 to 11 carbons per molecule, and is about in the middle of the separation from lightest to heaviest. The lightest products are called napthas and have from 5 to 7 carbons per molecule. They are used as solvents and cleaning products due to their low boiling point and thus fast evaporation. Next from light to heavy is gasoline, which when we discuss engines, will show that due to its faster ignition generally results in more rapid vehicle acceleration. Next is kerosene, which has carbons in the 12 to 15 range, and is primarily used in jet fuel. Next is diesel, which as we've seen has higher energy content but due to a higher evaporation temperature tends to have less vehicle acceleration, so is favored for heavy equipment like tractors and large trucks. It is also used as heating oil. Diesel and heating oil are called Distillate Fuel Oil in the above chart. Finally the heaviest with 15 and higher carbons per molecule are used as lubricants (due to their high boiling point and thus slow evaporation), and finally, asphalt.

As mentioned most petroleum comes from wells, and flows up due to pressure in the reservoir. Generally, the pressure runs out before the oil does, so only about a third is recovered. More will be discussed in the how section on techniques to try to get at this unrecovered oil. Here, for purposes of discussion of other forms of petroleum, we just note that it requires very little energy to get the petroleum from an oil well, and thus the energy returned on energy invested (EROEI) of a standard oil well can be around 50:1.

Unconventional petroleum

Besides the roughly 69,500,000 barrels of conventional petroleum gotten from wells each day, there are several smaller sources:

Natural gas liquids

Natural gas wells will be discussed later, but suffice here that it is a well that hits a natural gas reservoir. When the gas flows up from these wells, it tends to take with it a variety of hydrocarbons besides methane which can be liquefied in the processing plant. These natural gas liquids are primarily ethane, butane, and propane, the latter two of which we are all aware of, that can be liquefied and easily transported with a slight pressurization. So, although they are not liquids are room temperature and pressure, these chemicals are counted as petroleum liquids. Approximately 8,000,000 barrels of natural gas liquids are produced per day. Propane is the greatest fraction of this, accounting for about 60 %, and most of the rest butane, which makes sense because of the gaseous alkanes, they are closest to being liquid, and only requires a small pressurization to become liquid. Propane is sold outright as "propane," or sometimes called LPG or Liquefied Petroleum Gas, which contains small amounts of other hydrocarbons. Besides barbeques, propane or LPG is used as a fuel in about 2 % of vehicles in the US, and about half the forklifts.

"Heavy" oil

Various petroleum reservoirs are much nearer the surface and contain much higher viscosity petroleum. They are classified separately since it requires special techniques to lift the oil to the surface and refine it into useful products. Heavy oil must be heated to refine, and thus takes energy to be used. The EROEI of heavy oil is often quoted as about 3:1. There are vast quantities of heavy oil, probably greater than conventional reserves, but due to the difficulties of producing and refining, and energy requirements, only about 2,000,000 barrels/day are produced.

"Tar" sands oil

"Tar" sands are not technically tar, but rather "bitumen," a mixture of sand and heavy oil just near the surface. Thus "oil sands" is a better name. They are mined like solid hydrocarbons, through huge shovels and strip mining, which typically contain about 10 times the sand to hydrocarbon ratio. These must be separated, then processed as heavy oil. Thus, the EROEI tends to be about 1.5:1, making it the most expensive oil produced today. Again, while there are vast quantities of oil sands, due to production difficulties and energy requirements, only about 1,500,000 barrels per day are produced.

This completes the description of petroleum mined today, about 81,000,000 barrels per day. Another 2,000,000 barrels per day of "refinery gain" are sometimes counted, which comes from the fact that as we see above every barrel of crude oil (42 gallons) results in 44.6 gallons of refined product. This is just due to the difference in density of crude and refined product, so is of dubious distinction to count as "production". Finally there are another million or so barrels a day counted as petroleum liquids, about half of which are biofuels, some of which are coal-to-oil, and the rest various chemical liquid production, so should not really be counted in liquid chemical energy mined from the earth, but rather mostly as biofuels or coal-to-liquids which will be discussed under those sections. This brings the total up to the 84,000,000 barrels/day often quoted in the news.

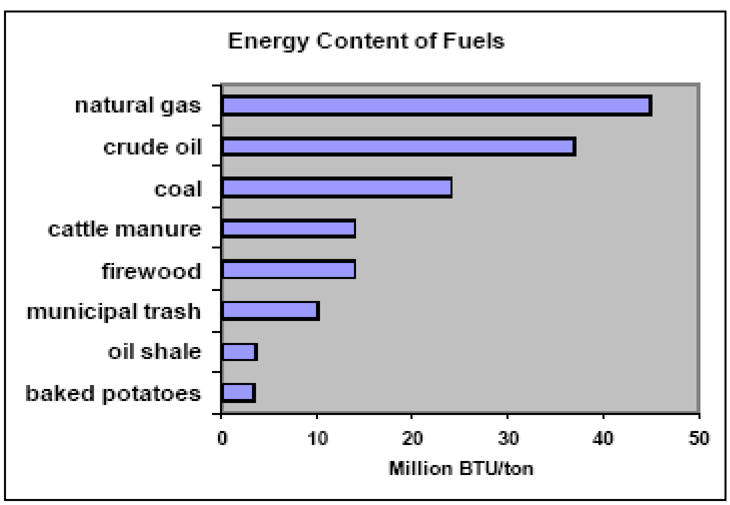
Oil shale

Finally we get to oil shale, which does not currently contribute to production in appreciable quantities. It is a rock with large quantities of kerogen, a biological sludge that basically is leftover from rotting living matter. Kerogen varies in composition but generally has a very high molecular weight, composed of molecules with several hundred carbon and hydrogen atoms. Oil shale is actually produced in some appreciable quantities (several tens of millions of tons per year) as a solid fuel like coal. To make it liquid and refine into gasoline or like products takes significant energy input. The Shell Oil Company has been developing a method under the name the Mahogany Research Project in Colorado, some 200 miles (320 km) west of Denver. First a freeze wall is constructed to seal off groundwater. (Drilling 2000' wells eight feet apart, around the perimeter of a 10 acre working zone then circulating with a super-chilled liquid to freeze the ground to -60oF.) The working zone is then dewatered. Recovery wells are drilled on 40' spacing within the working zone. An electrical heating element is lowered into each well and allowed to heat the kerogen to 650 to 700oF over a period of approximately four years, slowly converting it into oils and gases, which are then pumped to the surface. An operation producing 100,000 barrels a day would require a dedicated electrical generating capacity of 1.2 gigawatts. Since 100,000 barrels of crude a day equates to a power output of 7.1 gigawatts, this sounds pretty good, with an EROEI of 5.9. There are huge quantities of oil shale, perhaps greater than other hydrocarbon reserves combined.

So, the question is, if it is better than heavy oil or oil sands, why is it not produced? In the words of Senator Hatch from Utah,

After hearing the bullish projections so often, politicians are perplexed by the lack of progress. “I find it disturbing that Utah imports oil from Canadian tar sands, even though our oil shale resource remains undeveloped,” says Utah Senator Orrin Hatch. It’s a maddening paradox. If oil shale really is “the richest fossil fuel resource on earth,” why has no nation ever produced more than 16,000 barrels a day? And if there really are “one trillion barrels of hard, black gold” in the world’s shales, why is global production declining? It’s as if we are standing in front of a treasure vault fumbling with the key. Sixty percent of the world’s oil shale is in Colorado and Utah, we know exactly where it is, and yet those states produce none. Meanwhile, Alberta is producing one million barrels per day of oil from its tar sands. What’s with that? Are we dumber than Canadians?

Detractors of oil shale use the following chart (in part to ridicule oil shale):



Oil shale contains very little energy per weight, much less than trash or wood. In fact Native Americans were aware it could burn, but did not bother as wood provided more heat per effort to obtain it. Now, what is not shown is that oil sands have roughly the same energy content before separating the sand. The answer to, “why oil sands and not oil shale,” I think is an engineering one, that, it is fairly straightforward to separate heavy oil from sand, but not to separate kerogen from a rock. Thus, getting crude from oil sands is economically viable, but from shale is apparently not. A careful study would determine at what price of oil it is, but that number does not appear to have been carefully determined in the absence of one's fondness or lack of for shale oil. It apparently is in excess of $100 per barrel.

Another issue with shale oil is that it would use tremendous amounts of water. The same is true with oil sands, which consume about 5 barrels of water (that is contaminated and must be placed in ponds devoid of life) for every barrel produced. The only difference is, there are not as many people in Alberta where the oil sands are dependent upon the available water resources as are in Utah and Colorado. Given apparent climate change and the effect on water resources in the American southwest, it would seem that only in a desperate energy situation would the investment of water be considered worthwhile. Summarizing this, it would seem that shale oil is not something that will be produced until such a time as that the economic paradigms have shifted completely, and energy resources are not longer quantified simply by having a dollar value.

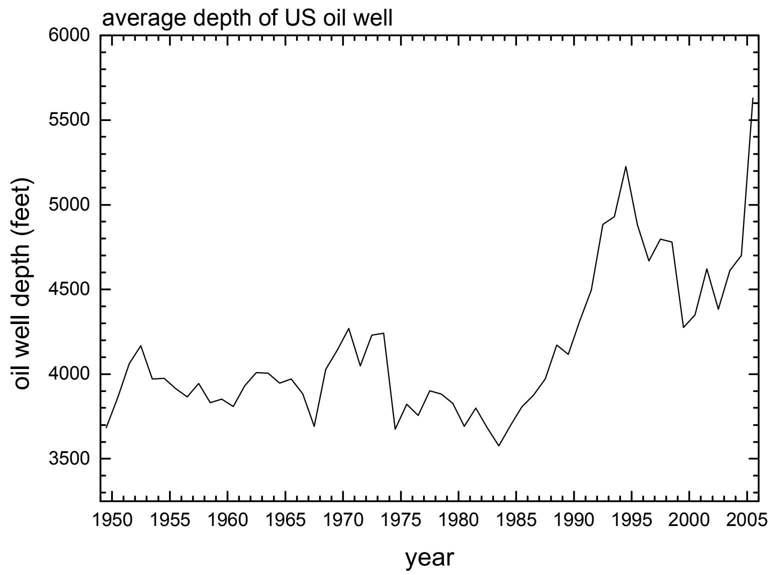
Approximate summary of <u>what</u> is petroleum:

The Saturated Hydrocarbons, or Alkanes

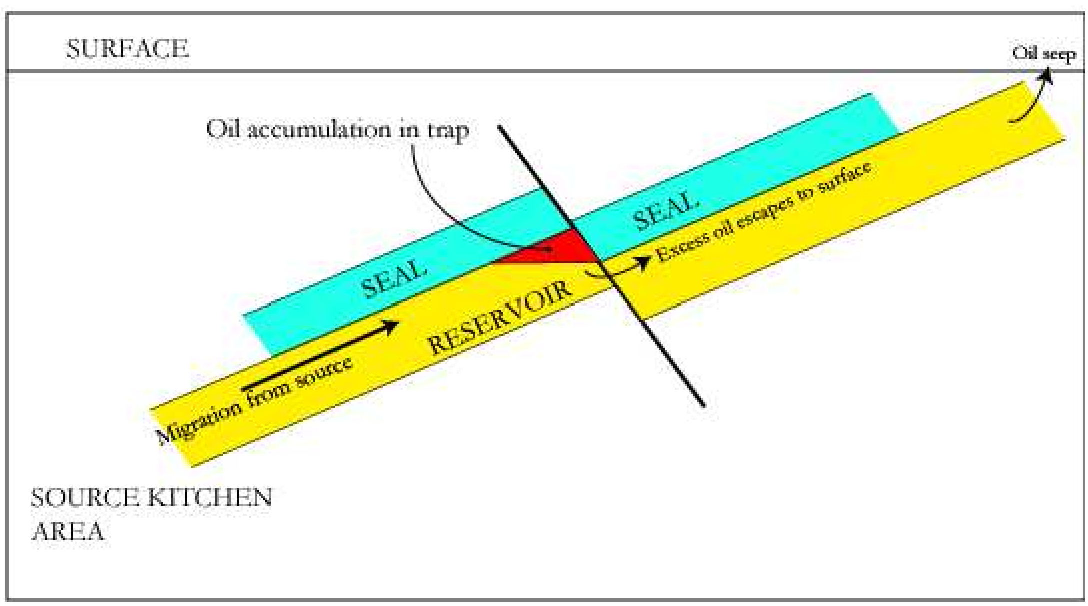
	Name	*Molecular Formula*	*Melting Point (^oC)*	*Boiling Point (^oC)*	*State at 25^oC*
natural gas →	methane	CH_4	-182.5	-164	gas
natural gas "liquids" ↕	ethane	C_2H_6	-183.3	-88.6	gas
	propane	C_3H_8	-189.7	-42.1	gas
	butane	C_4H_{10}	-138.4	-0.5	gas
crude oil ↕	pentane	C_5H_{12}	-129.7	36.1	liquid
	hexane	C_6H_{14}	-95	68.9	liquid
	heptane	C_7H_{16}	-90.6	98.4	liquid
	octane	C_8H_{18}	-56.8	124.7	liquid
	nonane	C_9H_{20}	-51	150.8	liquid
	decane	$C_{10}H_{22}$	-29.7	174.1	liquid
	undecane	$C_{11}H_{24}$	-24.6	195.9	liquid
	dodecane	$C_{12}H_{26}$	-9.6	216.3	liquid
	eicosane	$C_{20}H_{42}$	36.8	343	solid
	triacontane	$C_{30}H_{62}$	65.8	449.7	solid

<u>Where</u> is petroleum found:

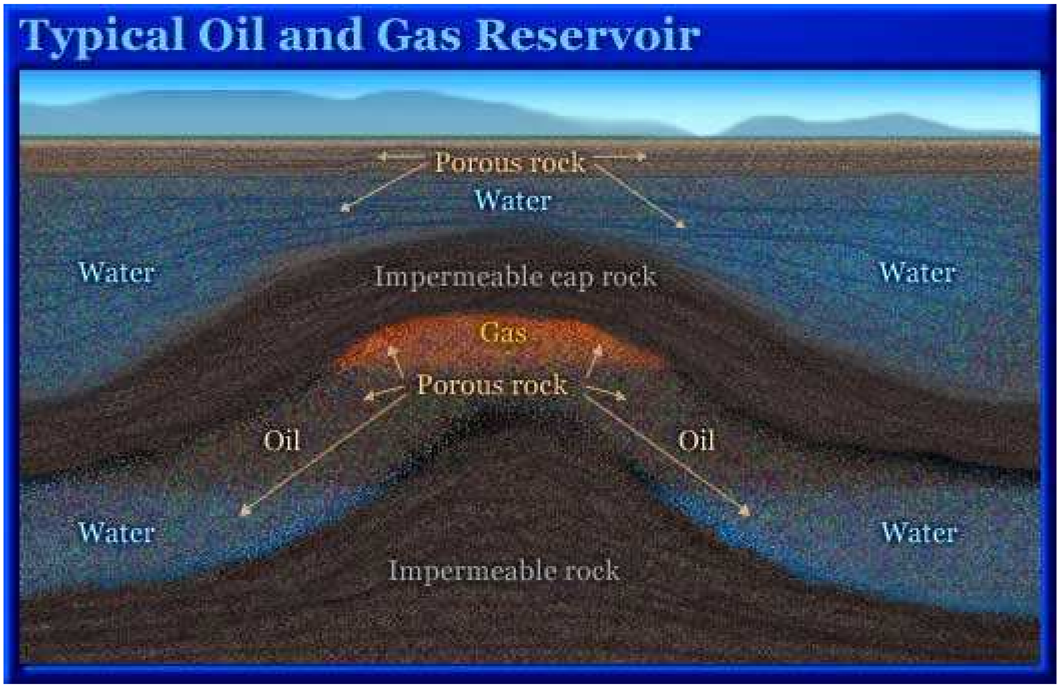
Petroleum is generally found deep in the ground, with exceptions such as the La Brea tar pits in Los Angeles. Here the average oil well depth is shown vs. year:



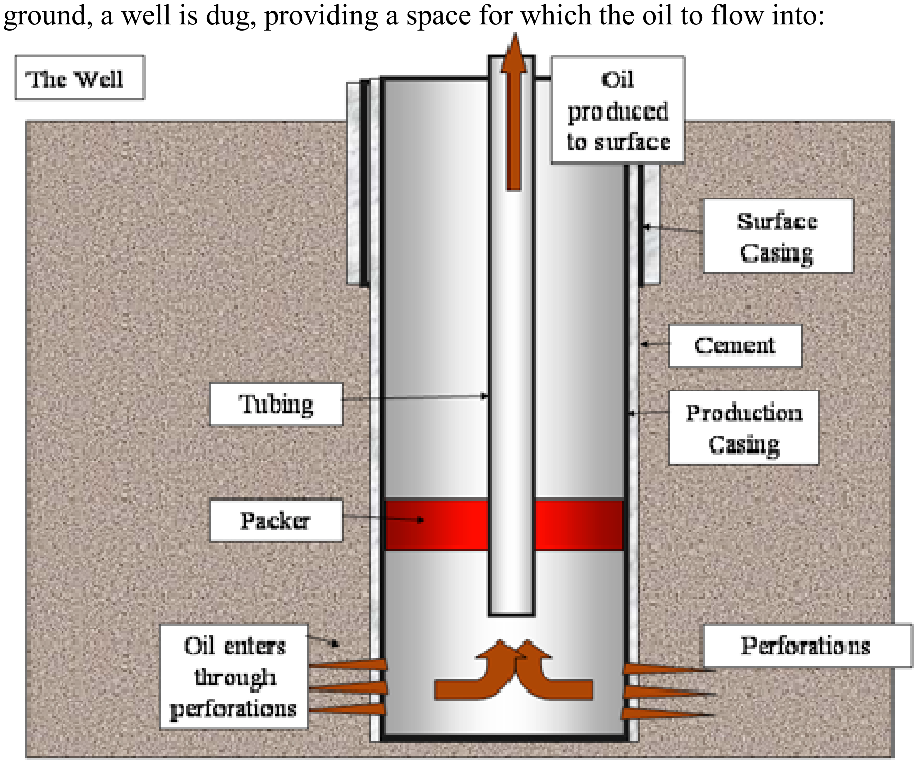
Clearly we're having to go deeper to get at the oil. How deep can an oil well be? If one believes the biological formation theory of oil, the maximum depth will be the maximum depth at which biological matter would have settled, after sedimentary rock buried it. That has to do with plate tectonics, etc., but basically it is about 25,000 feet. I cannot find a plot of oil quantity vs. depth (perhaps no one knows), but generally one would expect to find it higher than where it has formed. The following diagram explains this, showing how an oil strata forms a "trap" against harder rock:



In the above diagram, the "seal" layer is usually a layer of harder rock such as limestone or granite. Here is another diagram showing usual rock formations about oil reservoirs:

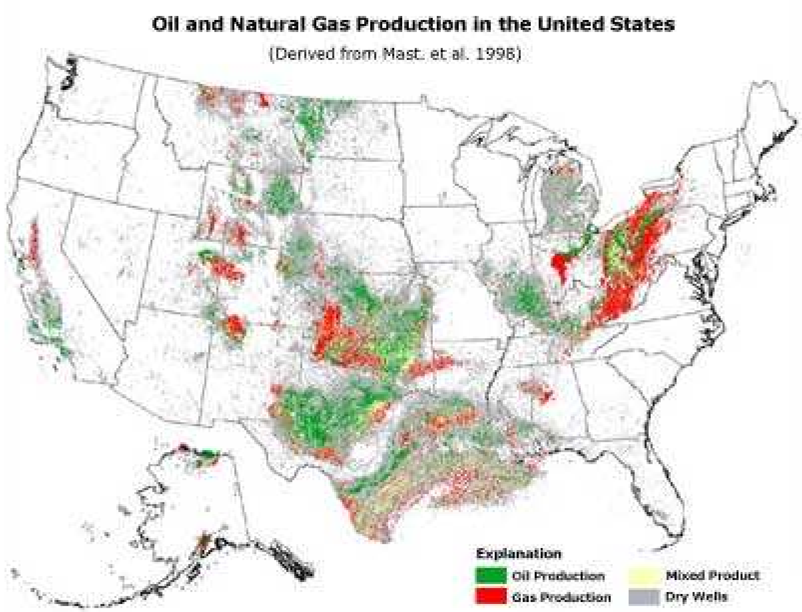


Many people think that oil sits in vast "lakes" under the surface, which is not true. Oil is present in porous rock such as sandstone and exists between the pores. In the above diagram, the "reservoir" layer is a layer of porous rock. To get liquid oil out of the ground, a well is dug, providing a space for which the oil to flow into:

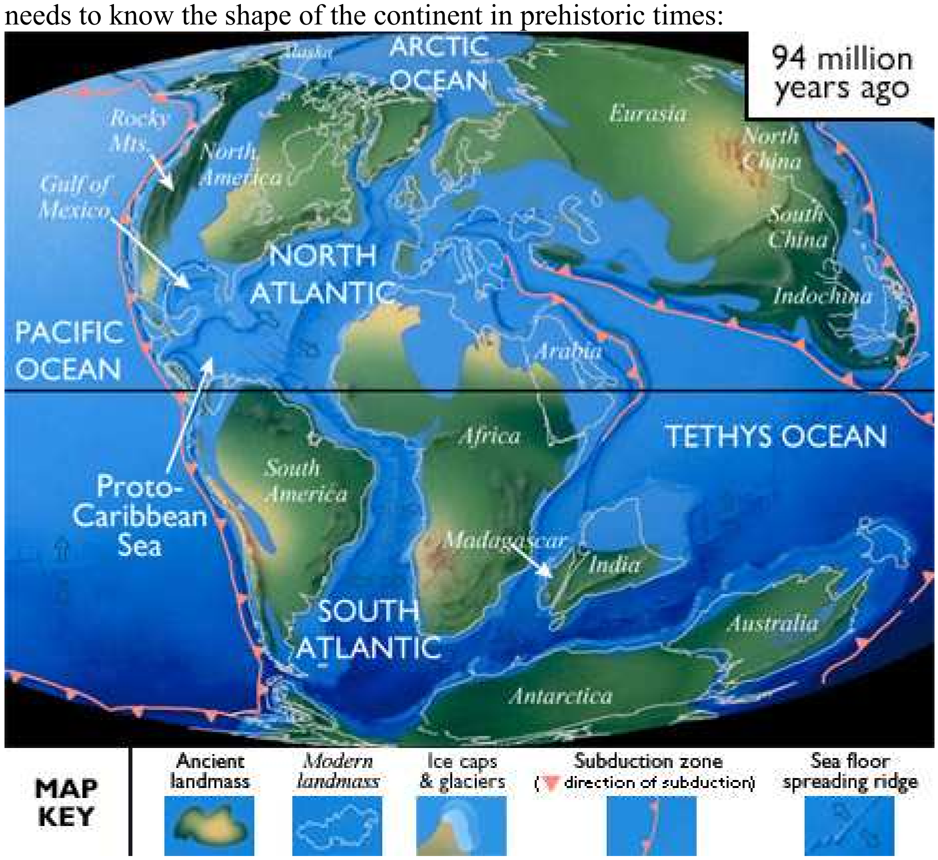


Note that oil flows through the porous rock then enters the well through perforations. It is under pressure, so then flows upward to the surface.

As to where oil is found, the following map of oil fields in the United States is instructive:



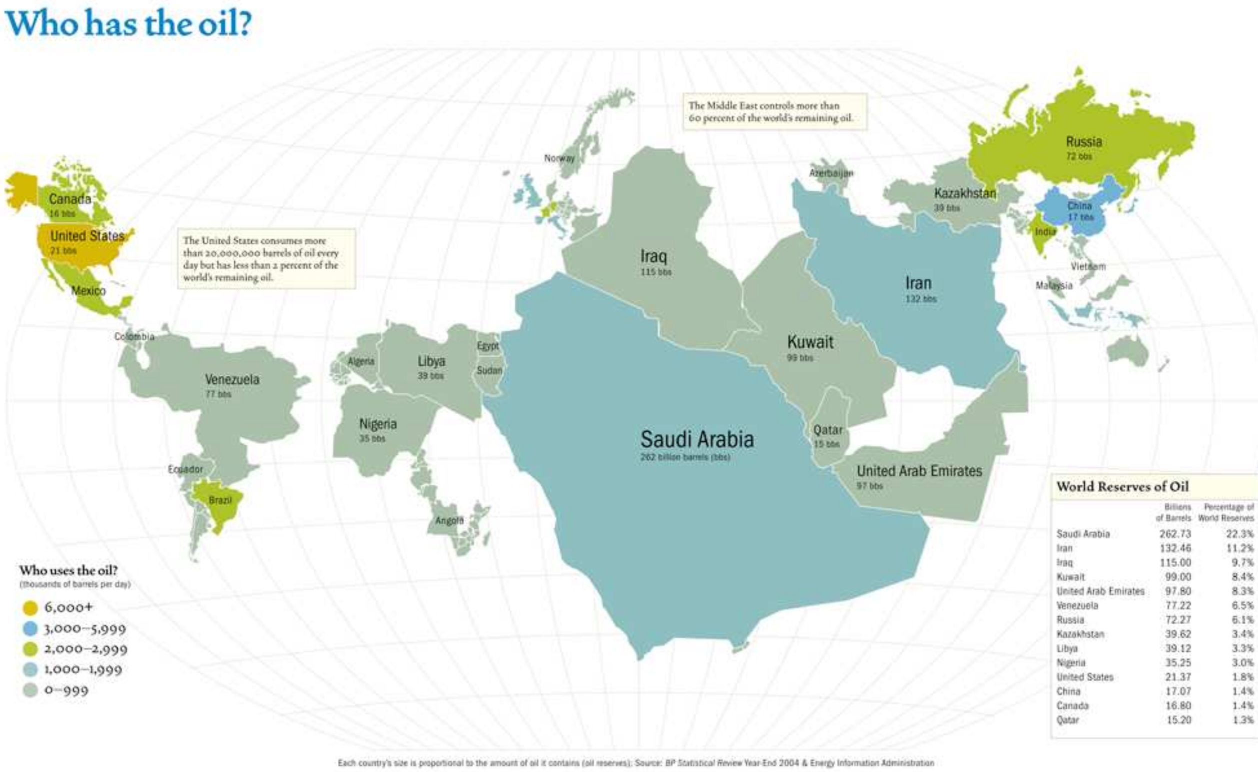
One sees first of all that oil and gas are interrelated, which we would expect if they have the same origins, chemistry (alkanes), and trap formation. To understand this map, one needs to know the shape of the continent in prehistoric times:



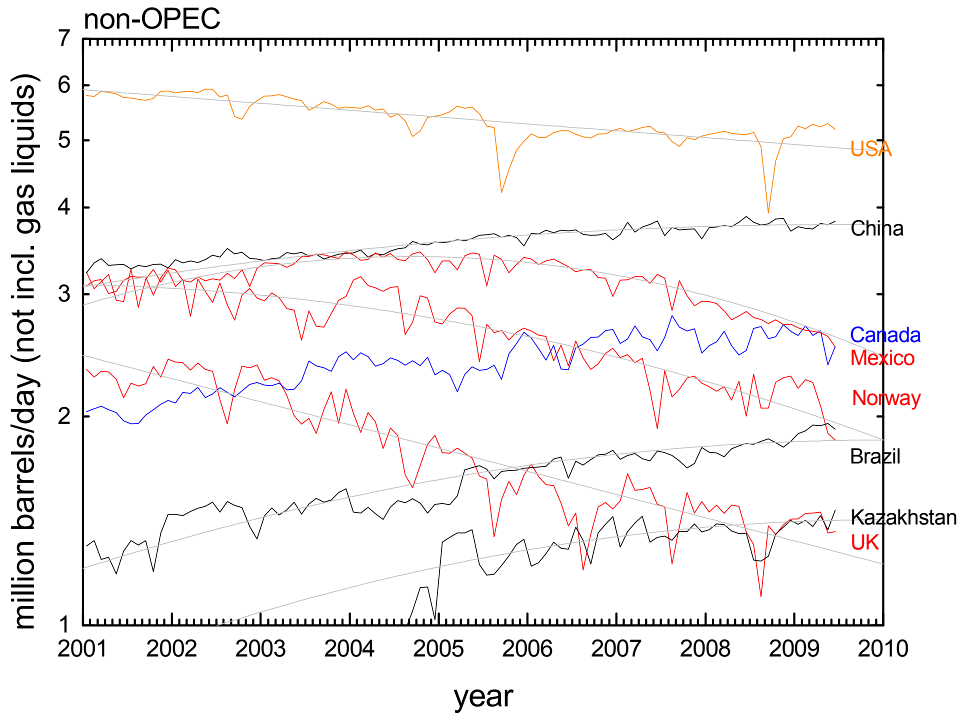
One sees that the center of North America was an inland shallow ocean, allowing organic deposit and covering with sediment, which was then covered when the two sections of the continent came together. Roughly, one can approximate where to find oil based upon knowing where shallow seas were some hundred million years ago, that would form strata of biological matter covered by sediment. For example, in the above one sees that Arabia was a shallow sea. So, to go out and find oil, first study continental drift.

Okay, you are now petroleum engineers, capable of understanding where to find oil!
Who has oil and who uses it.

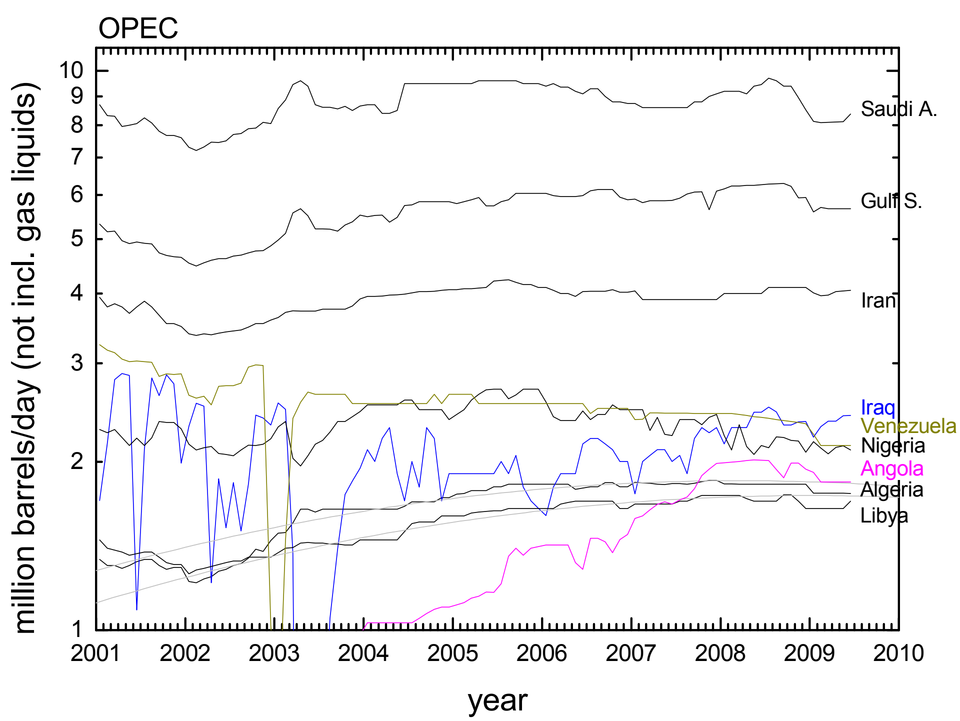
Who has oil today follows from the understanding of where it would be likely to be found from the above discussion. This is a good map showing oil producers and consumers:



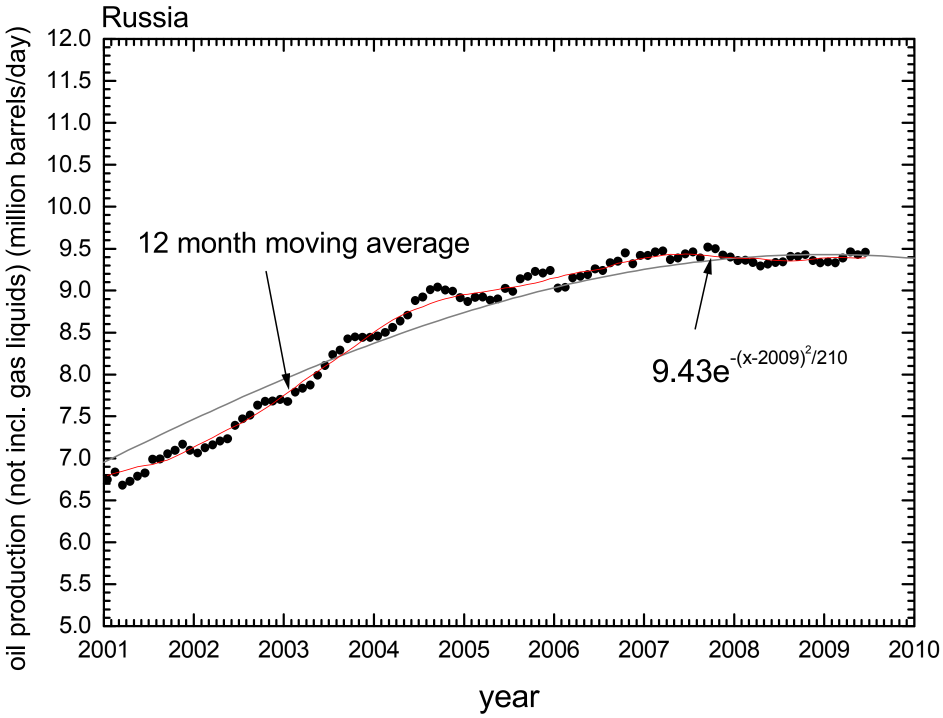
This map summarizes oil production and consumption; the size of the country on the map indicates its oil reserves, and the color indicates its oil consumption. Here is the production of crude oil by non-OPEC countries (not including Russia):
Here is the production of crude oil by non-OPEC countries (not including Russia):



Here is the production of oil by OPEC countries:



Here is recent production by Russia:



One sees that recently Russia has surpassed Saudi Arabia as the top producer. One also sees that the US is the top non-OPEC producer other than Russia, although its production has been declining for several decades. At its peak, the US produced nearly as much as Russia does now.

Note that the above graphs include only crude oil. As we have discussed, natural gas liquids, refinery gain (because products have lower density than crude), and biofuels and coal-to-liquids are included in the following chart:

Top World Oil Producers, 2006		
Rank	**Country**	**Production**
1	Saudi Arabia	10,719
2	Russia	9,668
3	United States	8,367
4	Iran	4,146
5	China	3,836
6	Mexico	3,706
7	Canada	3,289
8	United Arab Emirates	2,938
9	Venezuela	2,802
10	Norway	2,785
11	Kuwait	2,674
12	Nigeria	2,443

13	Brazil	2,163
14	Algeria	2,122
15	Iraq	2,008

Thus, this chart is somewhat misleading as it shows, for example, that US production is 8.3 million barrels/day, which crude oil production is only about 5.2 million barrels/day. For the US, about 1 million barrels/day of the 8.3 is refinery processing gain (of dubious distinction to be counted as a "source" as it is just based upon how much refinement of crude goes on in a particular country), about 1.7 million barrels/day are natural gas liquids (a real source, but gasoline and diesel cannot be made from it), and about 0.5 million barrels/day are "other" liquids, primarily ethanol.

Similarly, one can list the primary consumers of oil:

Top World Oil Consumers, 2006		
Rank	**Country**	**Consumption**
1	United States	20,588
2	China	7,274
3	Japan	5,222
4	Russia	3,103
5	Germany	2,630
6	India	2,534
7	Canada	2,218
8	Brazil	2,183
9	Korea, South	2,157
10	Saudi Arabia	2,068
11	Mexico	2,030
12	France	1,972
13	United Kingdom	1,816
14	Italy	1,709
15	Iran	1,627

Of course, the US tops the list, followed by China and Japan. Of recent interest is that countries that have traditionally been thought of a "third world" like Saudi Arabia and Iran have joined the top 15. Of course, they have it.

Following these lists, one can list the primary exporters of oil:

Top World Oil Net Exporters, 2006		
Rank	**Country**	**Net Exports**
1	Saudi Arabia	8,651
2	Russia	6,565
3	Norway	2,542
4	Iran	2,519
5	United Arab Emirates	2,515
6	Venezuela	2,203
7	Kuwait	2,150

8	Nigeria	2,146
9	Algeria	1,847
10	Mexico	1,676
11	Libya	1,525
12	Iraq	1,438
13	Angola	1,363
14	Kazakhstan	1,114
15	Canada	1,071

The most unusual item here is that Norway is the third top exporter, owing to its large difference between production and consumption. Here one should note that its production has recently seen large declines, above.

Finally, one can list the primary importers of oil, using similar mathematics of production and consumption:

Top World Oil Net Importers, 2006		
Rank	**Country**	**Net Imports**
1	United States	12,220
2	Japan	5,097
3	China	3,438
4	Germany	2,483
5	Korea, South	2,150
6	France	1,893
7	India	1,687
8	Italy	1,558
9	Spain	1,555
10	Taiwan	942
11	Netherlands	936
12	Singapore	787
13	Thailand	606
14	Turkey	576
15	Belgium	546

Not many surprises here, US, Japan, and China top the list. Perhaps the only thing to note here is that Japan imports nearly all its oil.

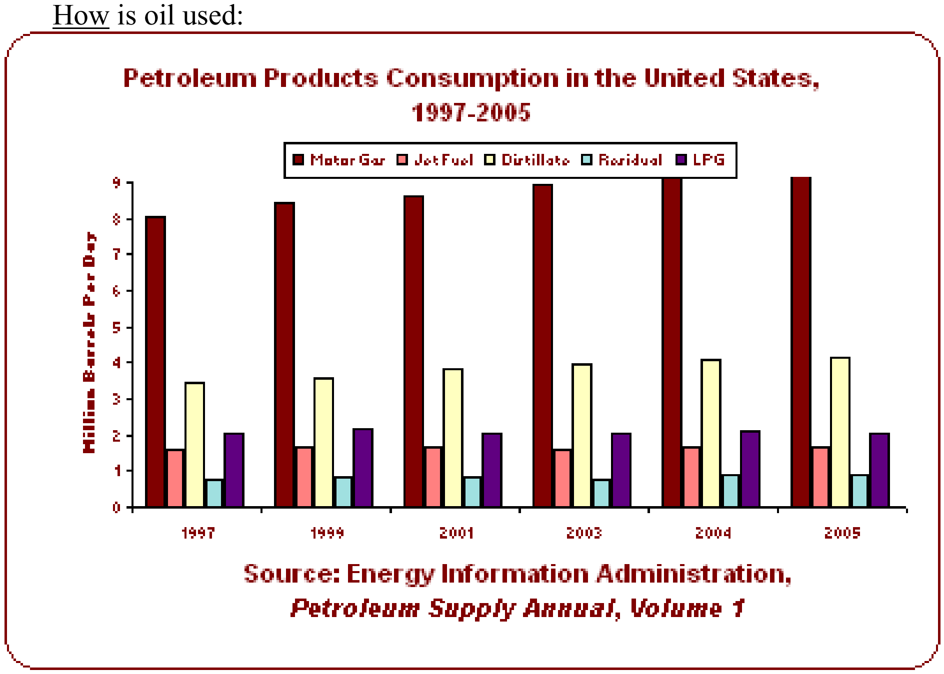
How is oil produced and used:

As we've noted, when a well is first drilled, the oil under pressure flows up on its own. As we've also noted, the pressure runs out before the oil does, much like an aerosol can that runs out of pressure before liquid. Usually about 20 % of the oil is recovered with its internal pressure. To get more of it, secondary techniques are used. These include the use of pumps (read: energy input), and the injection of water or gas to "sweep" the oil through the pores toward the well bore hole. With these techniques another 5-15 % of the oil is recovered. Water injection is used currently in the world's largest oil field, called Ghawar, in Saudi Arabia. Ghawar produces about 4.5 million barrels a day. To get this, 7,000,000 barrels of seawater are pumped into it each day. This leads to about 30-50 % of what comes out of the well being water, which must then be separated. This growing “water cut” in Ghawar’s output has some authors suspecting it is rapidly running out of oil.

The third largest oil field in the world, Cantarell in Mexico, was producing 1.16 million barrels/day in 1981, and then dropped to 1 million barrels/day in 1995. In the year 2000, nitrogen gas injection was started, production increased to 1.6 Mb/day, increased to 2.1 Mb/day in 2003, at which time it peaked. Today, Cantarell’s production is about 1.5 Mb/day. One sees that secondary techniques can revive production dramatically but tends to hasten depletion, which is somewhat logical.

Finally, tertiary techniques can be used to raise production further. These techniques lower the viscosity of the oil so it can flow easier between the pores of the source rock. They include injecting steam (read: energy input) to heat the oil, or even burning some of the oil in place to heat the remainder. Another technique being is to inject carbon dioxide which decreases the viscosity when it is dissolved in the oil. The CO_2 must first be liquefied (read: energy input) in order to inject it into the field. This sounds wonderful if CO_2 from the atmosphere can be collected to inject into the well, but doing that requires cryogenic separation and is prohibitively energy intensive. There are projects where CO_2 is recovered from the waste stream of industrial plants and injected into nearby wells. It must be economically unfavorable as all the projects involving CO_2 injection seem to be government funded. Tertiary techniques allow another 5-15% of the oil to be recovered, for a total of about 30-50 % overall recovery rates.

How is oil used:



One sees that, perhaps remarkably, or just a fortunate coincidence, that consumption matches the ratio of product available from crude oil, being primarily gasoline, then distillates (diesel and heating oil), then jet fuel. Here, Residual fuel oil is heavier than distillate fuel oil; i.e., it has a higher density, viscosity, and boiling point. It is used mainly by electric utilities, large apartment and commercial buildings, and industries that maintain kilns, open-hearth furnaces, and steam boilers.

Roughly 3 % of US electrical power generation is through using oil as the primary fuel, consuming about 600,000 barrels per day, or about 3 % of US petroleum consumption. Similarly, about 700,000 barrel per day are consumed as feedstocks for industrial production of materials, like chemicals, lipstick, etc., about 4 %. About

1,000,000 barrels per day are consumed for space heating, or about 5 %. This leaves 88 % of petroleum consumed for transportation.

In the world overall, it is difficult to obtain similar data, but from piecing together different articles, it appears to be higher in the electrical generation (due to the prevalence of diesel generators in the third world), and in heating (again due to the relative unavailability of other heating fuels in the third world). My best guess is 75 % transportation, 10 % heating, 10 % electrical generation, and 5 % feedstock for chemical plants.

II. **Energy sources**

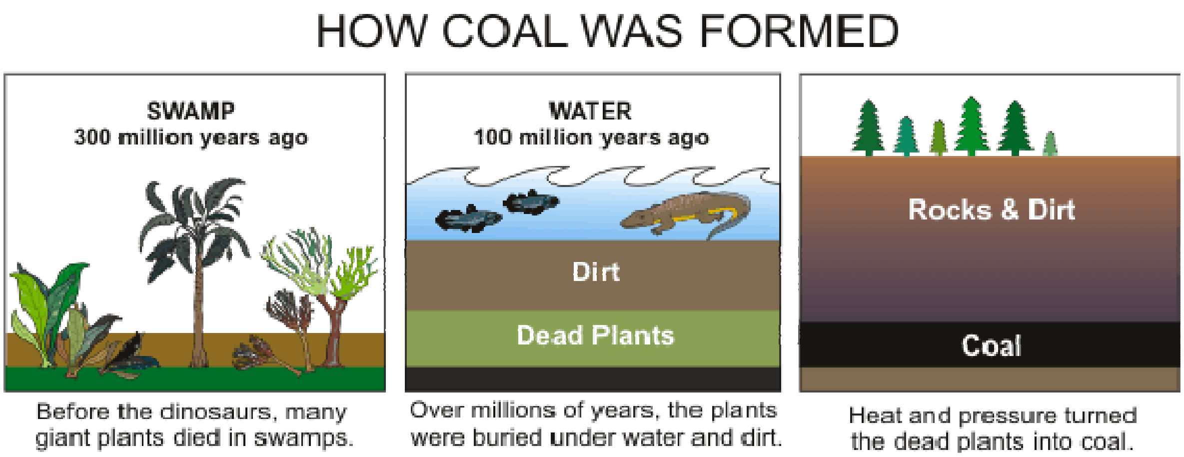
1. **Chemical energy mined from the earth.**

b. **Coal.**

What is it:

Coal is a more complex substance than oil with several types. The lineage of these various types can be traced from peat, which is basically compressed plant matter (for sure, peat and coal are of biological origins). Peat forms when plant material is inhibited from decaying by acidic conditions, usually found in marshy areas. These peat bogs cover approximately 3 % of the world's land. After drying, peat can be used as a fuel, and has been throughout history, including today. As peat bogs grow at about a millimeter per year, it perhaps can be considered a "renewable" biofuel, but on a slow time scale. It is used as a fuel for electric power plants around the world: there is a peat-fired power plant in Maine, and extensive use in Finland and Russia. Although precise numbers are unavailable, it appears that peat provides a few 10's of gigawatts of electricity generation world wide.

As peat is buried by geological processes, the pressure turns it into coal:



The first variety is *brown coal or lignite*, that still contains a great deal of water and oxygen. It is basically what it sounds like, halfway between peat and the black stuff we usually think of as coal. Its energy content ranges from 10,000-20,000 BTU/kg (recall from an earlier section that on average coal contains 22800 BTU/kg. Lignite is still extensively used as a fuel for electric power generation, but its low energy content prohibits economic transportation of it, so the power plants are usually placed right at the lignite mine.

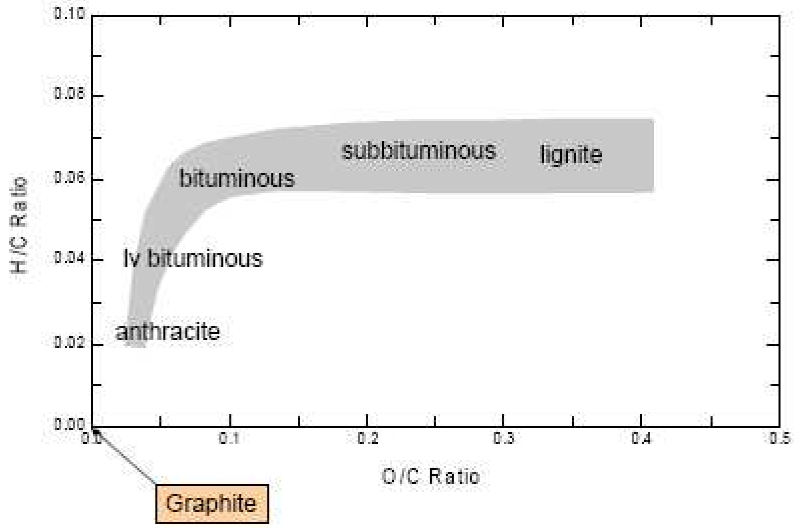
After lignite, there is a range of coal called *sub-bituminous* between it and *bituminous coal*, the most common variety. (So apparently you don't just find lignite or bituminous, sometimes something between the two. This makes sense if you think of the process of forming the higher grades of coal happening over time and pressure continuously.) Here is a photograph of bituminous coal:

If it reminds you of oil sands, there is a good reason, since oil sands are bitumen, a tar-like organic substance, mixed with sand, and here it is infused into stone. Bituminous coal has an energy content of 24,000-35,000 BTU/kg.

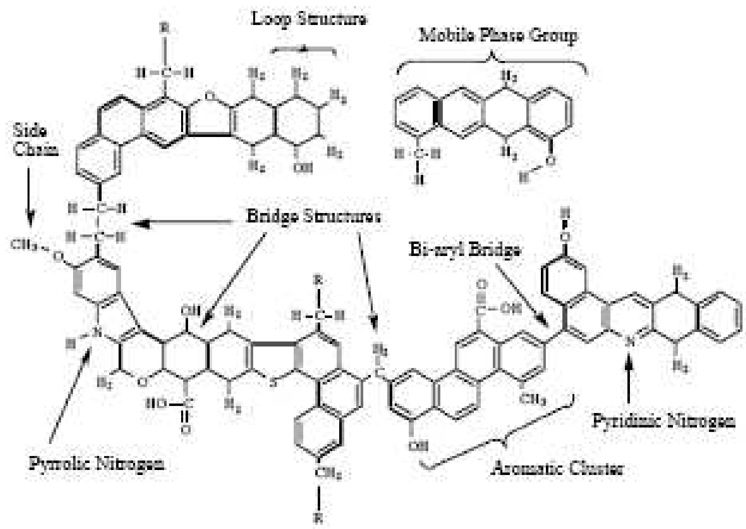
Next is *anthracite*, the stuff we usually think of as coal:

It has an energy content of between 26,000-33,000 BTU/kg.

Finally in the evolution of coal it becomes *graphite* or pure carbon. Here is a chart showing the chemical content of various forms of coal:



As one can imagine, coal is very complex and cannot be generally shown as a specific molecule like alkanes for petroleum. However, it has been found that using chemical formulas such as $C_{137}H_{97}O_9NS$ for bituminous coal and $C_{240}H_{90}O_4NS$ for high-grade anthracite yield correct energy delivery when it is burned. But before we try doing an energy content calculation based upon bond energies, look at the chemical diagram:



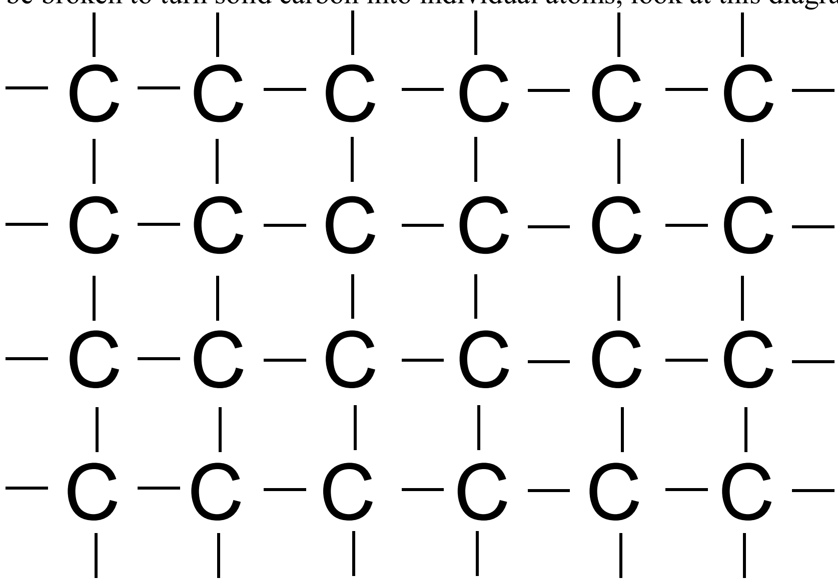
Clearly coal is more complex chemically than petroleum.

We can note some general aspects of coal vs. alkanes from these chemical formulas, however. Alkanes contained 2-4 hydrogen atoms for every carbon atom. Coal contains more carbon than hydrogen, tending toward pure carbon. As when a hydrocarbon is burned, the products are mostly water and carbon dioxide, we would expect the ratio of carbon dioxide to water in the product to go roughly with the carbon to hydrogen ratio in the fuel. That is indeed the case, with a coal-fired electric power plant emitting about 2 pounds of CO2 per kilowatt-hour, while petroleum emits 1.7 pounds and natural gas, 1 pound.

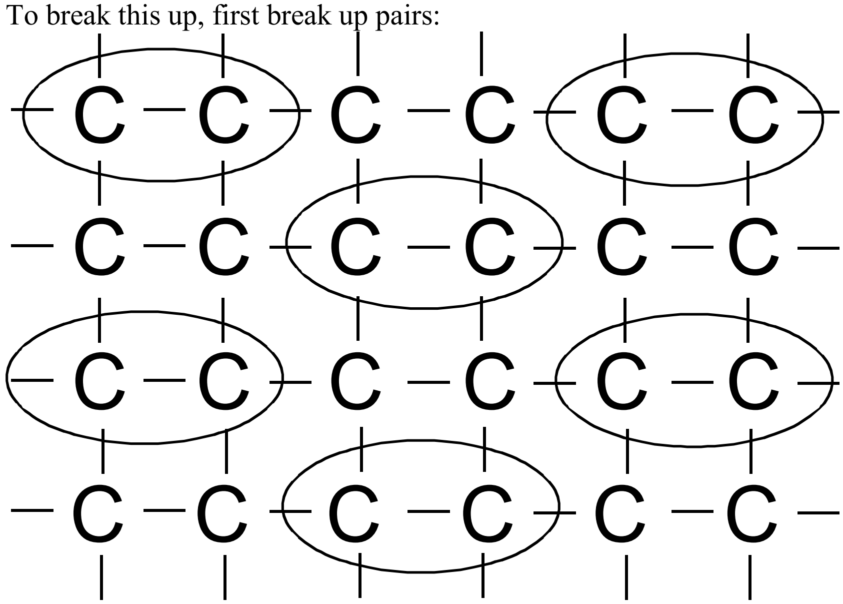
While we cannot do a chemical reaction bond energy analysis for coal in general, we can for pure carbon:

$$C + O_2 \rightarrow CO_2 + energy \qquad \text{(II.1.b.1)}$$

Analyzing this reaction in terms of bond energies is complicated by needing to understand how many carbon-carbon bonds are broken when breaking up solid carbon into individual atoms. This is not as simple as you might think. Carbon, whether it be diamond or graphite, forms four bonds with four neighboring carbon atoms (in the form of graphite, the fourth bond is a weaker one, as graphite is formed of planes of 3-bonded carbons, with a weak bond between planes, but we'll ignore that complication for now). To see how many bonds must be broken to turn solid carbon into individual atoms, look at this diagram:



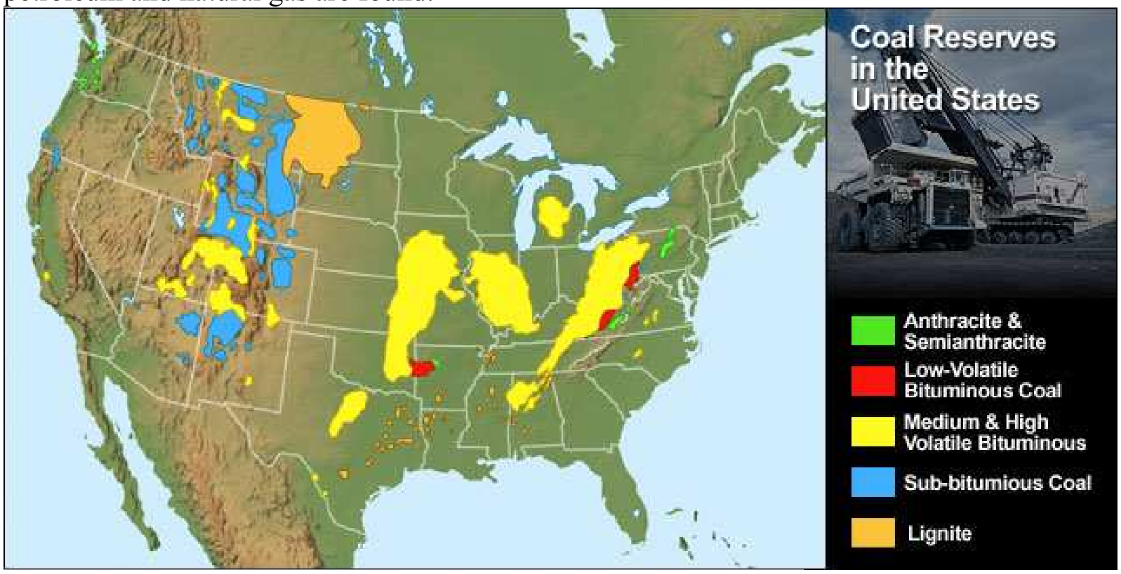
To break this up, first break up pairs:

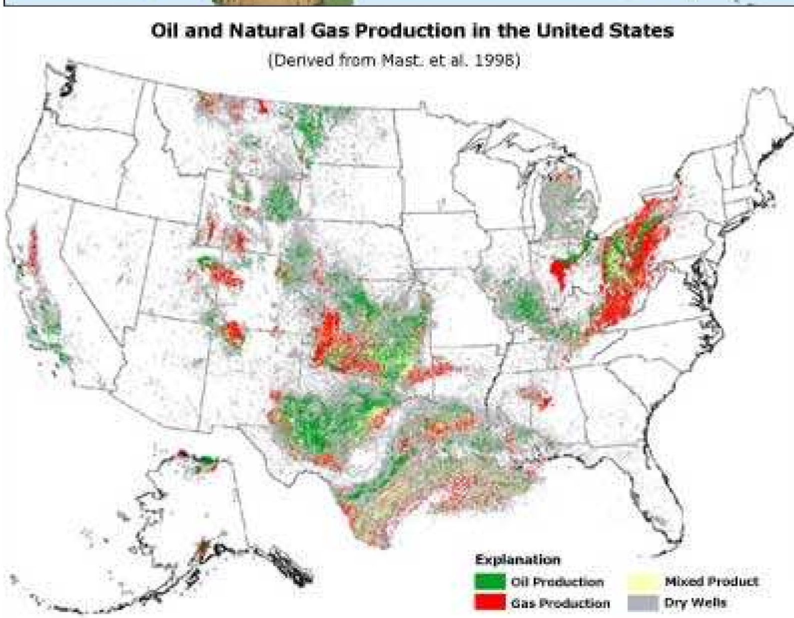


Note that to break up the solid of 24 atoms into 12 pairs required breaking 36 bonds. Then, breaking those 12 pairs requires breaking 12 bonds. So, 48 bonds were broken, or 2 per carbon atom.

Thus in the reaction above, we must break 2 C-C bonds, 1 O=O bond, or put in 2(3.6)+5.17 = 12.37 eV. When the CO2 is formed, we get back the energy in 2 C=O bonds, or 16.72 eV, for a net energy release of 4.35 eV. The actual value has been measured to be 4.11 eV (for diamond), and 4.09 eV (for graphite). Using 4.1 eV, and a molecular weight of carbon of 12x1.66E-27 kg., we obtain 31,000 BTU/kilogram for pure carbon, in line with that noted for anthracite. Note however, that pure graphite must be raised to "very high" temperatures before it will burn, so is not used as a fuel. Evidently the hydrogen and oxygen content of anthracite lowers the ignition temperature to a reasonable value for fuel purposes.

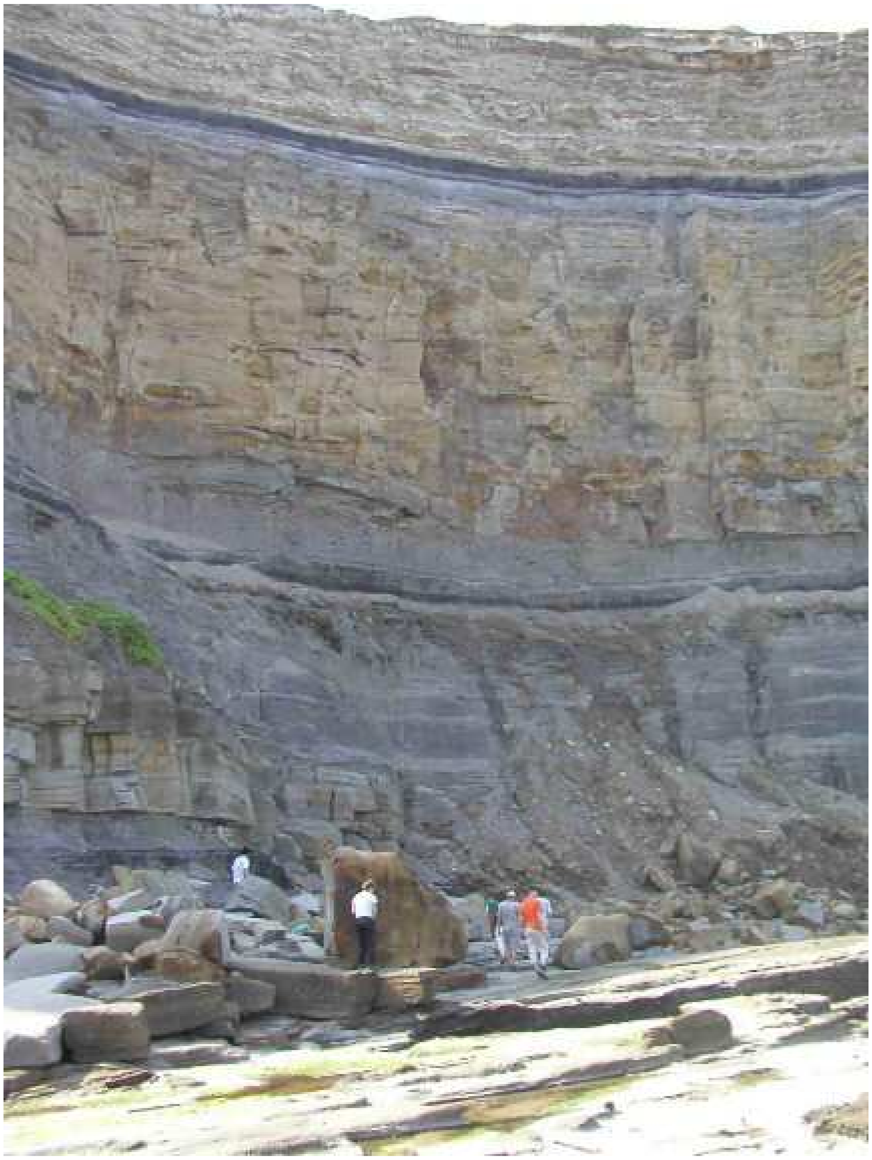
Where is coal found:
From above, coal will be found where ancient peat bogs were located. Although this does not mean "shallow prehistoric seas," there does appear to be a correlation with where petroleum and natural gas are found:



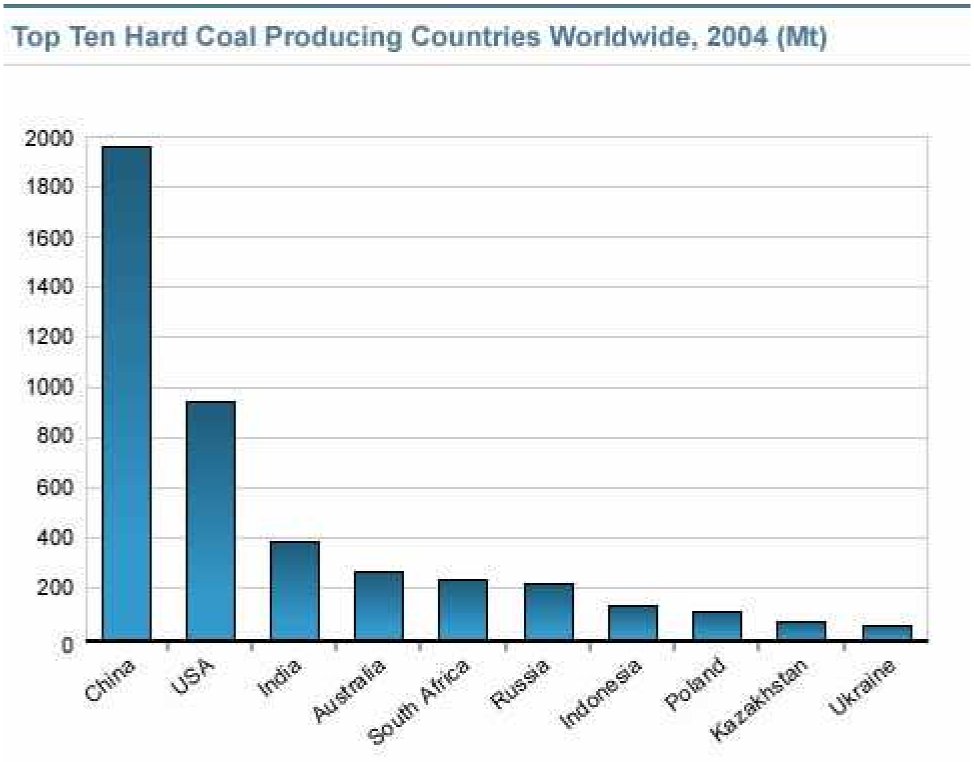


Since coal is definitely biological, this correlation could support the biological theory of oil and natural gas.

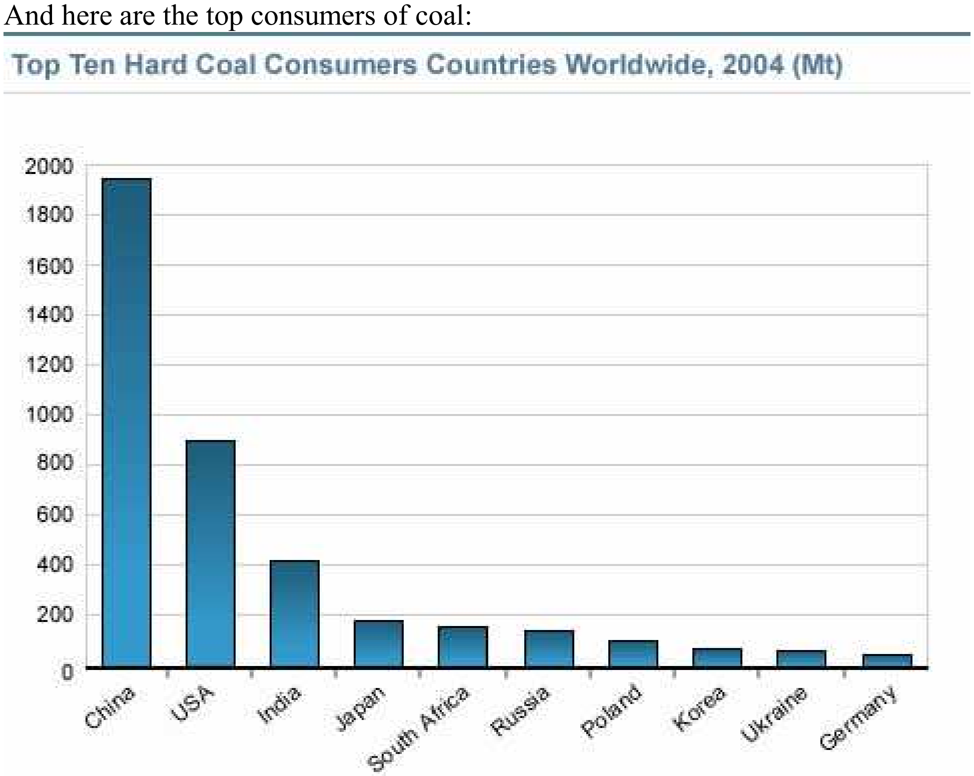
However, while oil and gas are typically drilled for, coal is mined by digging tunnels into the ground and extracting it, or "strip" mining by completely removing the ground and then separating the coal. Here is an example of where coal is found in a cross-section of a mountain:



You can see the black layers of coal. Evidently over the geological time scales that these strata were laid down, at those times indicated by the coal strata, a peat bog was present.
Who has coal and who uses it:
The answer to these questions is about the same, as since coal is a solid with lower energy content per weight than oil, it is not typically transported internationally as the cost of transportation vs. the value of the coal is too high. 84 % of coal is used in the country in which it has been mined from. Here are the top producers of coal:

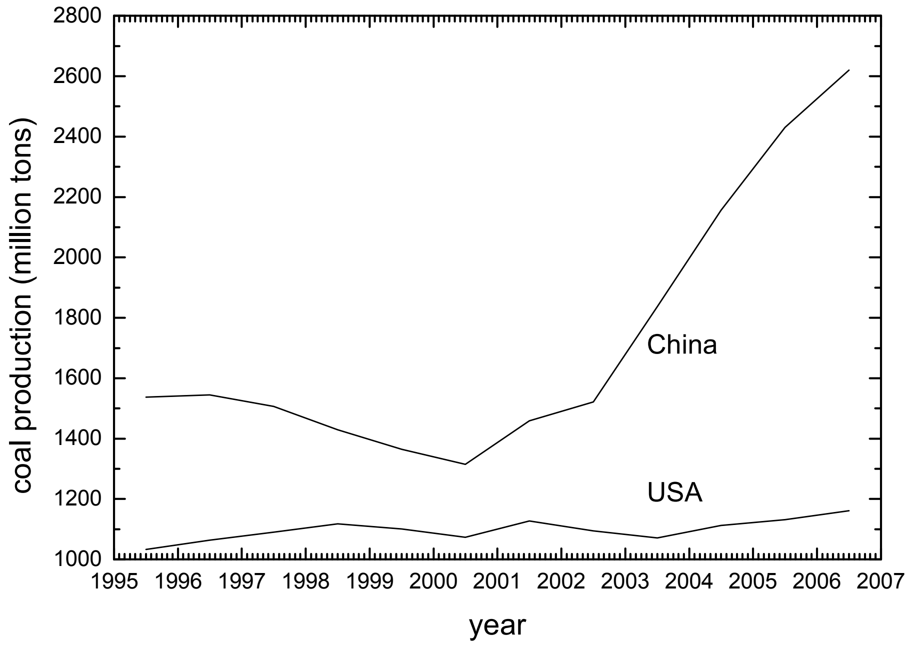


And here are the top consumers of coal:



It would seem that most of the international trade of coal is Australia selling to Japan.

Recent coal production of China and the US is shown here:



I think that the bar graphs above are in metric tons. Note that the US has seen a slight rise, about 0.2 %/year. China, however, has seen dramatic rise in recent years. This can be attributed to the fact that China is by new accounts building "2 new coal fired electric power plants each week." Go, global warming!

That's a joke (maybe). The thing to be learned from this graph is to what extent coal production can be increased if other hydrocarbon production like oil starts to reduce. Here are the estimated coal reserves per nation:

country	Coal reserves (million tons)
US	267,554
Russia	173,074
China	126,215
India	101,903
Australia	86,531
South Africa	53,738

As production rates in China were able to increase by 250 Mton/year, one might expect US production to be able to in principle increase by 500 Mton/year (?) given the nearly twice as much reserve. The difference is probably in safety considerations: in 2006, according to the China State Work Safety Supervision Administration, 4,746 Chinese coal miners were killed in thousands of blasts, floods, and other accidents. In comparison, in the US, 47 coal miners died in accidents in 2006. So the limiting factor is probably miner safety.

Similarly to the earlier homework problem, if gasoline supplies decreased by 4 % per year, and coal-to-liquids (discussed below) were used to make up the difference, an equivalent of 23 gigawatts of average power would have to be in the increased coal production. Note here that coal-to-electricity-to-moving your car has about the same efficiency as gasoline-to moving your car. 23 gigawatts of coal production translates into 23E9x365.25x24.3600/(22800x1055) = 3.02E10 kg/year, or 33 million tons per year. Thus, it seems to be in the realm of possibility, even with safety considerations.

We'll skip the how coal is produced; it is dug out of the ground and nearly all is used for producing electricity, with some for heating in steel furnaces. Rather, given the preceding paragraph, we'll take a special look at using coal to produce liquid fuel like gasoline or diesel.

Coal-to-liquids:

In the coal-to-liquids process called Fischer Tropsch, coal is first *gasified*, by mixing coal with steam to produce carbon monoxide and hydrogen, sometimes called syngas:

$$C + H_2O \rightarrow H_2 + CO. \qquad \text{(II.1.b.2)}$$

Once the hydrogen and carbon monoxide are obtained, they can be reacted to produce synthetic alkanes per the reaction

$$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O, \qquad \text{(II.1.b.3)}$$

with water as a by-product. Overall, these reactions are endothermic, so energy input is required by the burning of coal. (This makes sense as you are producing a product with higher energy density from one with lower energy density.) By adding oxygen in the coal and steam flow, energy can be inputted directly per the exothermic reaction

$$C + 0.5O_2 \rightarrow CO. \qquad \text{(II.1.b.4)}$$

So far, looks okay, except we have too much *CO*. For high carbon count alkanes, reaction II.1.b.3 requires roughly two hydrogen molecules for every one carbon monoxide molecule, but co-reactions II.1.b.2, 4 are producing two carbon monoxide molecules and one hydrogen molecule. To fix this, the steam content can be adjusted to induce the reaction

$$CO + H_2O \rightarrow CO_2 + H_2, \qquad \text{(II.1.b.5)}$$

thus using up a carbon monoxide molecule and producing a hydrogen molecule, bringing the overall reaction into balance. Summarizing II.1.b.2, 4, and 5, we can write an overall syngas reaction resulting in a roughly 2:1 hydrogen to carbon monoxide ratio as

$$2C + 0.5O_2 + 2H_2O \rightarrow CO_2 + 2H_2 + CO, \qquad \text{(II.1.b.6)}$$

then allowing the synthetic liquid reaction II.b.1.3 to approximately proceed. Examining II.1.b.6 and II.1.b.3, one sees that to make an alkane molecule with *n* carbon atoms requires roughly *2n* carbon atoms, and has as a by-product *n* carbon dioxide molecules. *n* carbon dioxide molecules weigh *n*(12+2x16)=44*n* atomic mass units. An alkane molecule with *n* carbon atoms weight 12*n*+2*n*+2=14*n*+2 atomic mass units. Thus, for diesel, for example (*n*=14), 44(14)/[14(14)+2]=3.1 pounds of carbon dioxide are produced for every pound of diesel produced.

Thus although there appears to be sufficient coal to convert to liquid fuel in a situation of declining petroleum production (*perhaps*; we'll examine this more closely in the section on hydrocarbon depletion models), the process produces copious amounts of carbon dioxide, and its use would substantially add to its content in our atmosphere, unless techniques for sequestering it in the ground were developed. In addition, as for oil sands or oil shale, producing one barrel of liquid fuel from coal requires 5 barrels of water. These are the main objections to coal-to-liquids. Note when the liquid product is burned in a vehicle, that carbon ends up in carbon dioxide as well.

Note that burning coal to generate electricity to power electric cars is not better on a per carbon basis; all the carbon still has to wind up in carbon dioxide. Coal is inherently a "dirty" fuel either way when it comes to carbon dioxide, due to its high carbon to hydrogen ratio: this means the product of burning it is more carbon dioxide than water.

However, one can examine the efficiency of coal-electricity-motive force, vs. coal-liquid-motive force to determine if less coal is required for one or the other. To do this, one must know the energy efficiency of converting coal to liquid, which is 42 %. Part of the reason for this low efficiency is that in coal-to-liquid, something with a lower energy density (coal) is converted into something with a higher energy density (diesel or gasoline). As we will see later, this goes against the second law of thermodynamics unless energy is added to the process. The efficiency is roughly the difference in energy concentration divided by the energy concentration in the product. Since the energy concentration in coal is 22,800 BTU/kg, and the energy concentration of oil is 38,700 BTU/kg, we have that the efficiency should be (38700-22800)/38700 = 41 %, approximately what is measured.

Now, the energy efficiency of liquid fuel to motive force can be seen from the energy flow chart in the introduction, as 5.2/25.9 = 20.1 %. So the overall **efficiency of coal-liquid-motive force** is 0.42x0.201 = 0.084, or **8.4 %.** The efficiency of coal-to-electricity can be estimated from the "spaghetti" chart as 11/34.4 = 32 %. The efficiency of an electric motor is about 90 %. The efficiency of a battery charging system is also about 90 %. So, together, we can estimate the efficiency of electricity-to-motive force as about 80 % (we'll be examining this more closely in the section on vehicle engine technologies). Thus, the efficiency of **coal-electricity-motive force** is about 0.32x0.8 = 0.256, or **25.6 %**. Therefore, using coal-to-liquids rather than coal-fired generators and electric cars wastes about 3 times the energy, and in the process, 3 times the carbon dioxide is generated.

II. Energy sources

1. Chemical energy mined from the earth.

c. Natural Gas.

What is it:

Natural gas is typically delivered as pure methane, CH_4, the simplest alkane, so much of what we've learned about petroleum applies. Particularly, refer to the solution to homework 4, problem 1, for the energy content of methane. We see that it has the highest energy content per unit weight of the alkanes, and thus is about twice as high as coal. Of course, methane is a gas at normal temperatures and pressures, so is usually not sold per unit weight, but by volume, and we also see from the solution to that problem that methane has approximately 1000 BTU/cubic foot.

Since methane has the highest hydrogen to carbon ratio of any of the hydrocarbons, it also produces the lowest amount of carbon dioxide when burned. From the general alkane reaction

$$C_nH_{2n+2} + [(3n+1)/2]O_2 \rightarrow nCO_2 + (n+1)H_2O\,, \qquad \text{(II.1.c.1)}$$

and the solution to homework 4 that the energy released in this reaction is

$$\text{energy released} = 6.43n + 2.08 \text{ eV}, \qquad \text{(II.1.c.2)}$$

we have that the number of carbon dioxide molecules released per energy released is

$$\frac{\#CO_2}{eV} = \frac{n}{6.43n + 4.15}\,. \qquad \text{(II.1.c.3)}$$

Thus, methane produces the fewest carbon dioxide molecules per energy released. Given the weight of CO_2 of 44(1.66E-27) kg, and the conversion of 1 eV = 4.44E-26 kWh, II.1.c.3 becomes

$$\frac{kgCO_2}{kWh} = \frac{0.26n}{n + 0.65}\,. \qquad \text{(II.1.c.4)}$$

Comparing with coal, treating coal as pure carbon, recall that

$$C + O_2 \rightarrow CO_2 + 4.1 \text{ eV}, \qquad \text{(II.1.c.5)}$$

So that coal releases 0.24 carbon dioxide molecules per eV, or 0.39 $kgCO_2 / kWh$.
Summarizing in this table,

fuel	$kgCO_2 / kWh$ (before conversion losses)	$lbCO_2 / kWh$ (before conversion losses)
methane	0.16	0.35
gasoline (*n*=8)	0.24	0.53
diesel (*n*=14)	0.25	0.55
coal (pure carbon approx.)	0.39	0.86

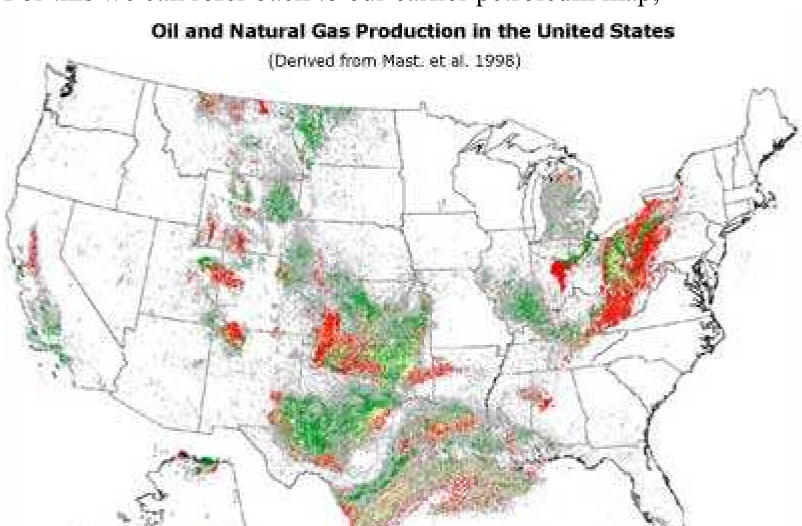
Recall earlier we quoted ~ 1 pound/kWh for natural gas, and 2 for coal, from electric power plants. The difference is the efficiency of the power plant in converting the fuel energy into electrical energy, which is from our spaghetti chart is 0.32. Using this conversion roughly results in 0.35/0.32 = 1.09 for methane, and 0.86/0.32 = 2.69 for pure carbon. Since coal is not pure carbon, it does a little better than this.

Thus natural gas is often called a "clean" fuel due to its low carbon dioxide emissions. In addition to this, since it has a high energy to weight ratio, natural gas could be considered a good transportation fuel; except, it has to be compressed or liquefied. Usually, it is compressed, so you see the term "compressed natural gas," or CNG. Vehicles run on CNG have the symbol

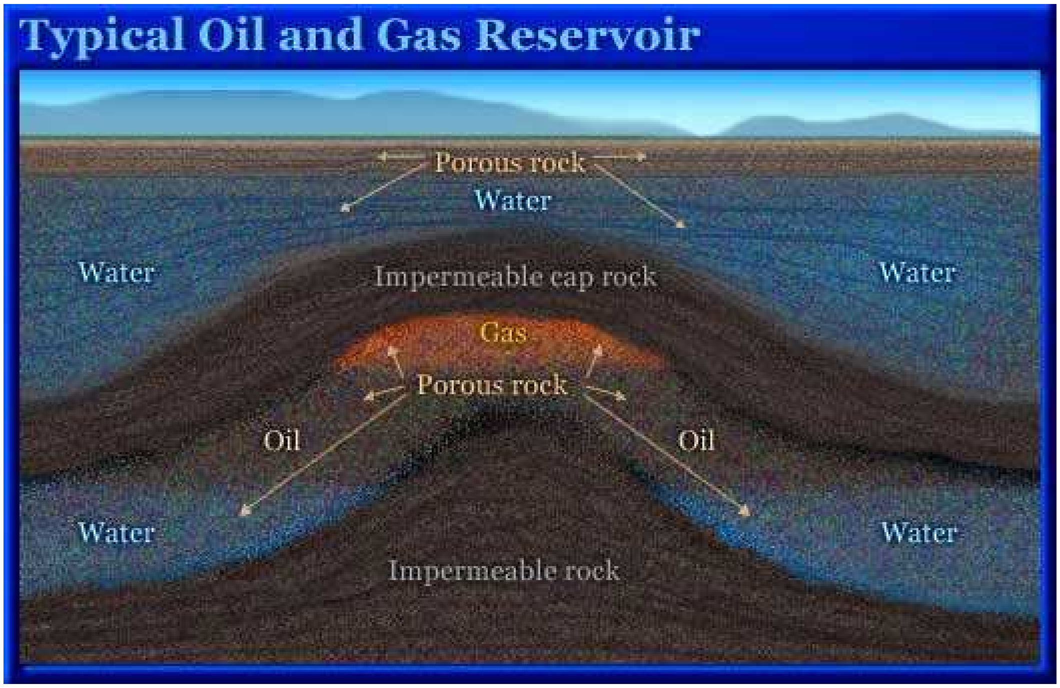
CNG

which you may have seen on busses, the primary users of CNG. Part of the reason is the very heavy fuel tank required to support the CNG, which is pressurized to ~ 210 times atmospheric pressure. If using the ideal gas law, mass density is proportional to pressure, so its density increases to 210(0.7) = 150 kilograms per cubic meter. Since the density of diesel is 900 kilograms per cubic meter, and the energy per unit weight of methane is only about 15 % higher, the energy per unit volume of CNG is only about 20 % of diesel (not including the tank). Thus, it is only competitive in large vehicles like busses.

<u>Where</u> is natural gas found:
For this we can refer back to our earlier petroleum map,

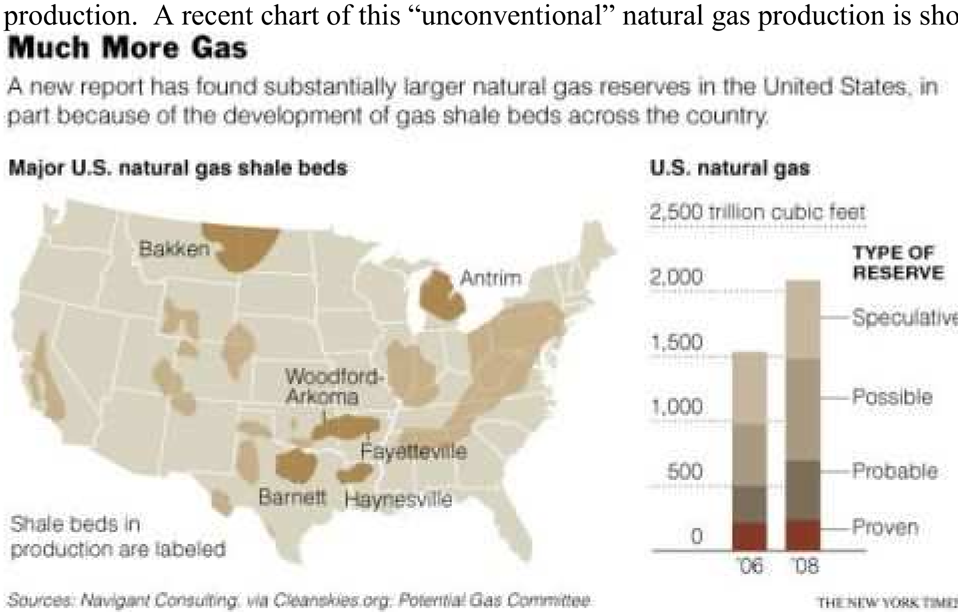


and see that there is a rough correlation between natural gas and petroleum, which we would expect given the earlier diagram of an oil field,



showing that natural gas typically occurs in the same geological formation. Indeed, natural gas is generally thought to have the same origins as petroleum, as both are alkanes, and then within the oil field the gas rises above the oil, given that it is lighter. The ratio of gas to liquid in a field may vary a great deal depending upon the "cooking" conditions of the field.

In addition to oil fields, natural gas is produced from recent biological activity in swamps, marshes, and landfills. Also, it is produced from coal fields (coalbed methane), where it exists due to the geological conversion of plant matter to coal. (It is actually very dangerous to coal miners as it can cause explosions). About 10 % of natural gas produced in the US is coalbed methane. Finally, another form of non-oil field natural gas is referred to as tight gas. This is gas that is stuck in a very tight formation underground, trapped in unusually impermeable, hard rock, or in a sandstone or limestone formation that is unusually impermeable and non-porous (tight sand). It currently also accounts for about 10 % of US production. A recent chart of this "unconventional" natural gas production is shown here:

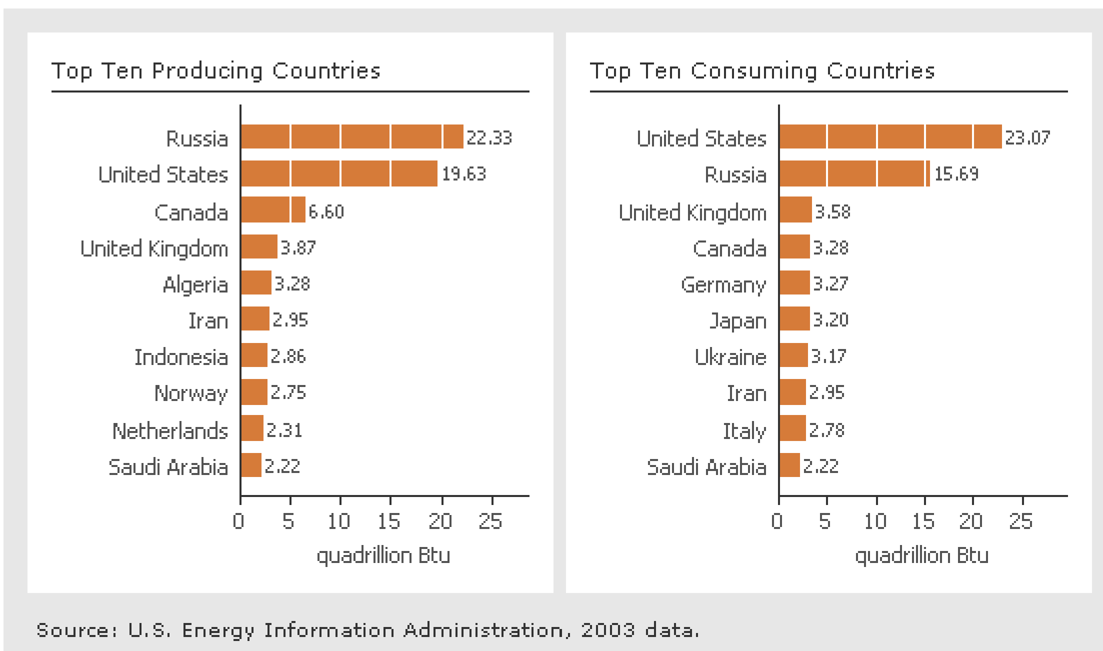


We will see in the section on depletion models that this unconventional natural gas appears to be pushing out its depletion curve.

Although not currently a production source of natural gas, a possibly important source is natural gas hydrates, which are formations are made up of a lattice of frozen water, which forms a sort of 'cage' around molecules of methane:

These hydrates look like melting snow, but they burn! There are vast quantities of methane hydrates at the bottom of the oceans (periodic release of the trapped methane has been hypothesized as the reasons for “Bermuda Triangle” disturbances). However, no one has a plausible technique for mining these deposits. It is impractical to mine them in their solid form. There is research into heating the deposits in situ to release the gas to then flow up to the surface. However, it could be dangerous: methane is a potent greenhouse gas.

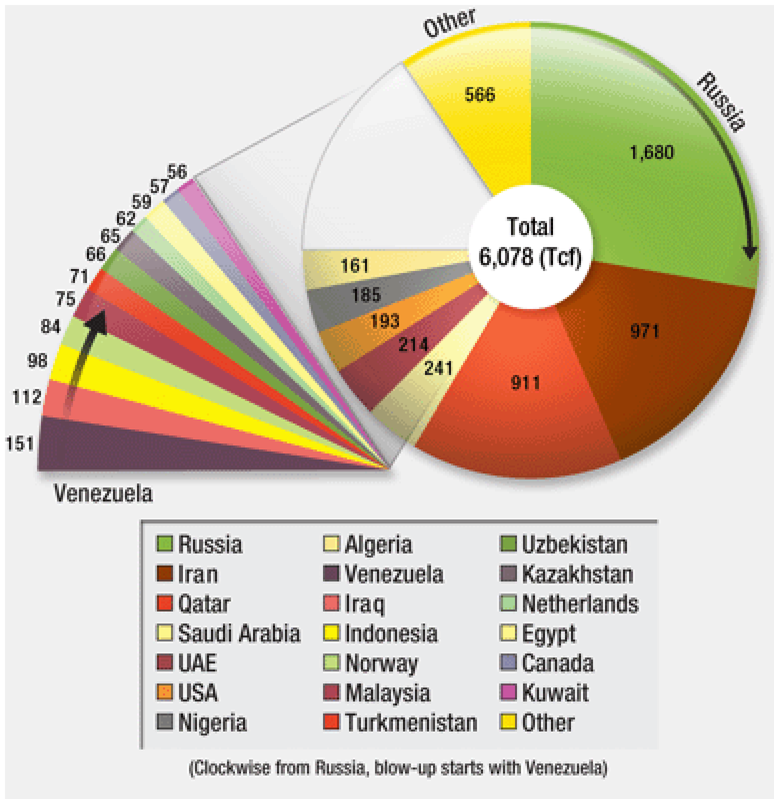
Here is a table of (producing) natural gas production and consumption by country:



What I found interesting about this immediately is that China does not appear on either side. However, China’s natural gas production at ~ 2 quads/year, has been increasing rapidly, doubling in the last five years. The other aspect of this chart is that, mostly, as in coal, the same countries are on both sides. While for coal this was due to its low energy content that makes transportation in general uneconomic, here it is due to the difficulty transporting natural gas on a ship, where it has to be liquefied cryogenically. Note that the US produces most of what it consumes. Nearly all the rest comes from Canada via pipeline. Currently about 3 % of natural gas consumed in the US is shipped cryogenically from overseas. Most of that is from the country of Trinidad and Tobago in the Caribbean, a tiny country that apparently is one big gas field.

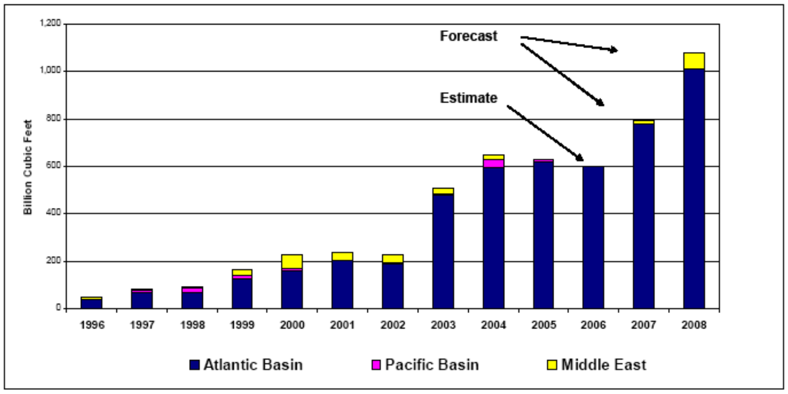
Note with the simple conversion at ~ 1000 BTU/cubic foot, that a quad is roughly a trillion cubic feet (Tcf).

Reserves of natural gas have been estimated and are shown here:



Note the total corresponds to roughly 6000 quads. Based upon this estimate, the US can only continue producing at this rate for 193/19 = 10 years! But, as we've seen above, new unconventional sources are pushing out this estimate. Canada can only continue producing for 57/6.6 = 8.6 years! (Recall that oil sands petroleum is produced by heating the sands with, natural gas!) Clearly this represents a problem, which is projected to be solved by vastly increased transportation of liquefied natural gas (LNG) by ship from countries like Qatar. Qatar is a tiny little country in the Middle East that apparently is one big natural gas field. It could supply US needs for 911/23 = 40 years. But, LNG is considered hazardous and nobody wants an LNG port near them. This has limited LNG imports:

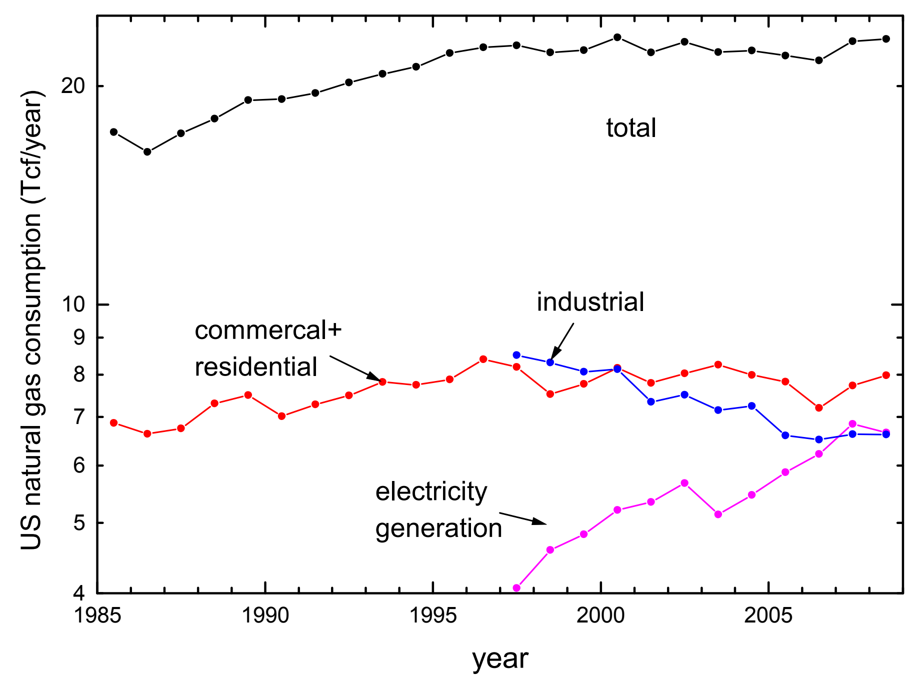
Figure 1. Historical and Projected U.S. LNG Imports, 1996-2008



Source: **1996-2005:** U.S. Department of Energy, Office of Fossil Energy. **2006-2008 (Estimates and Projections):** Energy Information Administration, Short-Term Integrated Forecasting System database.

Note that LNG imports have been flat over the last 3 years (but our DOE hopes pleasantly for a big increase in the next few years). In order to displace declining production in the US and Canada, it would have to increase by a factor of 100/3 = 30 in the next 10 years.

How is natural gas used:
Here the uses of natural gas in the US are shown:



On this graph, commercial and residential use is primarily for space heating. Thus, one sees in 2006 which was the warmest on record that consumption for space heating dropped dramatically. Electricity generation via natural gas has been increasing rapidly, while industrial use (primarily for process heating and as a chemical feedstock) has been declining. The reason for the latter is that many industries that use large amounts of natural gas have moved plants to parts of the world where there are ample supplies. Overall, this has lead to a slight reduction of use in the last couple of years.

Finally, we will discuss natural gas-to-liquid alkane conversion, just as coal-to-liquids were discussed in the previous section. If methane could be converted, to say, octane, then it would be a liquid at room temperature and its transportation issues would be solved. Whereas converting coal to liquid alkanes required transforming to a more concentrated energy material, here going from methane to liquid alkanes would result in less molecular concentration of energy. Thus, it would seem like a good idea. It would seem, for example, that we could do

$$8CH_4 \rightarrow C_8H_{18} + 7H_2 \qquad (?). \qquad \text{(II.1.c.6)}$$

Alas, this does not seem possible. Rather, as the accompanying article states, we must go through a process similar to with coal (but using oxygen rather than steam) to produce syngas (H_2 and CO), then produce alkanes using them as reactants. As the accompanying article states, the overall result, is that 10000 cubic feet of methane can be converted into 1 barrel of synthetic petroleum. Since 10000 cubic feet of methane contains 1E7 BTU's of energy, and 1 barrel of oil contains 5.8E6 BTU's, this process is only 58 % efficient. Better than coal, but not by much.

II. Energy sources

1. Chemical energy mined from the earth.

d. Depletion models, applied to hydrocarbons.

Clearly, it would be nice to know how much hydrocarbon resource is available to be mined from the earth. Unfortunately, an exact number is difficult to come by using a direct approach of attempting to count oil fields, etc., as they are buried and one is not able to direct measure the resource.

We will discuss another model for remaining resource here, which some authors (including for example, the Chairman of the Applied Sciences department at CalTech) believe in, while other revile. That is Hubbert's analysis (named after its inventor, Dr. Hubbert), which purports to determine the future availability of a resource based upon the production and production rates which have already occurred. It does so by postulating that at any given time, the cumulative production of a resource (that is, all that has been mined up to time *t*) (*Q*), is related to the production at time *t* (*dQ/dt*) by the equation,

$$\frac{dQ}{dt} = \frac{1}{\tau(URR)} Q(URR - Q) = \frac{1}{\tau} Q(1 - \frac{Q}{URR}), \qquad \text{(II.1.d.1)}$$

where *URR* is the *Ultimate Recoverable Resource*, that is, all that there ever was to begin with, and τ is a time constant. Of course, the existence of a *URR* follows from the fact that the resource is finite.

Let's parse this equation to understand it's meaning. It is saying that at any given time, the production is proportional to the product of how much has been produced and what is left. Thus, when production begins,

$$\frac{dQ}{dt} = \frac{Q}{\tau}, \text{ early time,} \qquad \text{(II.1.d.2)}$$

whose solution is

$$Q = Ae^{t/\tau}$$
$$\frac{dQ}{dt} = \frac{A}{\tau} e^{t/\tau}, \text{ early time.} \qquad \text{(II.1.d.3)}$$

The concept is clear here, that when production of a resource begins, it increases exponentially. This is almost always the case.

The other aspect of equation II.1.d.1 is more controversial, that as *Q* becomes a significant fraction of *URR*, production begins decreasing because it is proportional to $URR - Q$. Producers of a resource don't like to think that their production rate can be constrained by anything other than how hard they are willing to work at it. But, the logic of the equation is supportable: once $Q = URR$, production must be zero as there is nothing left.

The main argument against Hubbert's analysis is the *URR* is a function of time, in that new discoveries are constantly being made. What this means is that at any given time, the production rate is determined by the *URR* known <u>at that time</u>. Indeed, in the accompanying slide files, particularly for US natural gas it will be seen that before 1980 the production was obeying a different *URR* that it is today.

While the truth of equation II.1.d.1 is debated, it is the only theory that has been put forward to predict the future of a resource, and it has had some success at it. Continuing with the analysis, given production data

$$P(t) = \frac{dQ}{dt} \qquad \text{(II.1.d.4)}$$

which is available, one determines

$$Q(t) = \int_0^t P(t')dt' . \qquad \text{(II.1.d.5)}$$

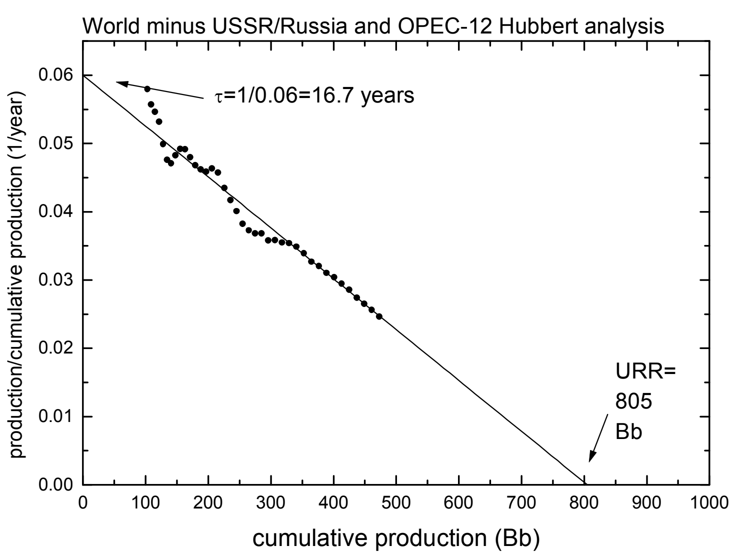
Note that sometimes one does not have production data going back to the beginning of production of a resource, but rather only back to $t_{databegins}$, so one must sometimes "guess" at $Q(t_{databegins})$ and determine $Q(t)$ using

$$Q(t) = Q(t_{databegins}) + \int_{t_{databegins}}^{t} P(t')dt' . \qquad \text{(II.1.d.6)}$$

Once $Q(t)$ is obtained, one sees from II.1.d.7 that

$$\frac{P(t)}{Q(t)} = \frac{1}{\tau}(1 - \frac{Q}{URR}) , \qquad \text{(II.1.d.7)}$$

so that if one plots $P(t)/Q(t)$ vs. $Q(t)$, one should obtain a straight line whose *y*-intercept is $1/\tau$ and whose *x*-intercept is *URR*. For example, here $P(t)/Q(t)$ is plotted vs. $Q(t)$ for oil production data from all nations other than OPEC and the USSR/Russia:

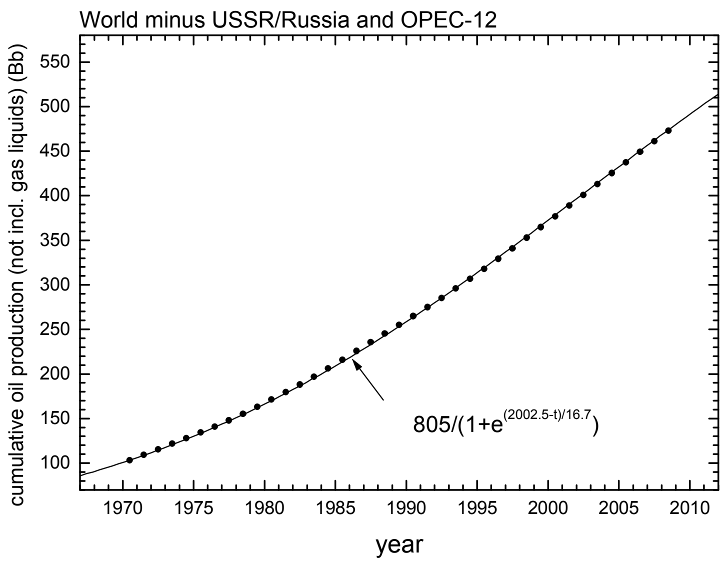


At left, Hubbert analysis for oil production of countries outside of OPEC and USSR/Russia, showing a *URR* of 805 billion barrels. 480 billion have been mined, leaving 325 billion left.

Once τ and *URR* are obtained from a straight line fit to $P(t)/Q(t)$ vs. $Q(t)$, one sees that the solution to equation II.1.d.1 is

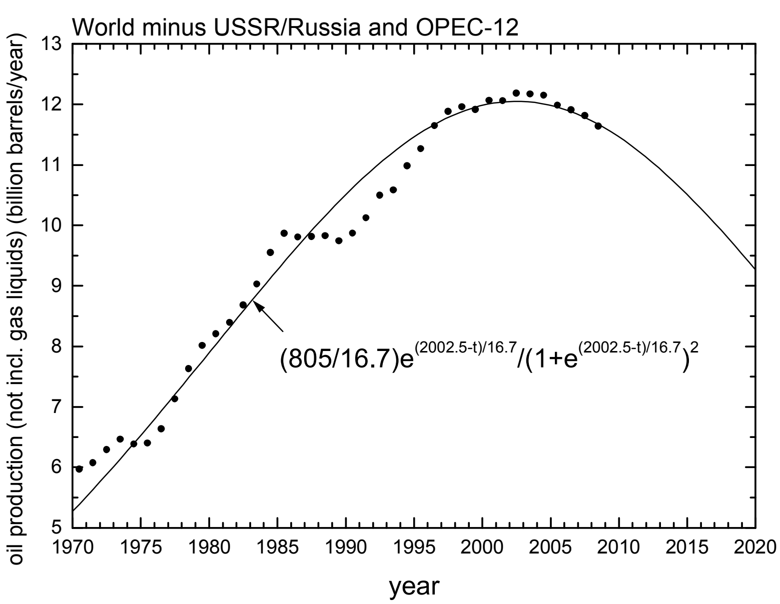
$$Q(t) = \frac{URR}{1+e^{(t_0-t)/\tau}}, \qquad \text{(II.d.1.8)}$$

where t_0 is a fitting parameter. For example, in the plot for oil production data outside of OPEC and USSR/Russia,

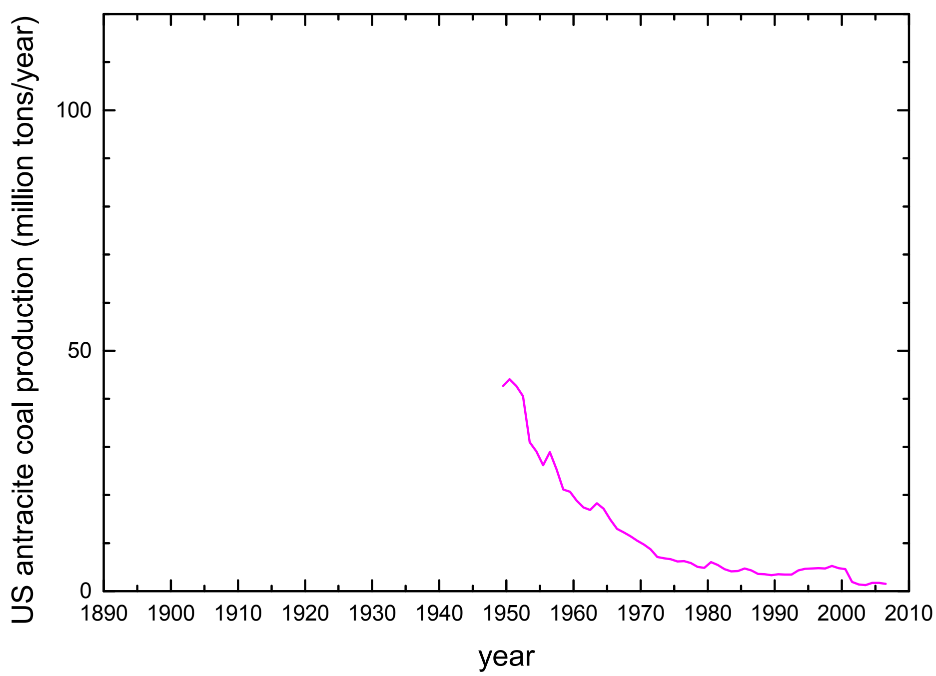


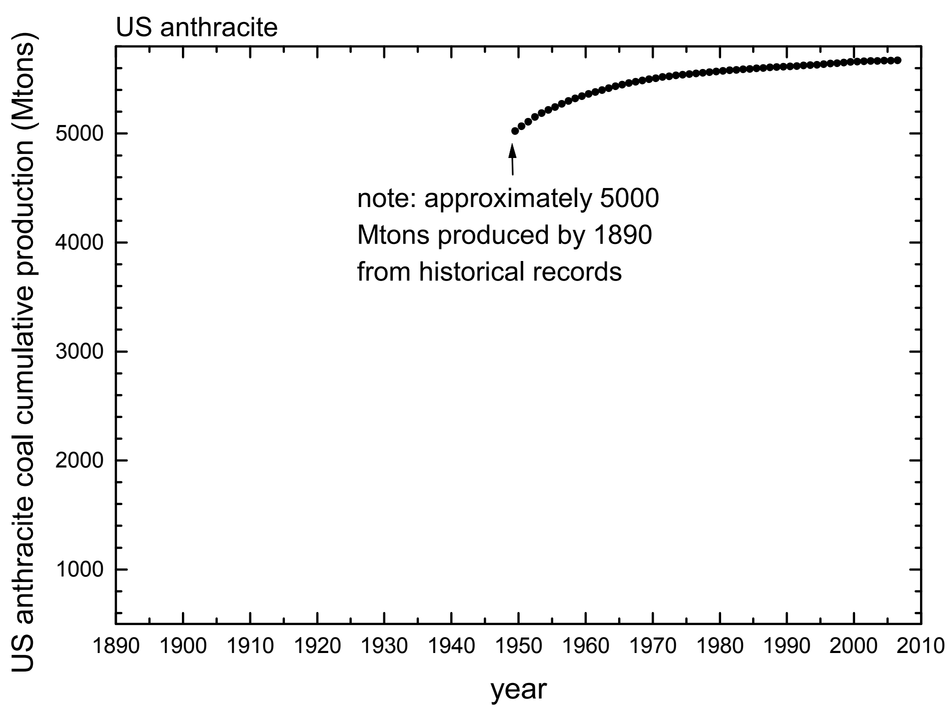
after obtaining τ and *URR* from a linear fit to $P(t)/Q(t)$ vs. $Q(t)$, one then varies t_0 to fit $Q(t)$. Finally, taking the derivative,

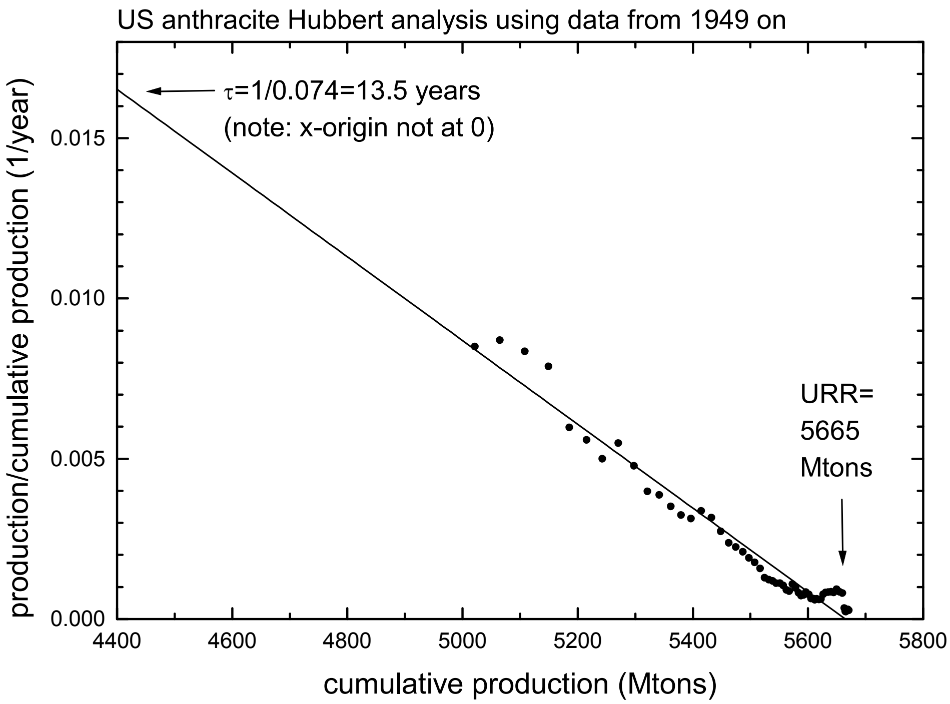
$$P(t) = \frac{(URR/\tau)e^{(t_0-t)/\tau)}}{[1+e^{(t_0-t)/\tau)}]^2}. \qquad \text{(II.d.1.9)}$$

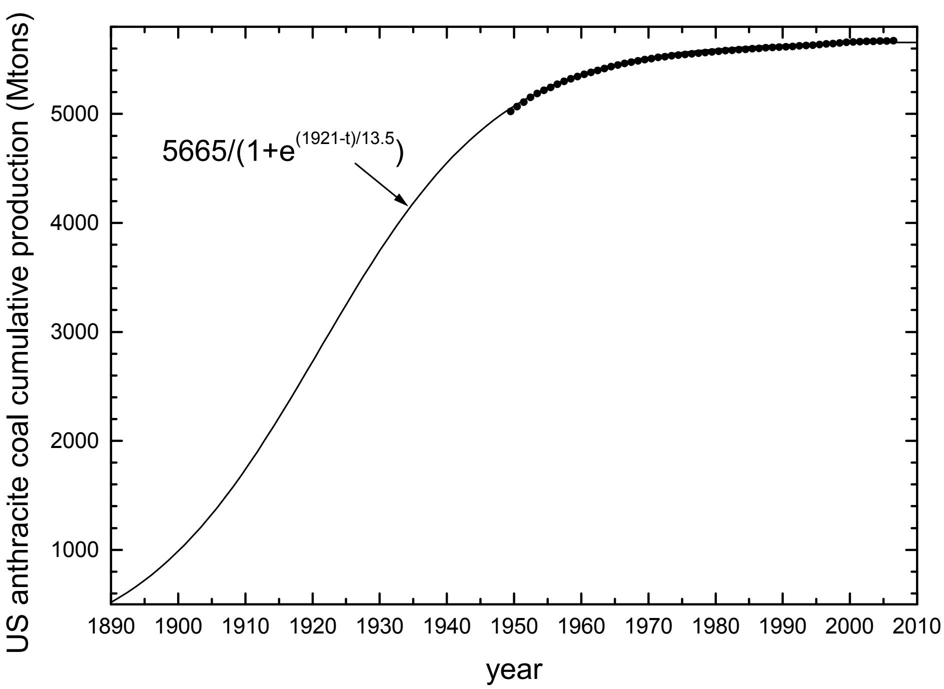


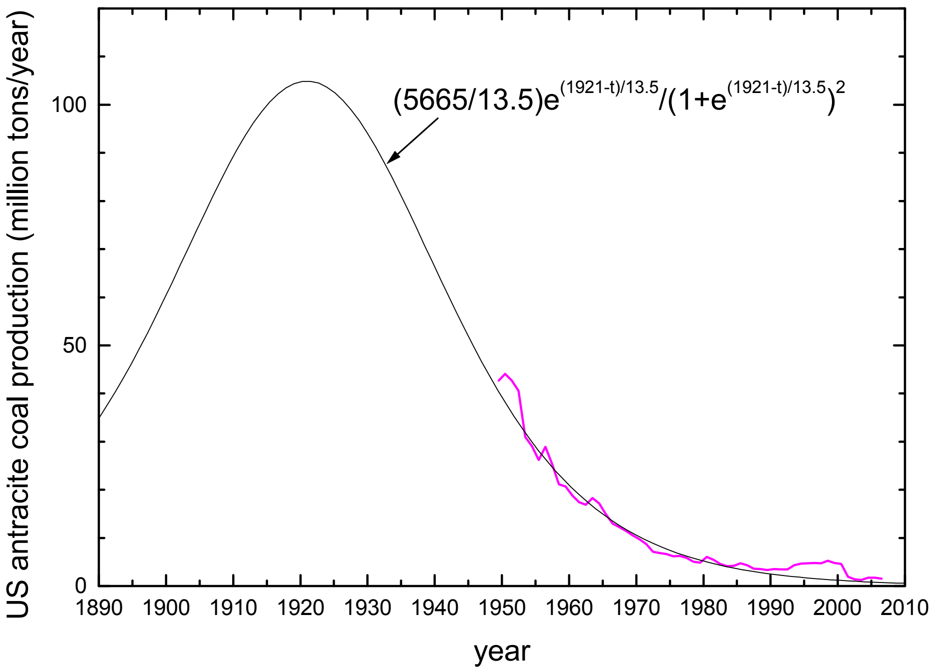
Following are sequences of Hubbert analysis (production data, cumulative production data, production/cumulative production, cumulative production with fit overlaid, then production data again with the Hubbert prediction overlaid, for various mined energy sources:



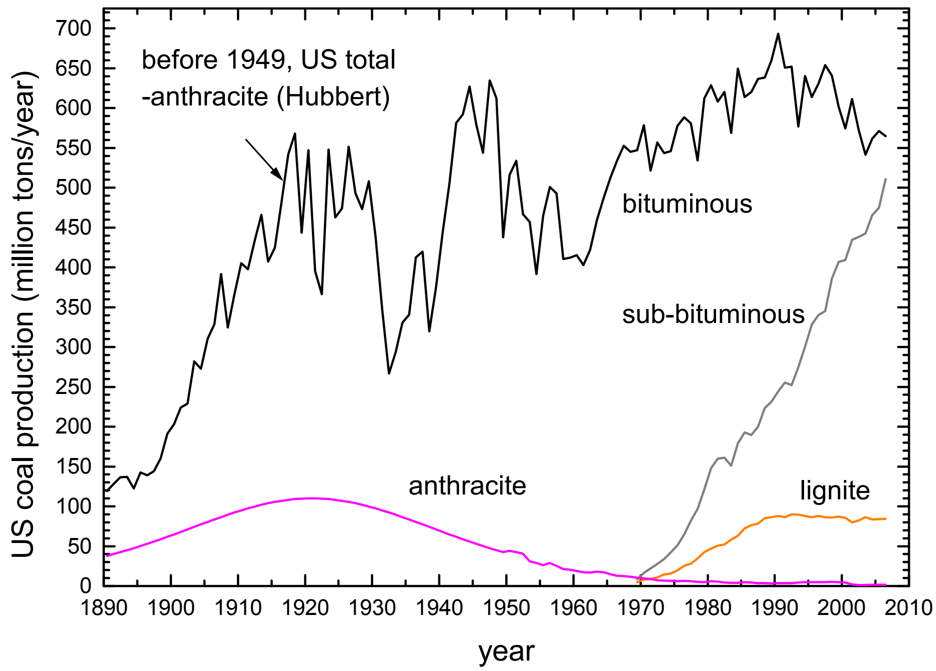


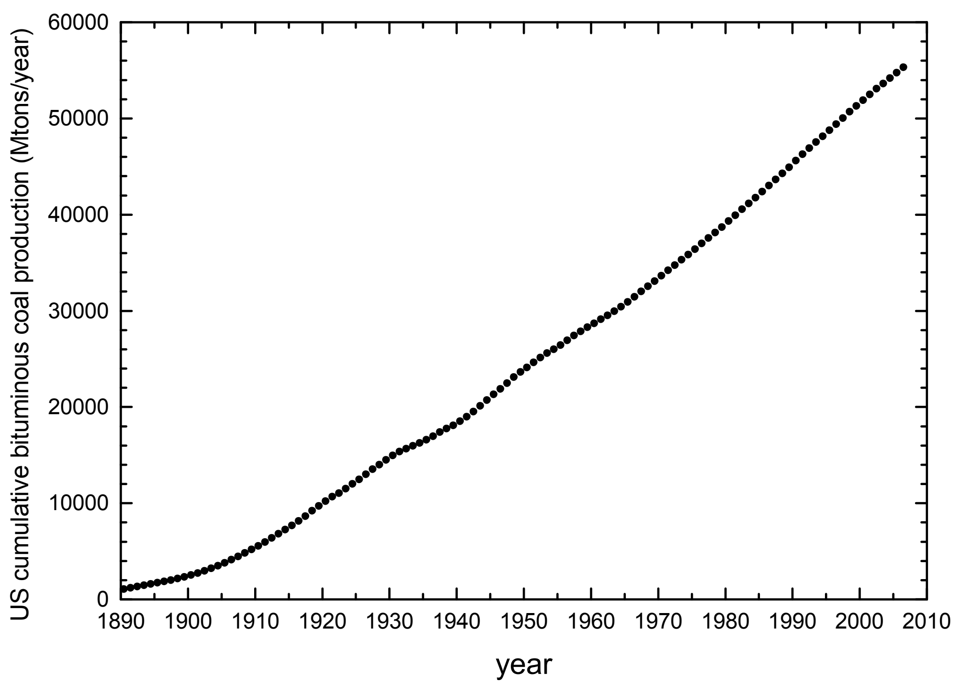

US anthracite Hubbert analysis using data from 1949 on
τ=1/0.074=13.5 years
(note: x-origin not at 0)
URR=
5665
Mtons
production/cumulative production (1/year)
0.000
0.005
0.010
0.015
4400
4600
4800
5000
5200
5400
5600
5800
cumulative production (Mtons)

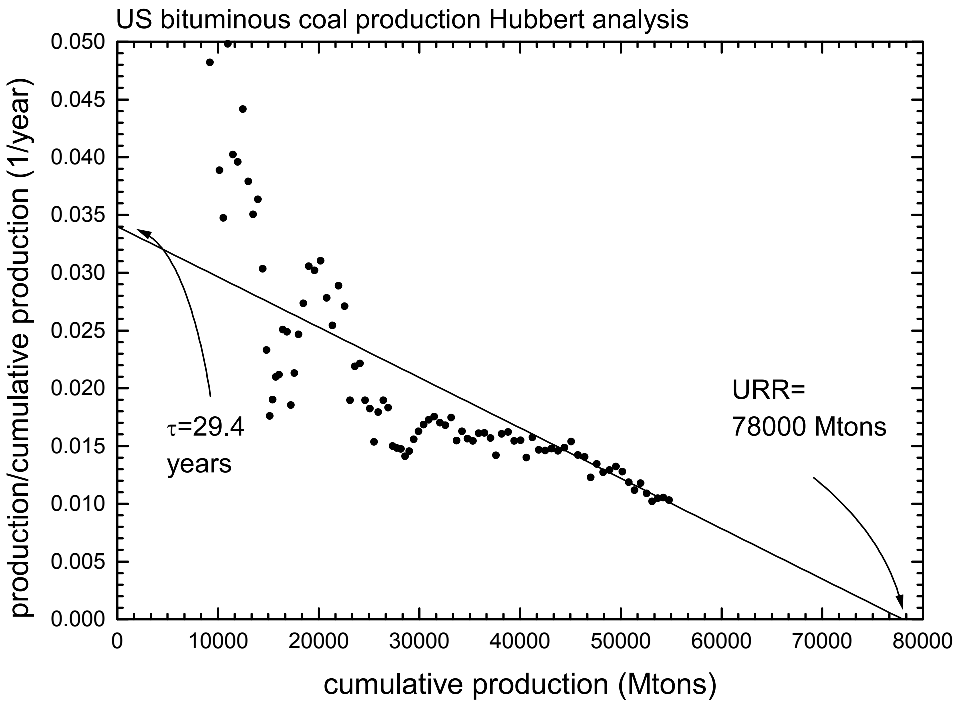

5665/(1+e^(1921-t)/13.5)
US anthracite coal cumulative production (Mtons)
1000
2000
3000
4000
5000
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
year

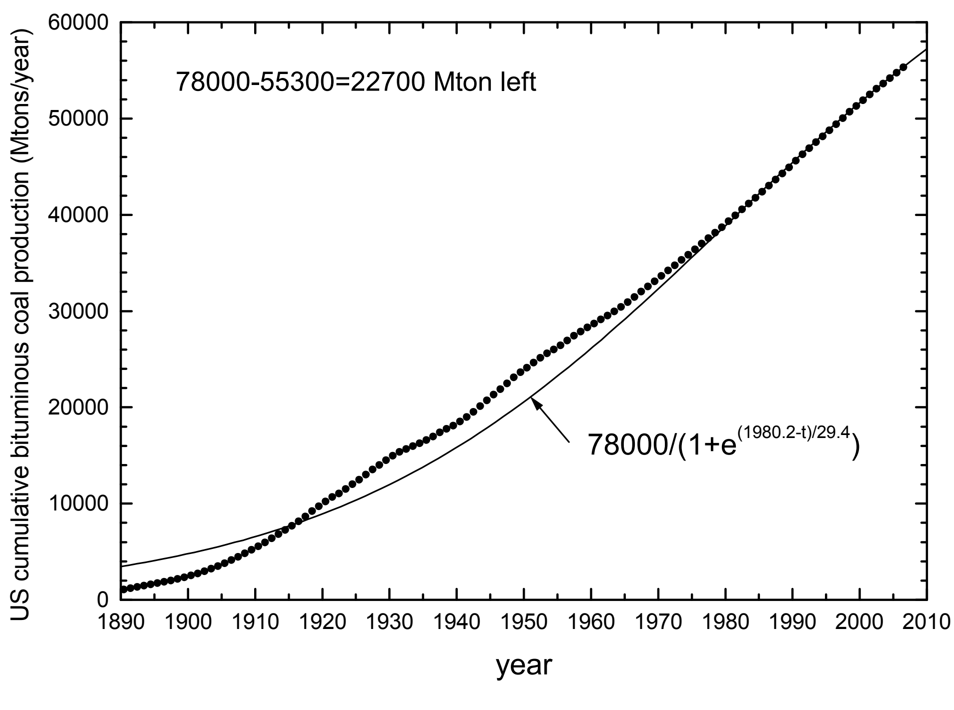


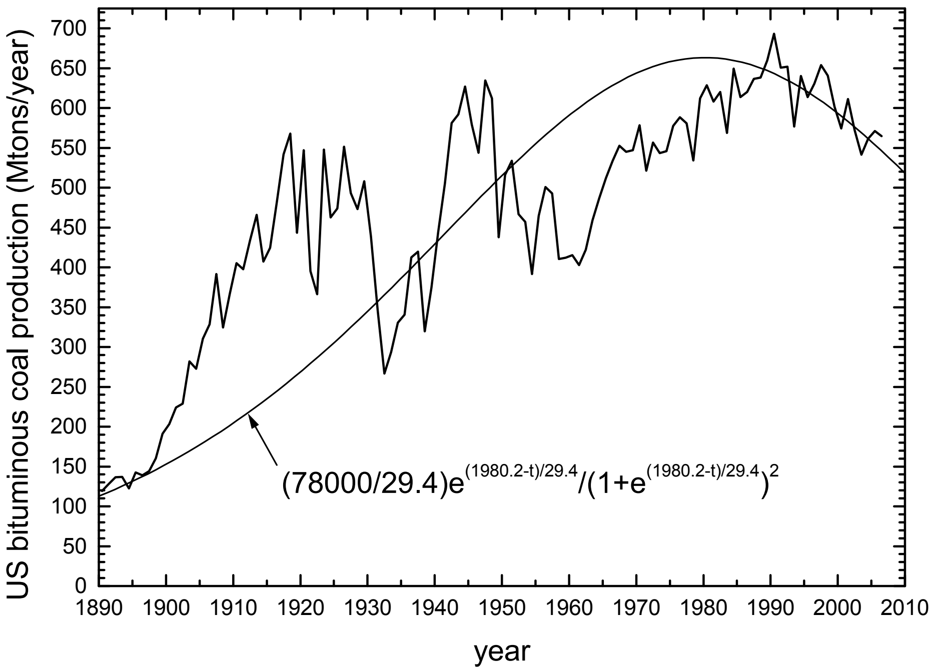
US antracite coal production (million tons/year)
(5665/13.5)e^(1921-t)/13.5/(1+e^(1921-t)/13.5)^2
0
50
100
1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
year


before 1949, US total
-anthracite (Hubbert)
bituminous
sub-bituminous
anthracite
lignite
US coal production (million tons/year)
year

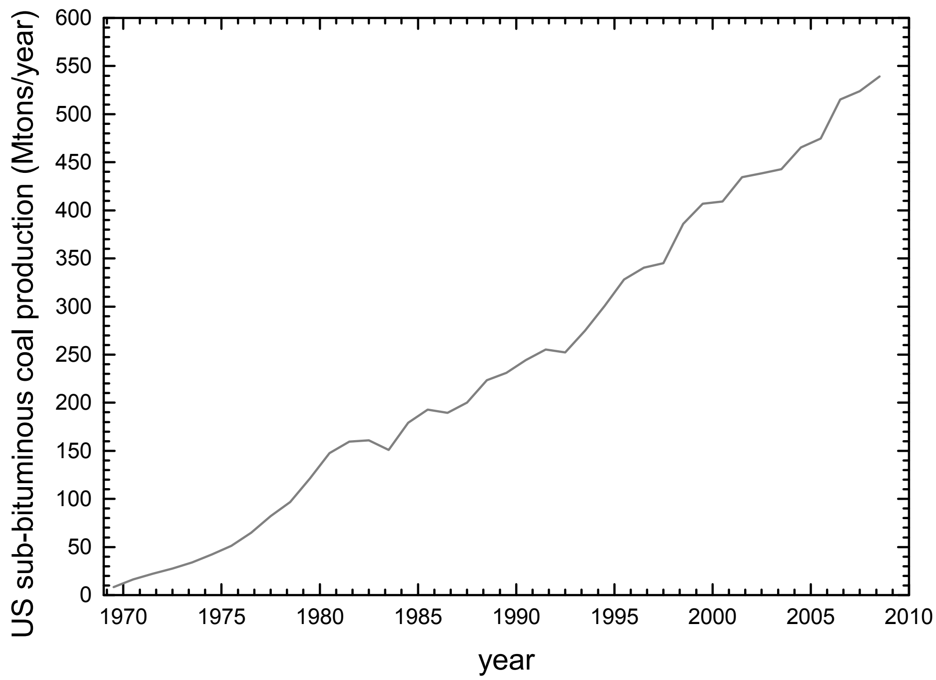

US cumulative bituminous coal production (Mtons/year)
year

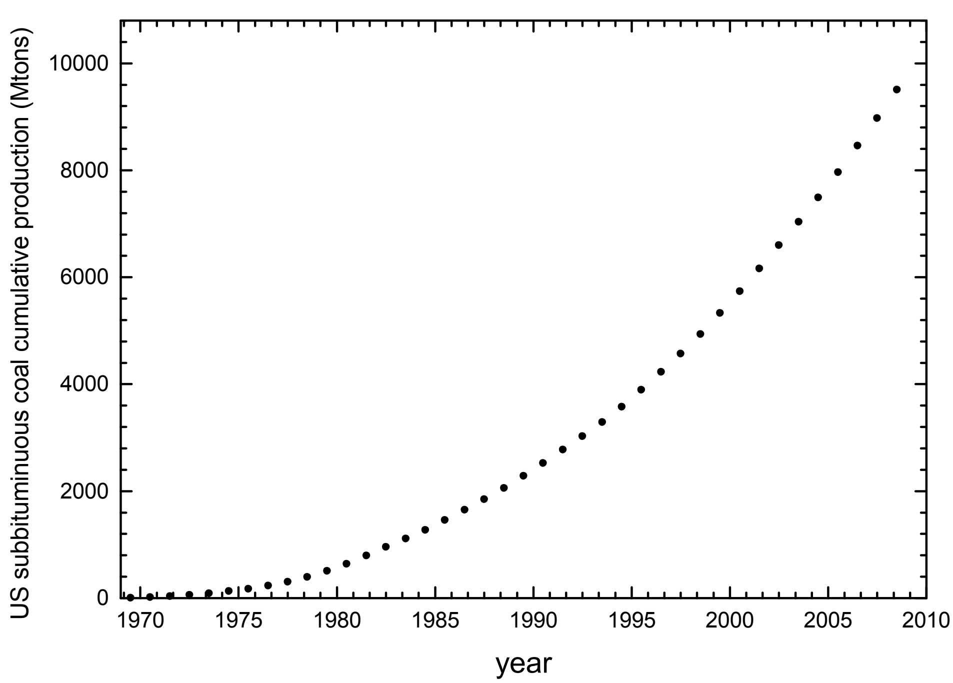

US bituminous coal production Hubbert analysis
production/cumulative production (1/year)
cumulative production (Mtons)
τ=29.4
years
URR=
78000 Mtons
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
0.050
0
10000
20000
30000
40000
50000
60000
70000
80000

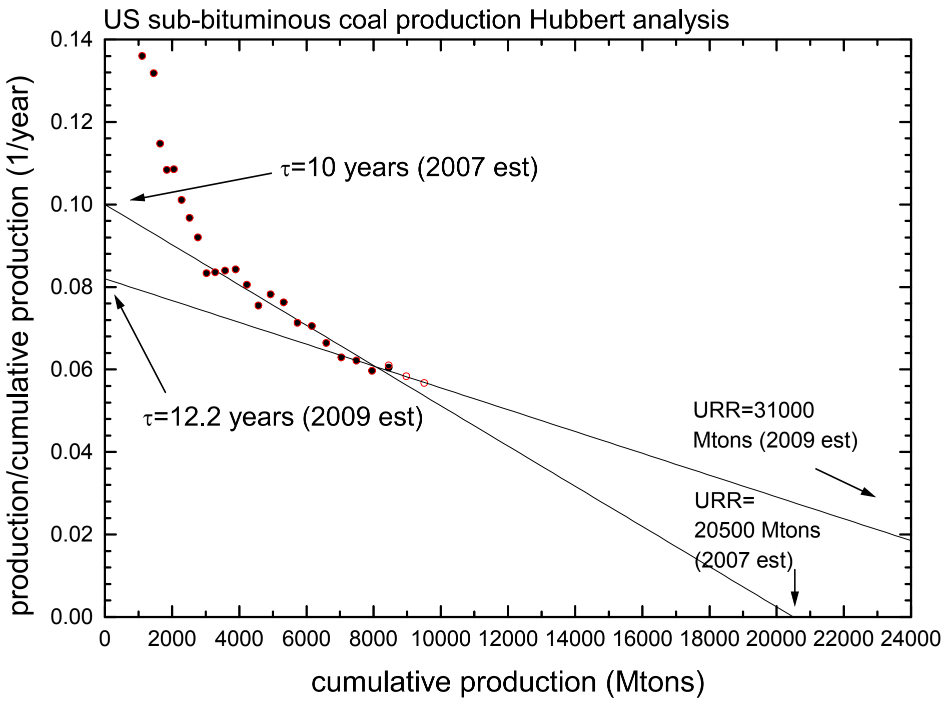

US cumulative bituminous coal production (Mtons/year)
year
78000-55300=22700 Mton left
78000/(1+e^((1980.2-t)/29.4))
0
10000
20000
30000
40000
50000
60000
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010



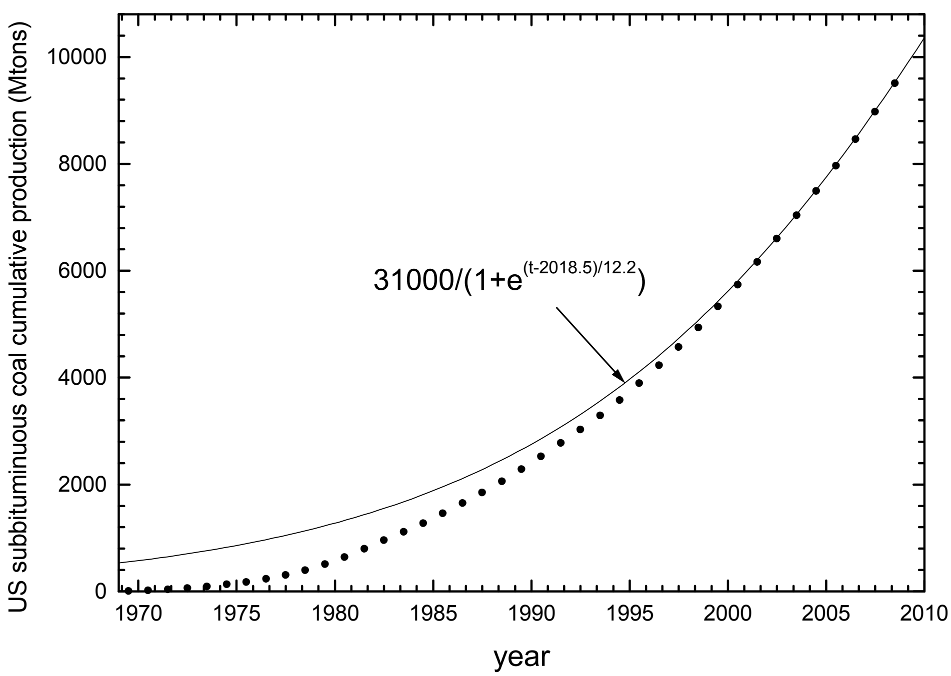
US bituminous coal production (Mtons/year)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
year
(78000/29.4)e^(1980.2-t)/29.4/(1+e^(1980.2-t)/29.4)^2


US sub-bituminous coal production (Mtons/year)
year
0
50
100
150
200
250
300
350
400
450
500
550
600
1970
1975
1980
1985
1990
1995
2000
2005
2010

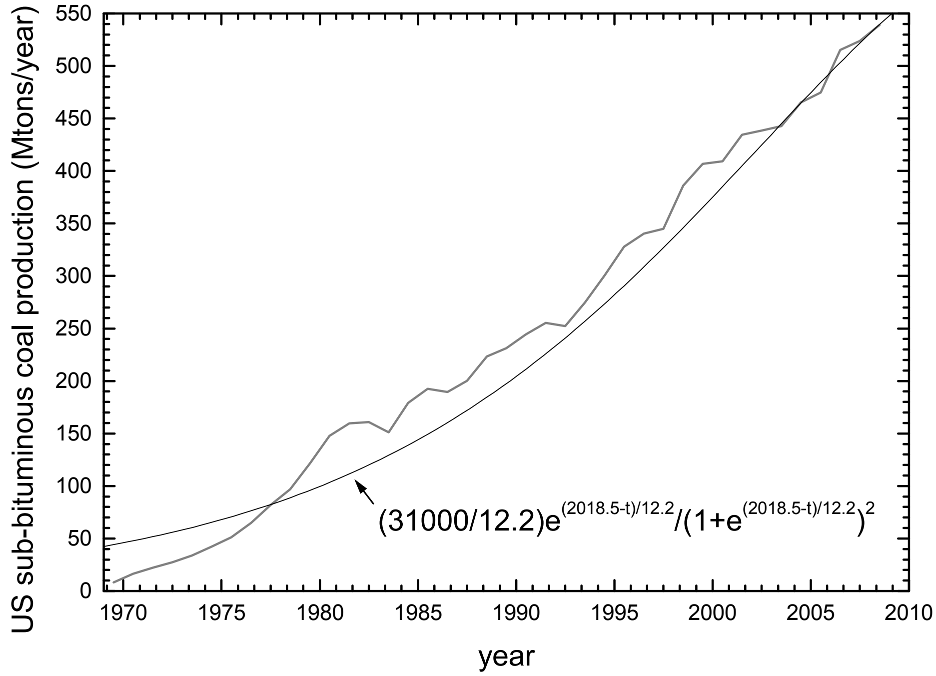

US subbituminous coal cumulative production (Mtons)
year
0
2000
4000
6000
8000
10000
1970
1975
1980
1985
1990
1995
2000
2005
2010

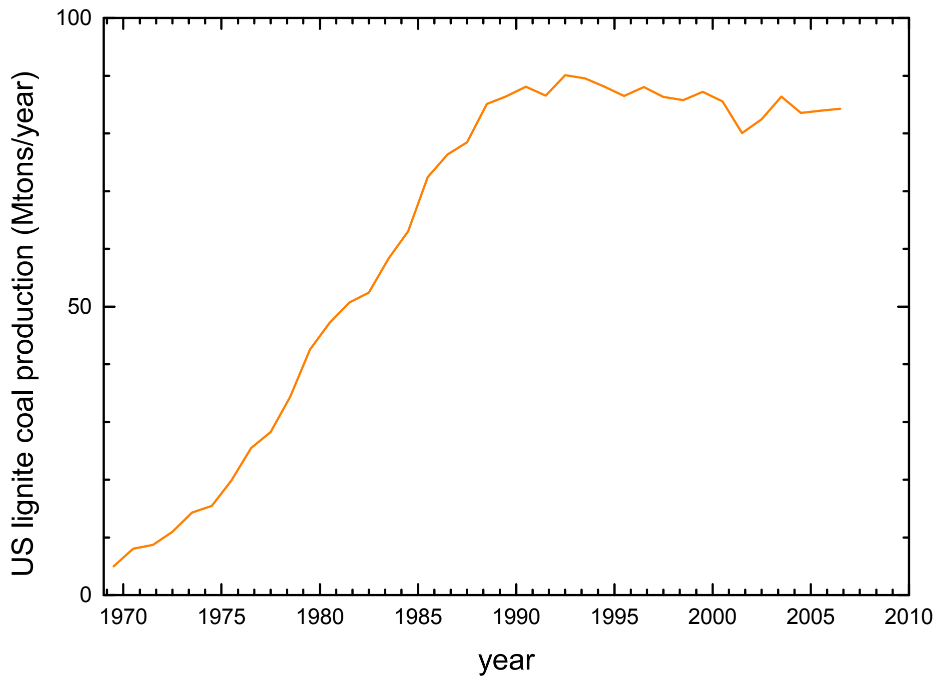


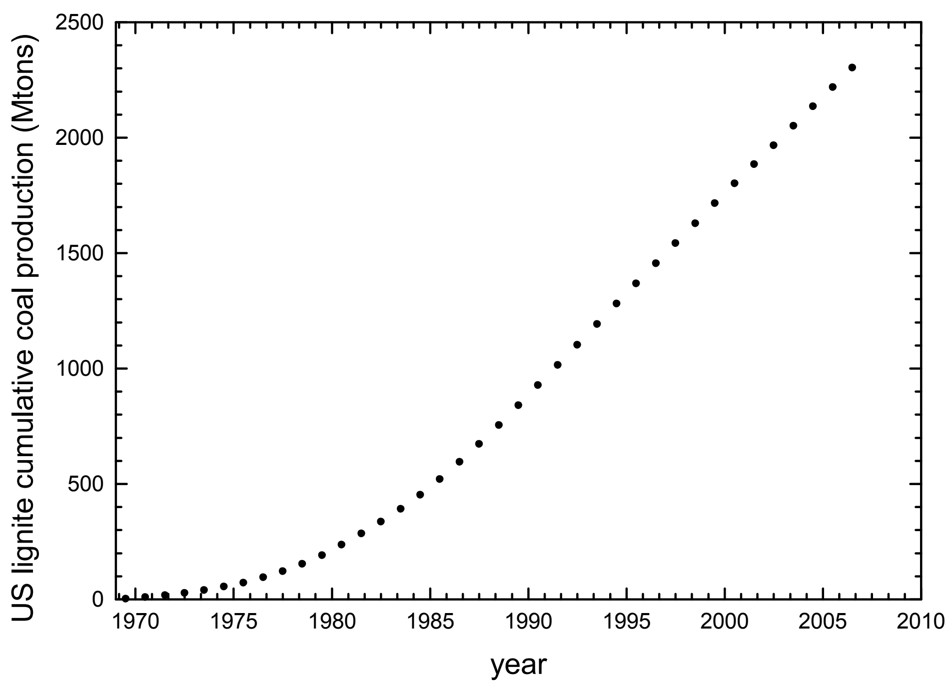
US sub-bituminous coal production Hubbert analysis
production/cumulative production (1/year)
cumulative production (Mtons)
τ=10 years (2007 est)
τ=12.2 years (2009 est)
URR=31000
Mtons (2009 est)
URR=
20500 Mtons
(2007 est)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000 22000 24000

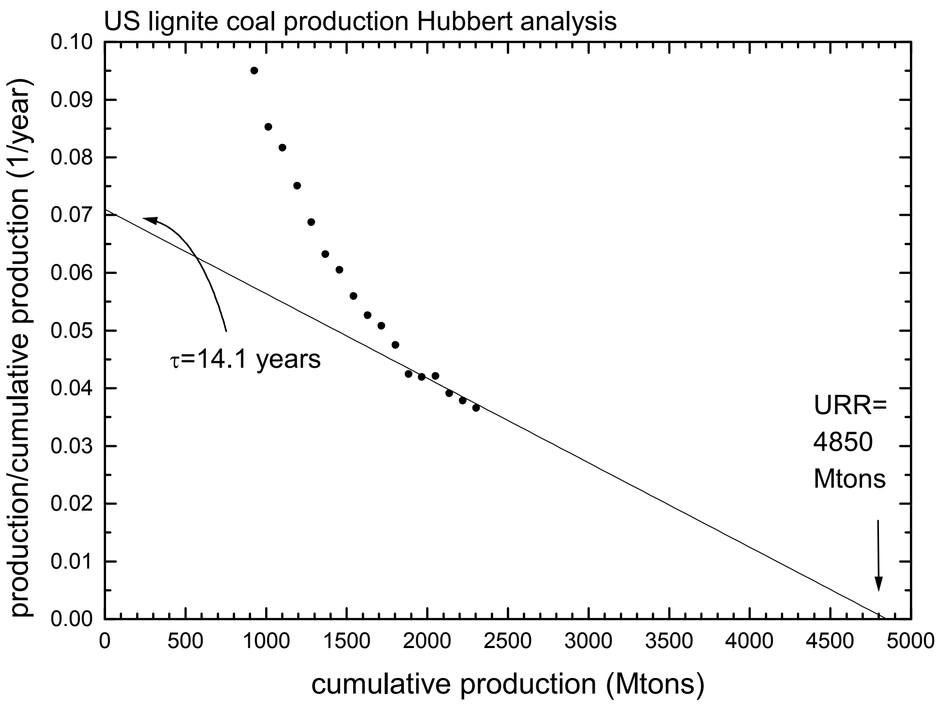


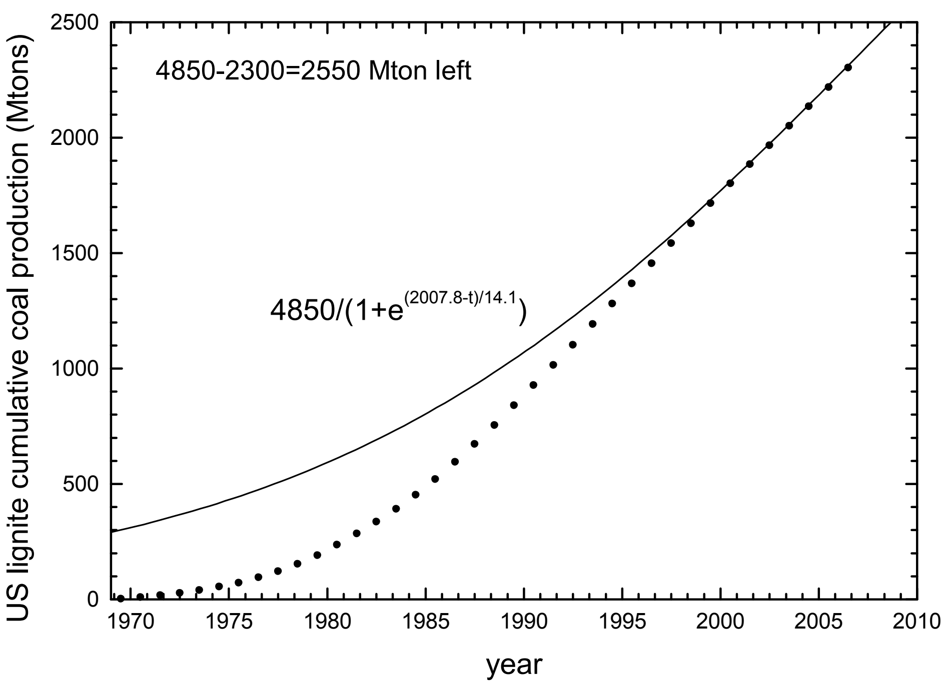
US subbituminous coal cumulative production (Mtons)
year
31000/(1+e^(t-2018.5)/12.2)
10000
8000
6000
4000
2000
0
1970 1975 1980 1985 1990 1995 2000 2005 2010

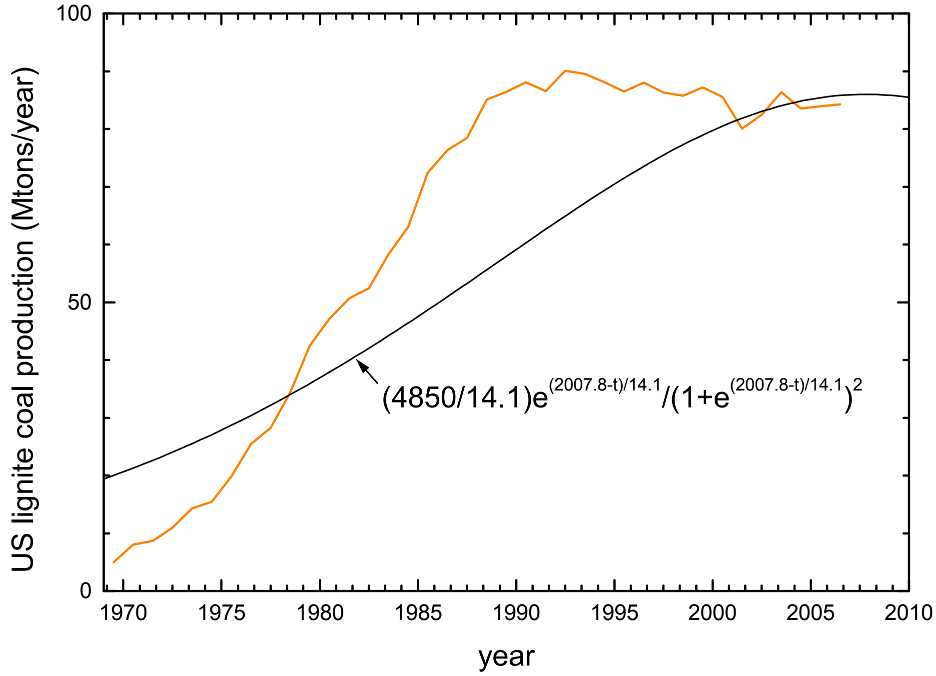

US sub-bituminous coal production (Mtons/year)
year
550
500
450
400
350
300
250
200
150
100
50
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
(31000/12.2)e^(2018.5-t)/12.2/(1+e^(2018.5-t)/12.2)^2


US lignite coal production (Mtons/year)
100
50
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
year


US lignite cumulative coal production (Mtons)
2500
2000
1500
1000
500
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
year

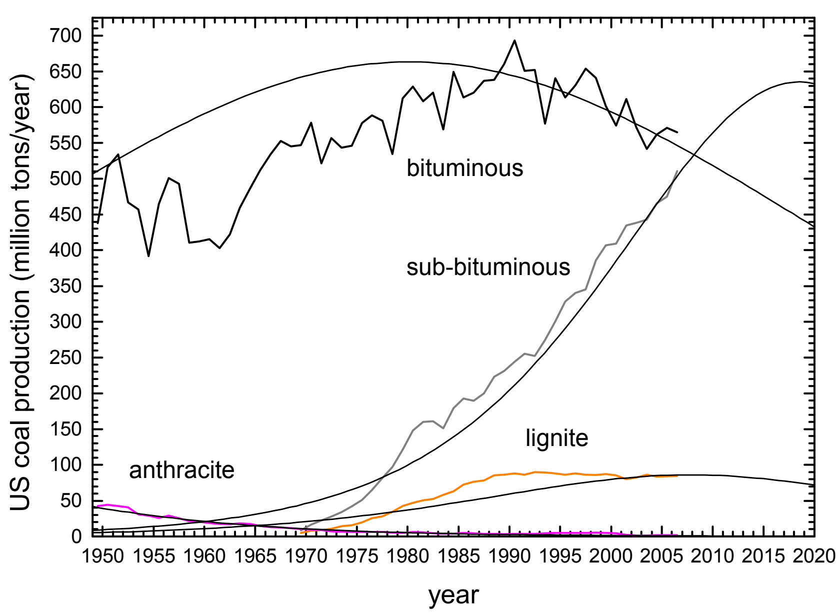

US lignite coal production Hubbert analysis
production/cumulative production (1/year)
cumulative production (Mtons)
τ=14.1 years
URR=
4850
Mtons
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

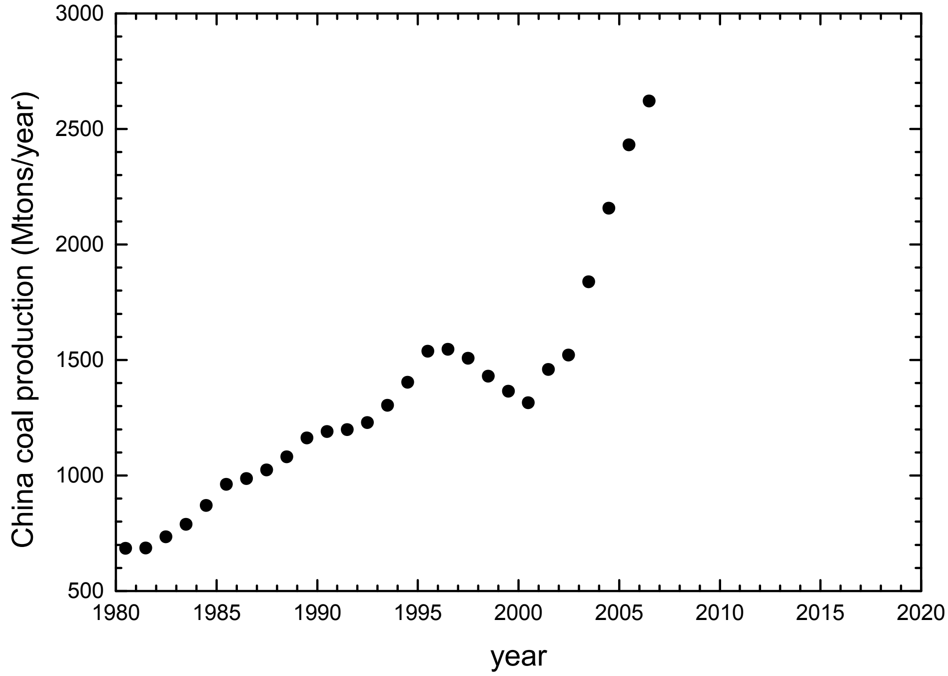

US lignite cumulative coal production (Mtons)
year
4850-2300=2550 Mton left
4850/(1+e(2007.8-t)/14.1)
2500
2000
1500
1000
500
0
1970
1975
1980
1985
1990
1995
2000
2005
2010



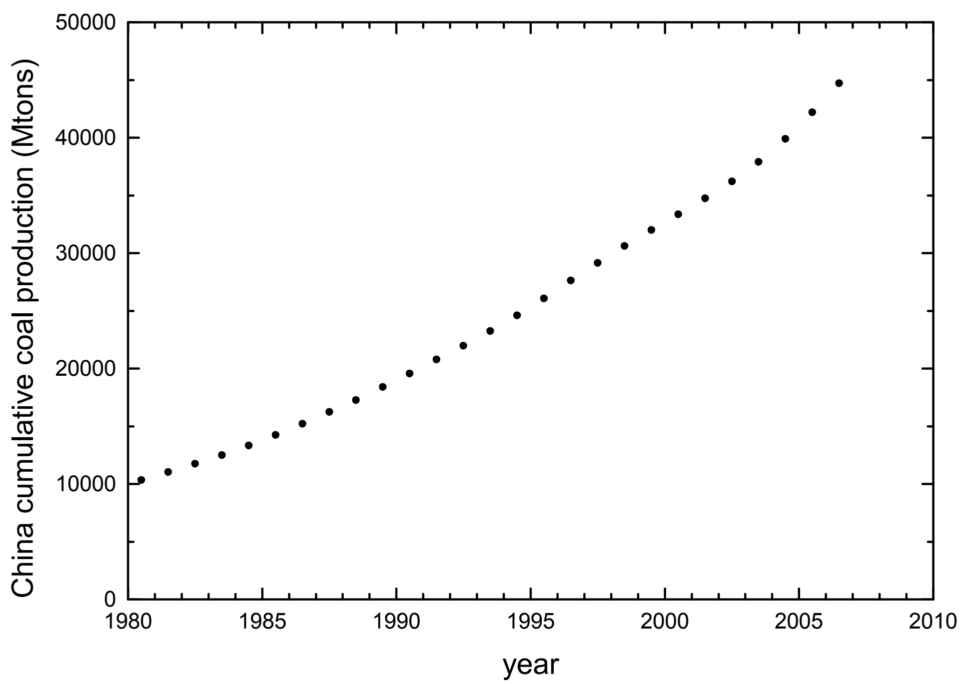
According to Hubbert analysis, US has left (2009 revision)-

21600 Mtons bituminous coal
21500 Mtons subbituminous coal
2400 Mtons lignite coal
~ 0 anthracite coal
45,500 Mtons remaining **US DOE estimate ~ 260,000 Mtons**

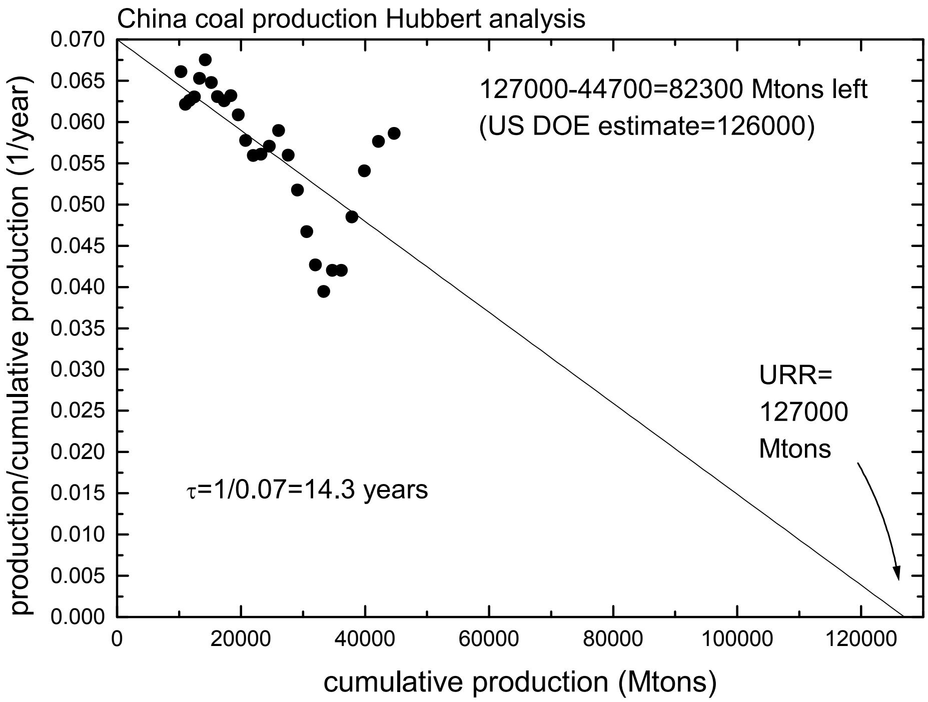




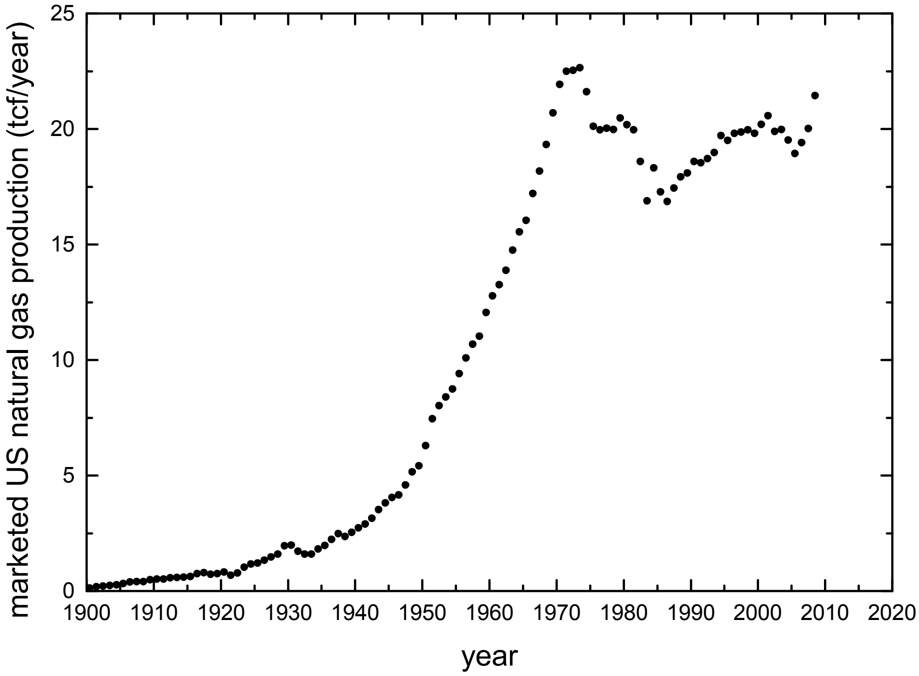
3000
2500
2000
1500
1000
500
China coal production (Mtons/year)
1980
1985
1990
1995
2000
2005
2010
2015
2020
year



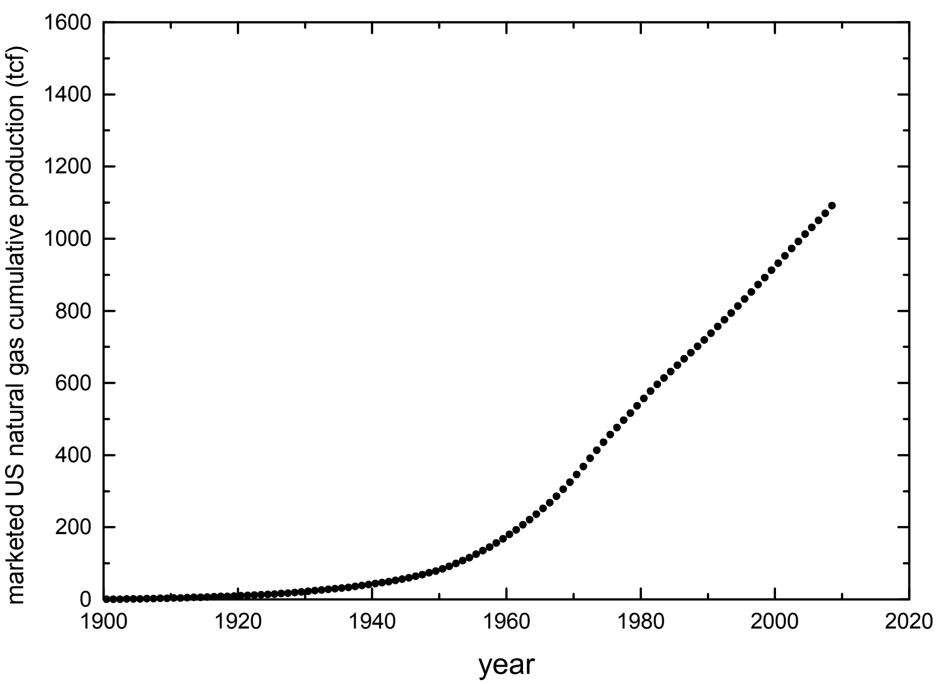
50000
40000
30000
20000
10000
0
China cumulative coal production (Mtons)
1980
1985
1990
1995
2000
2005
2010
year



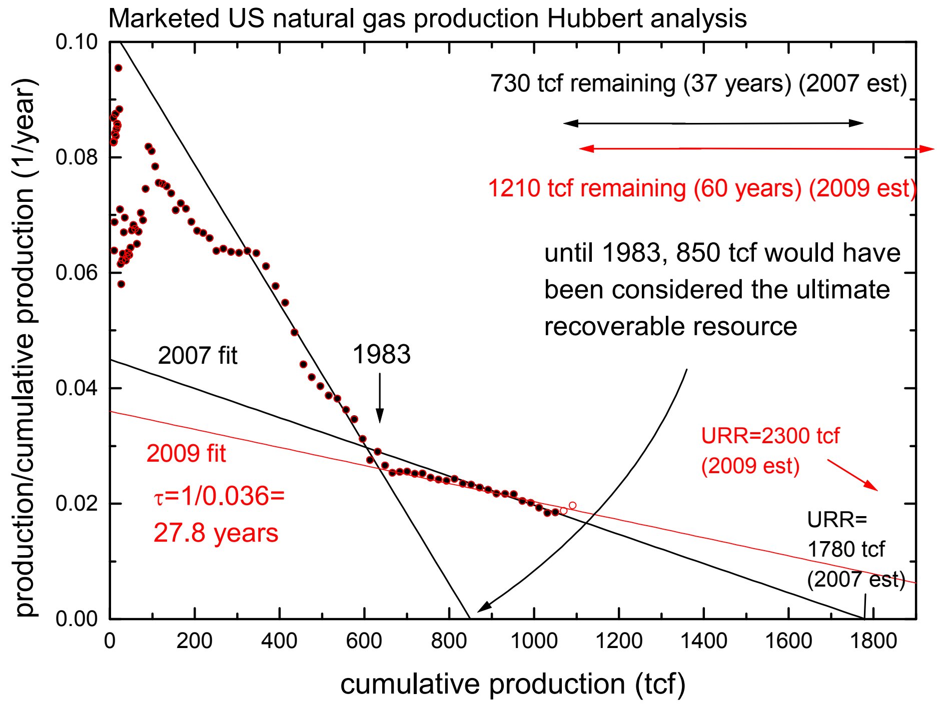
Hubbert analysis yields 82300 Mtons left in China, fairly close to DOE estimate of 126000 Mtons.



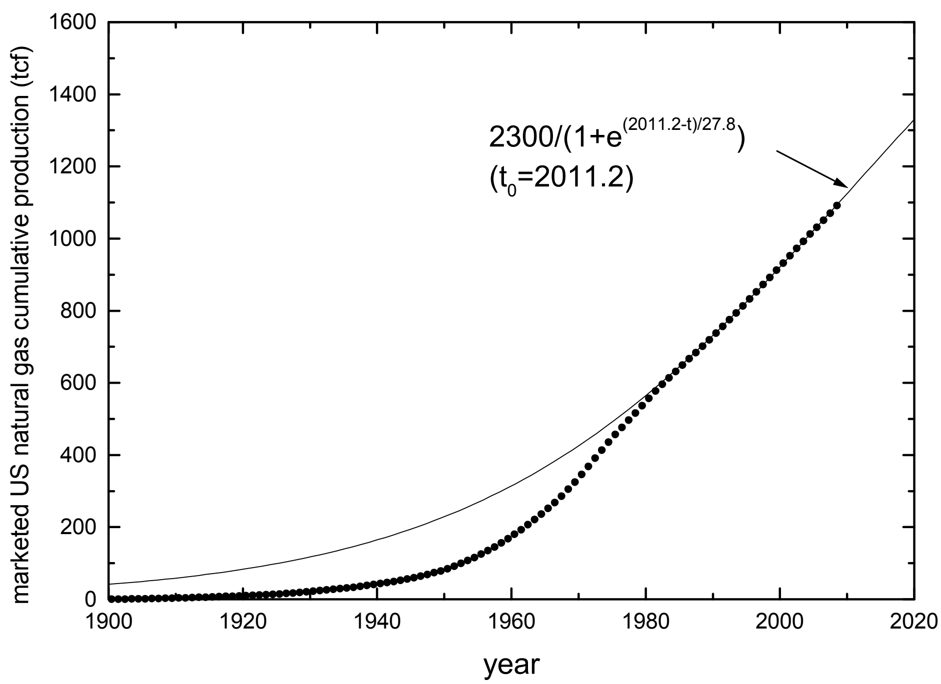
marketed US natural gas production (tcf/year)
25
20
15
10
5
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
year

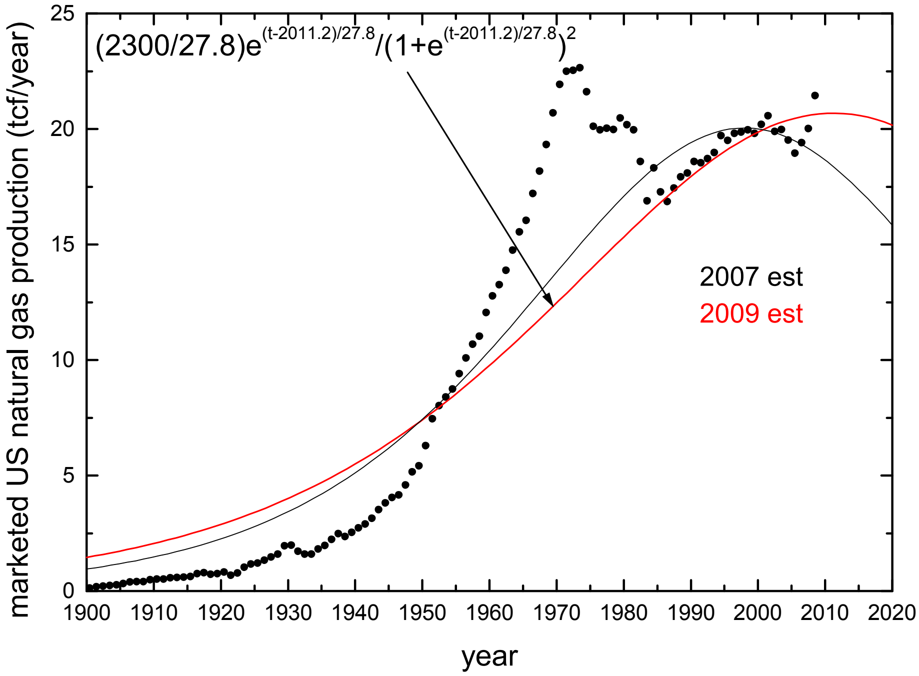


marketed US natural gas cumulative production (tcf)
1600
1400
1200
1000
800
600
400
200
0
1900
1920
1940
1960
1980
2000
2020
year

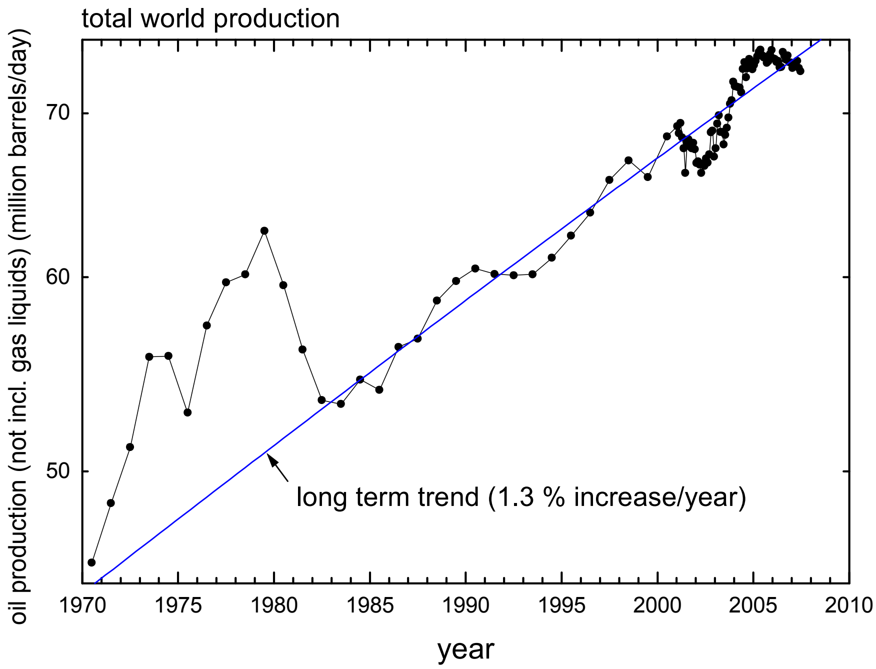


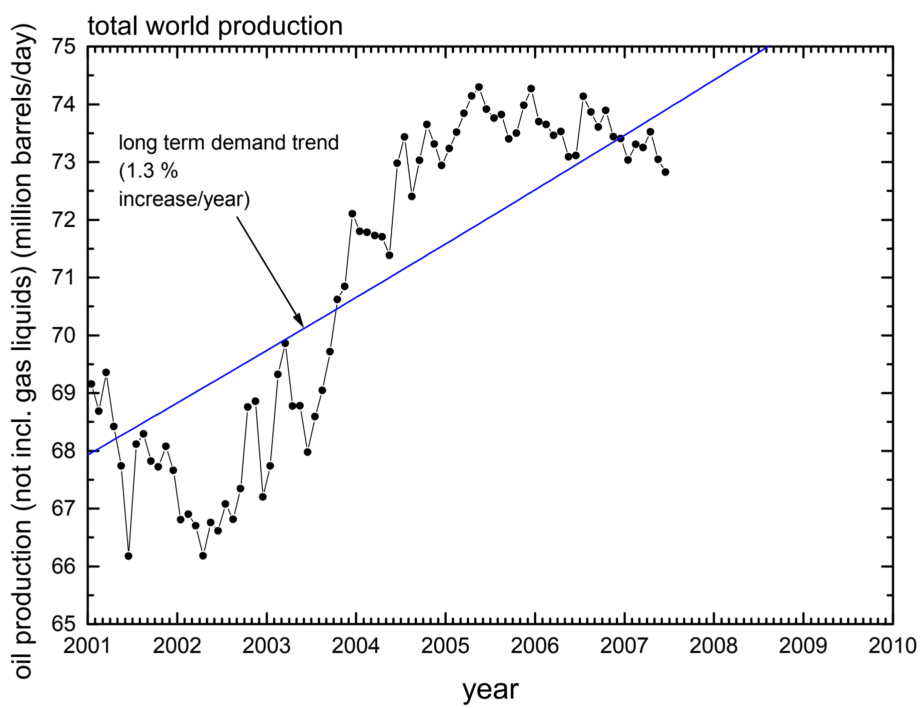
Note that the URR of US natural gas would have been estimated to be 850 Tcf before 1983, and that was <u>incorrect</u>; this shows the way Hubbert analysis can fail, that new production methods can increase the URR.

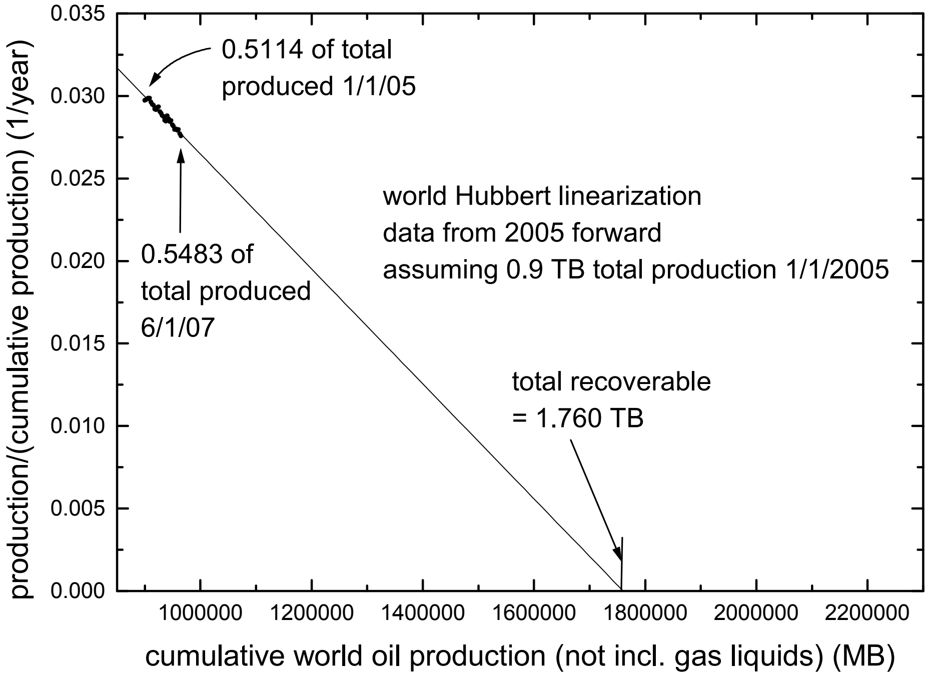


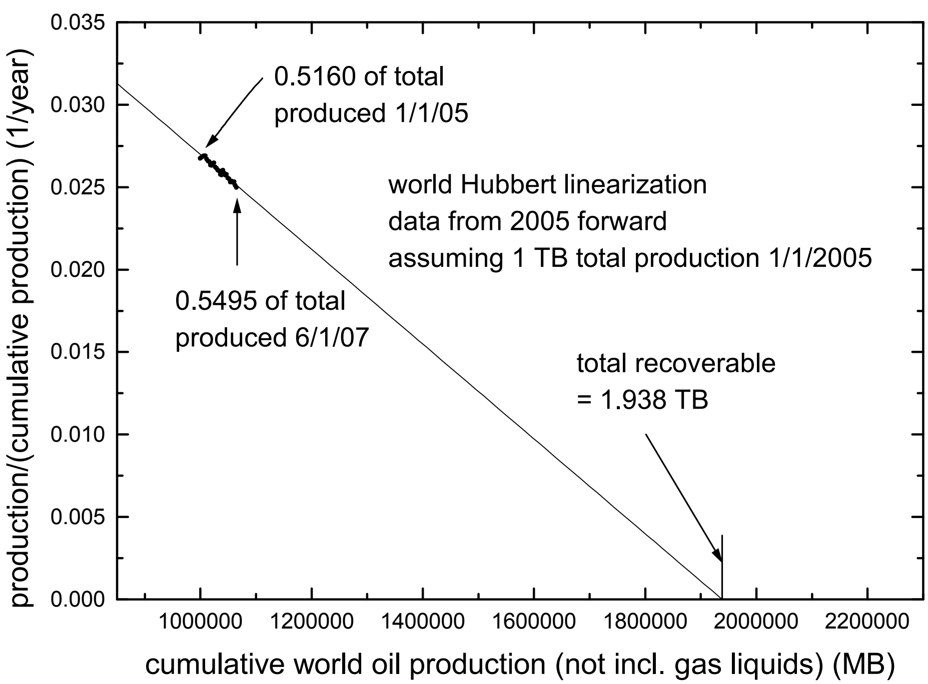


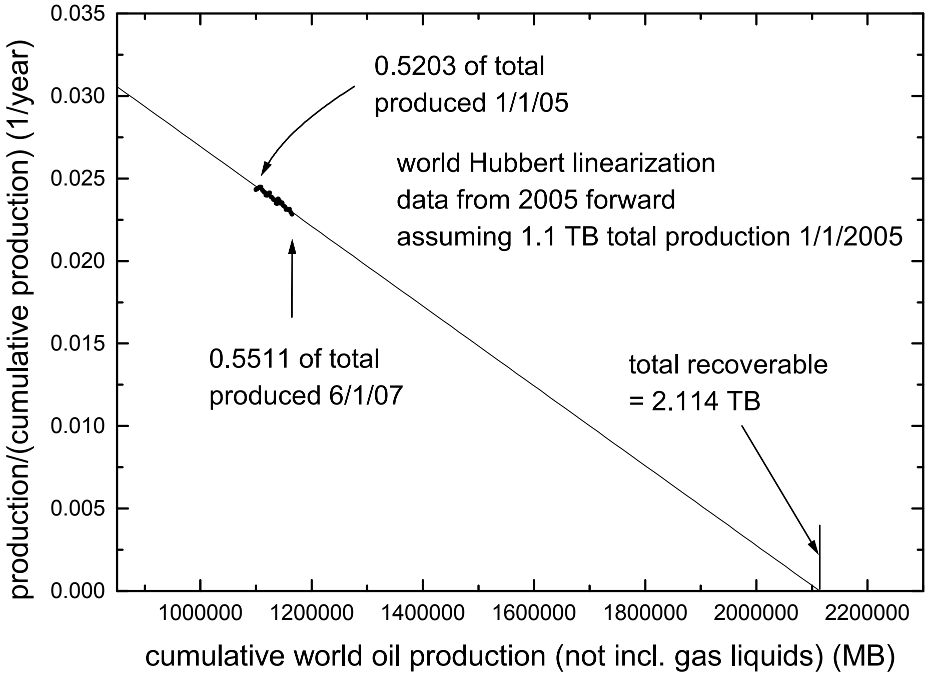
(2300/27.8)e^(t-2011.2)/27.8/(1+e^(t-2011.2)/27.8)^2
2007 est
2009 est
marketed US natural gas production (tcf/year)
year
0
5
10
15
20
25
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020

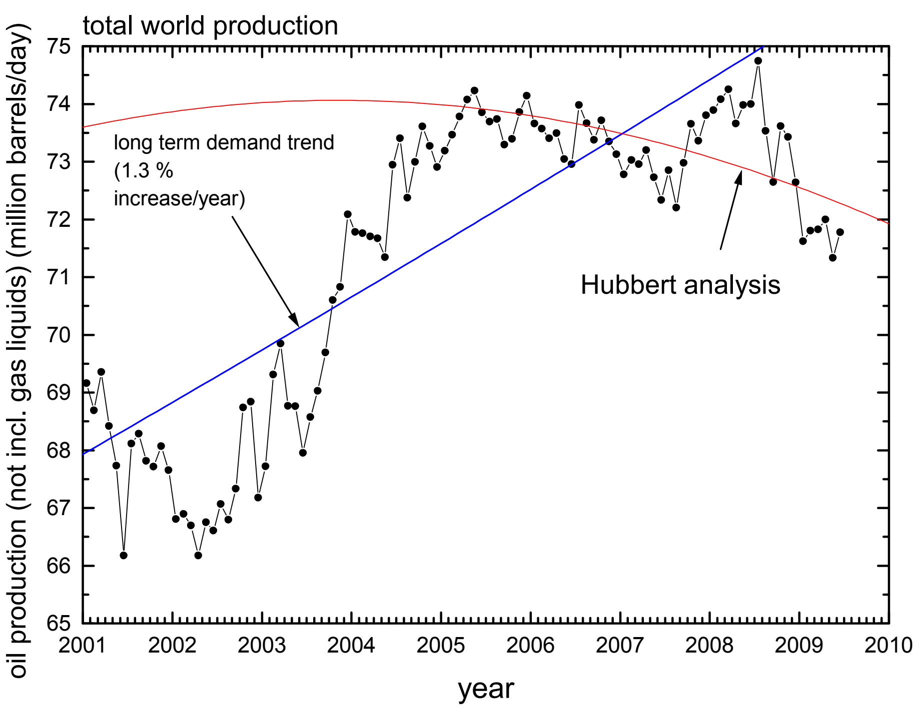

total world production
oil production (not incl. gas liquids) (million barrels/day)
70
60
50
1970
1975
1980
1985
1990
1995
2000
2005
2010
year
long term trend (1.3 % increase/year)


total world production
oil production (not incl. gas liquids) (million barrels/day)
75
74
73
72
71
70
69
68
67
66
65
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
year
long term demand trend
(1.3 %
increase/year)


0.5114 of total
produced 1/1/05
0.5483 of
total produced
6/1/07
world Hubbert linearization
data from 2005 forward
assuming 0.9 TB total production 1/1/2005
total recoverable
= 1.760 TB
production/(cumulative production) (1/year)
cumulative world oil production (not incl. gas liquids) (MB)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
1000000
1200000
1400000
1600000
1800000
2000000
2200000

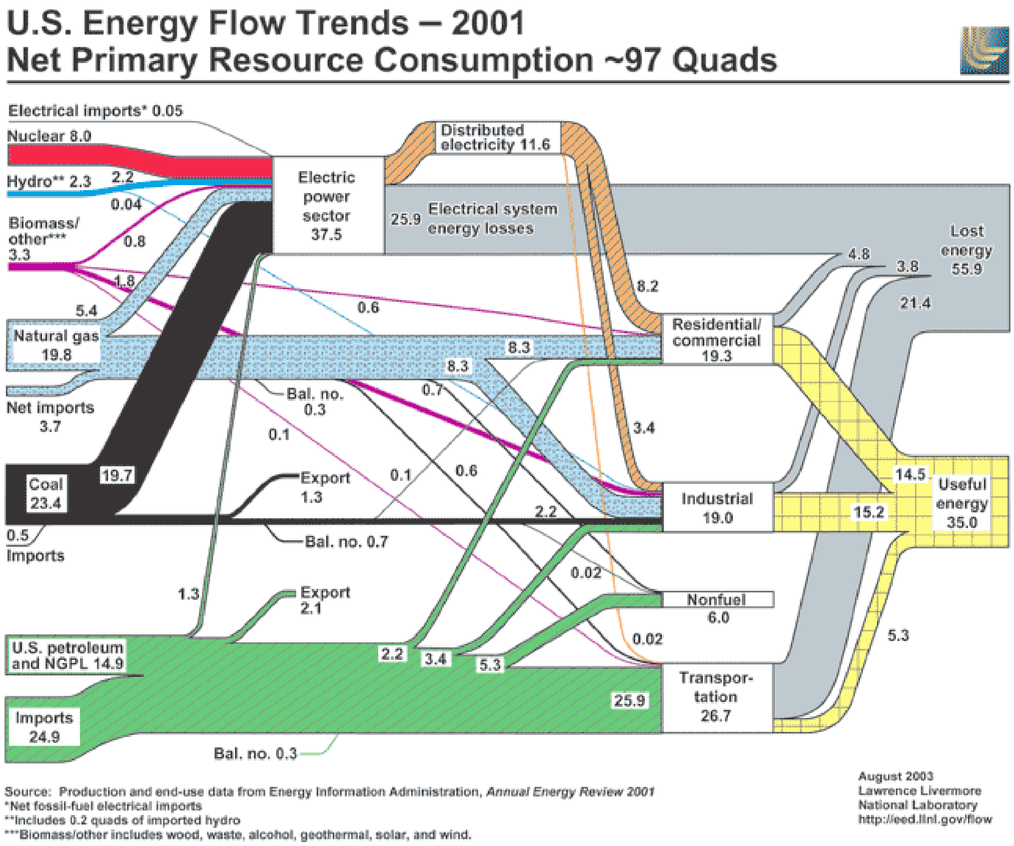

0.5160 of total
produced 1/1/05
0.5495 of total
produced 6/1/07
world Hubbert linearization
data from 2005 forward
assuming 1 TB total production 1/1/2005
total recoverable
= 1.938 TB
production/(cumulative production) (1/year)
cumulative world oil production (not incl. gas liquids) (MB)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
1000000
1200000
1400000
1600000
1800000
2000000
2200000


0.5203 of total
produced 1/1/05
world Hubbert linearization
data from 2005 forward
assuming 1.1 TB total production 1/1/2005
0.5511 of total
produced 6/1/07
total recoverable
= 2.114 TB
production/(cumulative production) (1/year)
cumulative world oil production (not incl. gas liquids) (MB)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
1000000
1200000
1400000
1600000
1800000
2000000
2200000


total world production
long term demand trend
(1.3 %
increase/year)
Hubbert analysis
oil production (not incl. gas liquids) (million barrels/day)
year
75
74
73
72
71
70
69
68
67
66
65
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010

II. Energy sources

Before going on with other energy sources, it should be noted that nuclear, geothermal, and solar sources (the latter including solar panels, wind, and hydroelectric but not biofuels) all mostly are for generating electricity. For example for nuclear, it is used for propulsion of naval vessels, but for energy production for use by society in general, it is all for electric. Wind is of course all for electric, and while solar energy is used for space and water heating, in the later section on solar (not biofuels), only electric production will be considered. That actually leads to some complications in our overall energy chart:



The complication comes from bringing these sources in from the left into the electric power sector box, because while, for example, the quads of coal necessary to be burned to make a quad of electricity makes sense, it does not make sense to discuss the "quads" of wind necessary to make a quad of electricity. So, here and in our final project, we will depart a bit from this chart, and use the following chart:

ELECTRICITY

fuel quads			
		total gen	463.9 GW
		coal	227
		nat. gas	93
		nuclear	90
coal	19.65	hydro	33
nat. gas	8.29	petroleum	5.2
petroleum	0.49	wood	4.2
wood	0.42	biomass	1.9
biomass	0.19	geothermal	1.6
		wind	7.9
		solar	0.1
		other	0

total distrib 417.51 GW

RESIDENTIAL/COMMERCIAL

electric	304.65 GW
total fuel	11.2
fuel wood	0.6
fuel nat. gas	8.3
fuel coal	0.1
fuel petro.	2.2
"fuel" solar (solar heating)	0

INDUSTRIAL

electric	112.2 GW
total fuel	15.7
fuel bio.	1.8
fuel nat. gas	8.3
fuel coal	2.2
fuel petro.	3.4

FUELS

BIO/WOOD	5.15
NAT. GAS	25.62
COAL	21.95
PETRO.	37.29

note: does not include exports
note: bio is biomass not biofuel, conv. at trans.

units in quads except where GW stated

NONFUEL

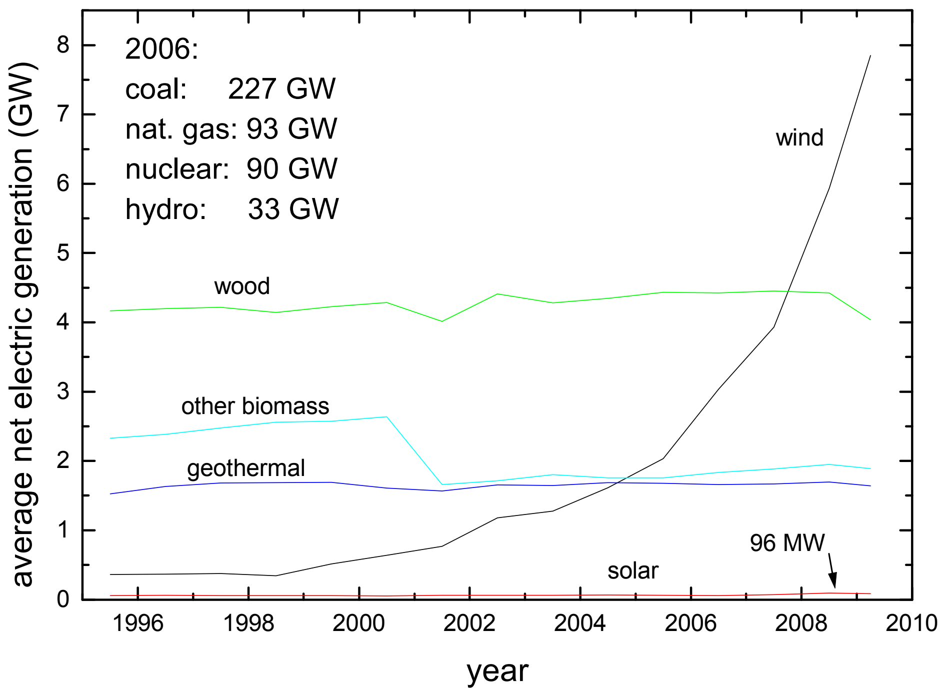
total	6
natural gas	0.7
petroleum	5.3

TRANSPORTATION

	total equiv. petro.	26.94
	elec. (0.66 GW)	0.11 eq. 0.02 act.
	natural gas	0.03
biomass input 2.14	biofuel	0.9
	petroleum	25.9

Here, shown for 2009, are the fuel inputs, final use numbers in the residential/commercial, industrial, nonfuel, and transportation sectors, but for the electricity section only generation is shown. That is, for 2009, 463.9 gigawatts total of electricity was generated. Note using our conversion of 1 quad/year equaling 33 gigawatts, that 463.9 gigawatts equates to 14.06 quads of electricity generated in the year 2009. Note this is before distribution through the wires and transformers to the end uses. In the chart, we assume that the wires and transformers result in 10 % loss, resulting in distributed electricity of 417.51 gigawatts (12.65 quads in 2009). This corresponds to the 11.6 quad value in the original chart for 2001.

The electricity generation values are found at http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html, and can be plotted vs. time:



One sees that all sources except for wind, which has been rising rapidly, are relatively stagnant. One also sees that of alternate energy sources, wind has greatly exceeded solar electric generation.

2. Nuclear energy mined from the earth (uranium).

What is it:

Controlled nuclear energy is the generation of intense heat (which can be used to power a steam generator) from a nuclear chain reaction that has been "slowed down" so that the reaction does not runaway as in a bomb, but rather proceeds at a steady pace. Recall that in a nuclear chain reaction,

$$n + U_{235} \rightarrow U_{236}(unstable) \rightarrow Kr_{92} + Ba_{141} + 3n \qquad \text{(II.2.1)}$$

the release of the neutrons from the reactions can initiate further reactions (fissions), and so on, so that the mass explodes. For this explosion to occur a critical mass of U_{235} must be present, or else the neutrons will escape the mass before causing further reactions. If we start to put together more and more U_{235}, there will be a moment when we reach the so called *critical mass* and a self sustaining reaction starts. That is the moment when one reaction causes more than one more. For example, for pure U_{235} the critical mass is about 50 kg. Because of the very high density (19.2 g/cm3) this amount of uranium makes a sphere whose diameter is about 17 cm. The number of reactions induced by a reaction is called the multiplication factor. If the multiplication factor is less than one, that is, for example, if you are holding an amount of U_{235} less than critical mass:

A subcritical mass of U_{235}.

the reaction process quickly dies down and nothing much happens. If you quickly and precisely bring two sub-critical masses together so that they form higher than a critical mass (what happens in a bomb) you get a multiplication factor greater than one and it explodes. In a nuclear reactor, we wish to keep the multiplication factor exactly equal to one, so that the reaction process is sustaining but not growing. This is done by introducing *control rods* into the mass, which absorb neutrons. Control rods are typically made of metal like silver, and the multiplication factor can be adjusted to be unity by the depth of insertion of the rods into the uranium.

Obtaining pure U_{235} is expensive, as naturally mined uranium is 99.25 % U_{238} and only 0.72 % U_{235}. The process of *enriching* uranium, that is, obtaining greater concentrations of U_{235}, can be done by for example by centrifuges which spin gaseous uranium causing the heavier U_{238} to move toward the outside of the centrifuge where it can be discharged, building up the concentration of U_{235} in the centrifuge until the desired enrichment is obtained.

If one enriches uranium partially, a critical mass can be obtained, albeit it is much larger as the density of the U_{235} is lower. In effect, one can think of the U_{235} in the uranium as the "fuel", while the U_{238} is "sort of" inert. (This is not really the case, see below). To make a bomb, uranium is enriched to ~ 90 % U_{235}, while for a reactor, 3-4 % is sufficient.

U_{238} does not undergo a fission reaction, but if slow or *thermal* neutrons are present, a U_{238} nucleus will absorb one to produce plutonium, which is fissile:

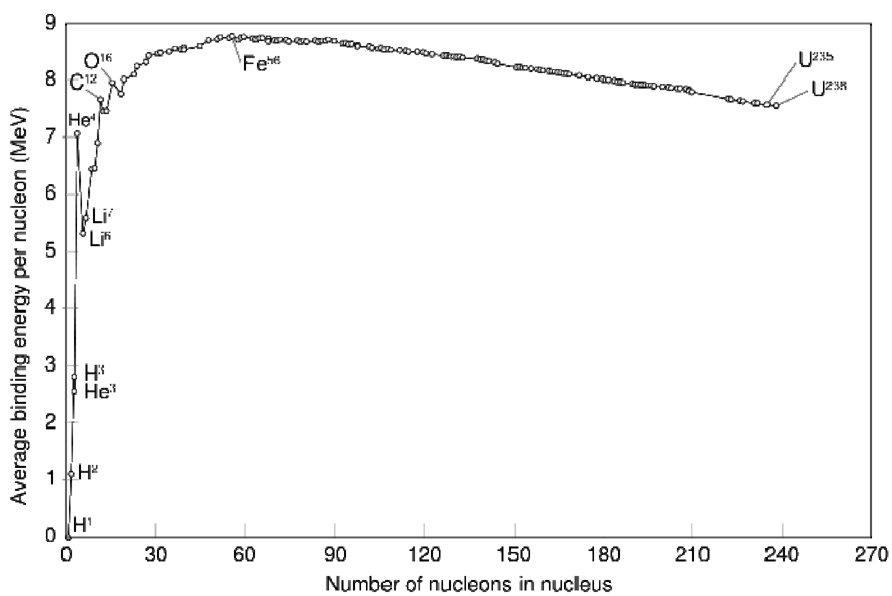
$$
\begin{aligned}
&n + U_{238} \rightarrow U_{239} \rightarrow Pu_{239} + 2e^{-} \\
&Pu_{239} \rightarrow Kr_{92} + Ce_{144} + 3n
\end{aligned}
\qquad \text{(II.2.2)}
$$

So, the U_{238} is not really inert, but can contribute to the energy generation through the step of first becoming plutonium. In a nuclear reactor, about 1/3 of the energy is produced from these plutonium fission reactions.

Uranium is typically not placed in the reactor in metallic form, as it would melt under the high temperatures. Rather, either uranium oxide, or a ceramic formed from uranium, is used. It is formed into pellets and rods are filled with them to create the nuclear *fuel rods* which are put together with the control rods to form the *core* of the reactor.

Since U_{238} requires a slow or thermal neutron to react, and even for U_{235} the probability of fission goes up if the neutron is slow, usually a *moderator* is present which is a material that slows down the neutrons without absorbing them. Typically, this is simply water. *(Light) water reactors* basically fill the spaces in the core with water as a moderator. These reactors are inherently safe, as if the temperature rises, the density of the water decreases, so that less moderation occurs (as the spaces between the water nuclei are larger) and the reaction slows down. Thus there is an inherent negative feedback that stabilizes the reaction rate.

The fuel rods typically spend about 3 years in a reactor, after which about 3 % of their uranium has underwent fission, and insufficient U_{235} remains to have a sustaining reaction. Going back to our chart of nuclear binding energy,



we see that upon fission the products of the reaction (with 90-150 nucleons) have about 8.4 MeV binding energy, compared to the uranium, which has about 7.7 MeV binding energy. Thus upon a fission reaction, about 0.7 MeV or 10^{-13} joules per nucleon is released. Thus if we divide this by c^2 (from $E = mc^2$) we obtain the mass per nucleon converted into energy. Then if we divide by the mass of a nucleon (1.66E-27 kg), we obtain the fraction of mass converted into energy:

$$\frac{m_{convertedtoenergy}}{m_{uranium}} \cong \frac{10^{-13}/(3x10^8)^2}{1.66x10^{-27}} = 7x10^{-4} \quad . \qquad \text{(II.2.3)}$$

Thus if 3 % of the uranium has underwent fission, (0.03)(0.0007) = 0.00002 of the mass of the fuel rod has converted into energy. Since to enrich the uranium requires going from ~ 0.7 % to ~ 3.5 % U_{235}, we require 5 times as much natural uranium to create uranium fuel.

Thus of the natural uranium, on an overall basis, (0.00002)/5 = 0.000004 of it has converted into energy. Therefore, the amount of energy in a kilogram of natural uranium (not oxide) is

$$E_{uranium} = 0.000002c^2 = 4x10^{11}\ \frac{\text{joules}}{\text{kilogram}} = 400,000,000\ \frac{\text{BTU}}{\text{kilogram}}. \quad \text{(II.2.4)}$$

Recall oil had about 40,000 BTU/kilogram, so uranium contains 10,000 times more energy.

The spent fuel rods still contain various radioactive products including plutonium, and basically have to be put somewhere for the rest of human history. That's a problem. But, no carbon dioxide is released in nuclear reactions!

Recall that uranium was produced in the supernova of the star from which our solar system was formed. One can estimate the amount of uranium in the Earth's crust per our earlier calculation concerning geothermal energy, by using the measurement of 0.008 parts per million in meteorites. Then, we found that there should be ~ $6x10^{16}$ kilograms of uranium in the earth. If this uranium is distributed evenly in the earth, and we can mine to a depth of *z*, the fraction of uranium accessible to us is based upon the fractional volume of the earth we can mine, or

$$f = \frac{4\pi R^2 z}{(4/3)\pi R^3} = \frac{3z}{R}. \quad \text{(II.2.5)}$$

If we can mine to a 1/3 kilometer (?), and the Earth's radius is 6400 kilometers, then the amount of uranium that can be mined is

$$m_{\text{minable}} = f m_{earth} = \frac{6x10^{16}}{6400} \sim 10^{13}\ \text{kilograms.} \quad \text{(II.2.6)}$$

(Note as an aside that production of uranium ore [U_3O_8] is running about 100 million pounds [45 million kilograms] per year. Subtracting the oxygen in the ore, this is 45[3x238]/[3x238 + 8x16] = 38 million kilograms of uranium. Thus based upon the estimate above there is a 260,000 year supply, if we can get at all of it within a third of a kilometer of the Earth's surface.) Based upon this, within a third of a kilometer of the Earth's surface there is uranium energy equal to

$$E_{uranium,accessible} = 4x10^8(10^{13}) = 4x10^{21}\ \text{BTU} = 4{,}000{,}000\ \text{quads,} \quad \text{(II.2.7)}$$

or, enough to power the US for 40,000 years.

This estimate is not usually employed, as uranium is difficult to mine since it is not concentrated typically in geological formations as for oil, coal, or natural gas, but is spread out throughout the Earth. Thus vast quantities of earth, typically using open-pit or strip mining, followed by extensive filtering, must be employed.

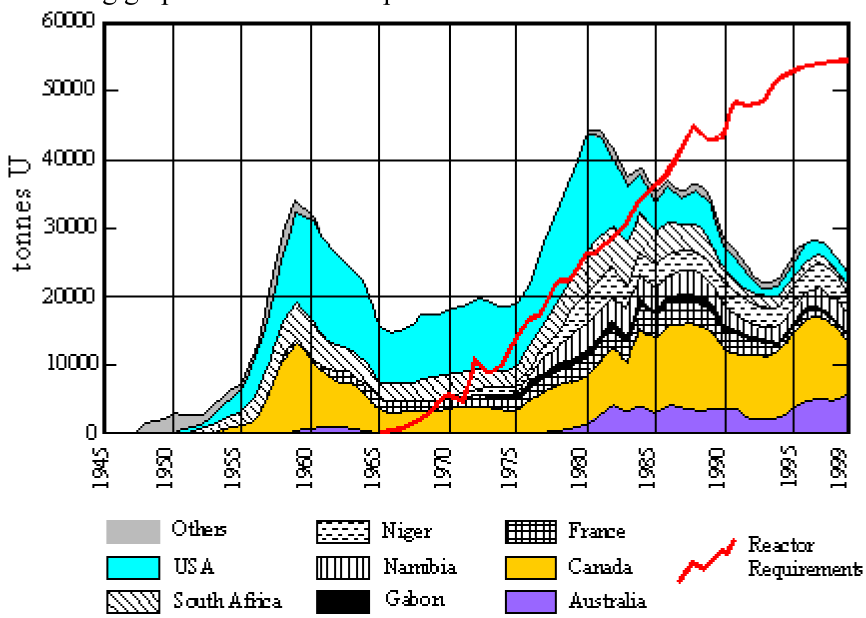
As estimated ~ 5 trillion kilograms of uranium are estimated to be present in the world's seawater, but no economical way of separating it has been found.

The supply of uranium can be extended through the use of *breeder reactors*, in which U_{238} is irradiated with neutrons to produce plutonium per the above reaction. Pu_{239} is a better fissile material than U_{235}, requiring only 10 kilograms for a critical mass, vs. 52

for U_{235}. For that reason it is also easier to make a bomb with plutonium, which has caused the international community to ban breeder reactors (?).

Where is uranium found:

As stated, uranium does not tend to be concentrated in particular locations. The following graph shows uranium production in various countries vs. time:



It can be seen that the US dominated uranium production until the 1980's. Then, due to the decline of the nuclear power industry as a result of safety concerns (per the accident at the Three Mile Island reactor primarily), the price of uranium dropped considerably and US mining declined. It continued strongly in Canada and various African countries, and Australia has become a major producer.

Note the red line on the above graph is basically the uranium consumed. The difference has been made up by the dismantling of US and Russian nuclear weapons following the end of the Cold War.

Here is the uranium consumption by country:

Table 1 Uranium demand, mining production and deficit in tonnes

Country	Uranium required 2005 (WNA)(1)	% of world demand	Indigenous mining production 2004 (UxC)(2)	Deficit
USA	22,397	33	835	21,562
France	10,431	15	0	10,431
Japan	8,184	12	0	8,184
Germany	3,708	5	77	3,631
Russia	3,409	5	454	2,955
South Korea	3,011	4	0	3,011
UK	2,409	3	0	2,409
Rest of world	14,808	22	37,934	-23,126
Total	68,357	100	39,300	29,057

France dominates on a per capita basis per attempts to generate most of its electricity through nuclear power. Note that since the energy content of uranium per unit weight is so high, it is perfectly economical to ship and export it across the globe.

How is uranium used:

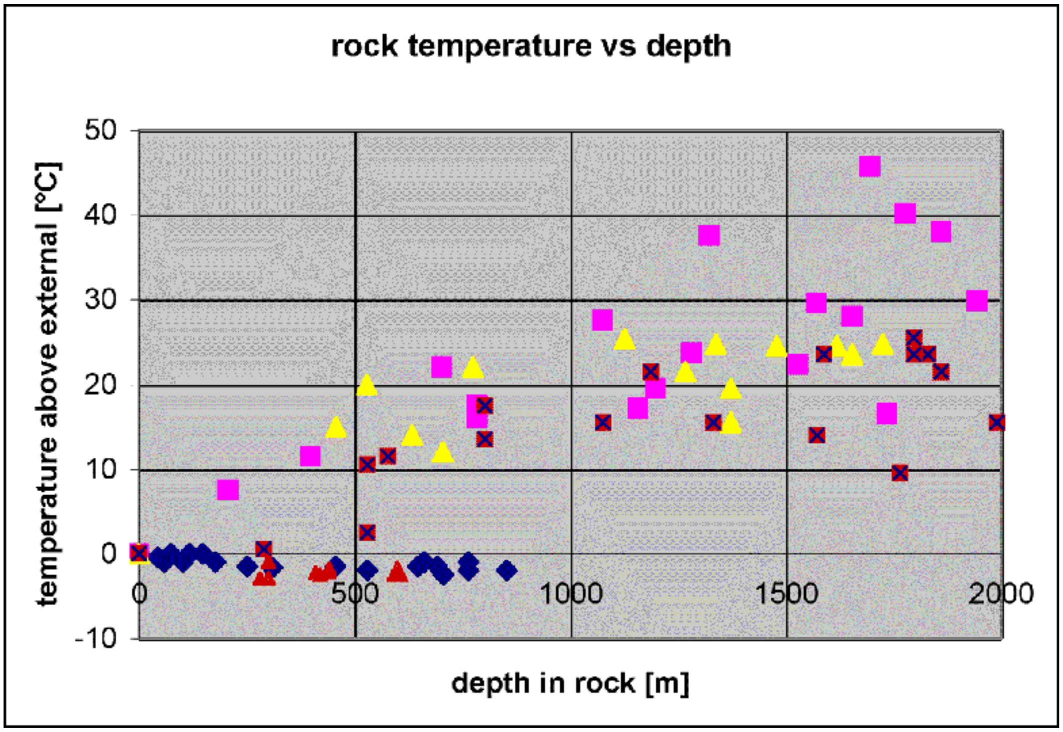
Uranium and nuclear power has so far been discussed as a source of intense heat. That heat is almost exclusively used to generate steam to power a turbine. The exact process for converting heat into steam and then into motive force will be discussed later in the course, and is relatively the same no matter the fuel used to heat the steam. As such nuclear power is almost exclusively used to generate electricity, apart from use on naval vessels where the steam turns the propeller shaft. Currently about 15 % of electricity generated in the world is via nuclear power.

II. **Energy sources**

3. Nuclear energy absorbed from the earth (geothermal).

What is it:

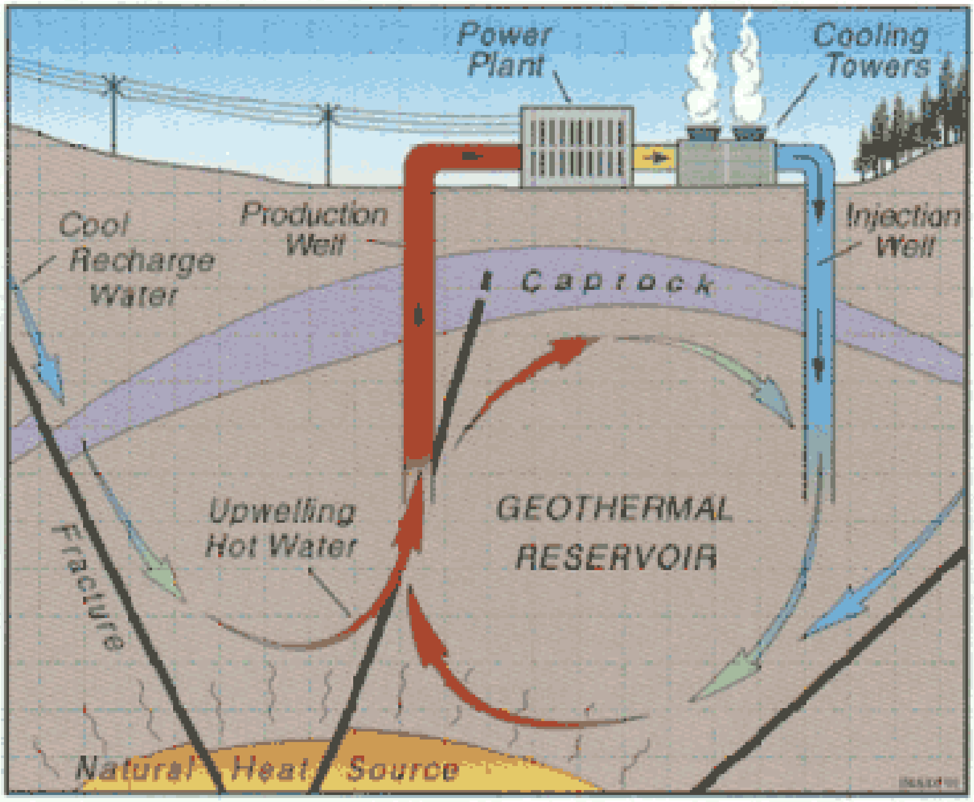
As we learned in the introduction, approximately 44 terawatts of heat is generated within the Earth. The title of this section is somewhat of a misnomer, as this heat is not only generated by radioactive decay of heavy elements in the Earth, but also by tidal heating of the Earth due to gravitational forces causing stretching of the Earth's matter. This heat generated in the Earth causes the temperature to generally rise as one moves down from the surface:



Actually, one sees that sometimes it gets cooler as one moves down into the Earth. This is due to how water flows in rock, either through veins in the rock or through permeable rock. Sometimes, the water flow is such that (generally down?) it conveys heat away from the cave or tunnel.

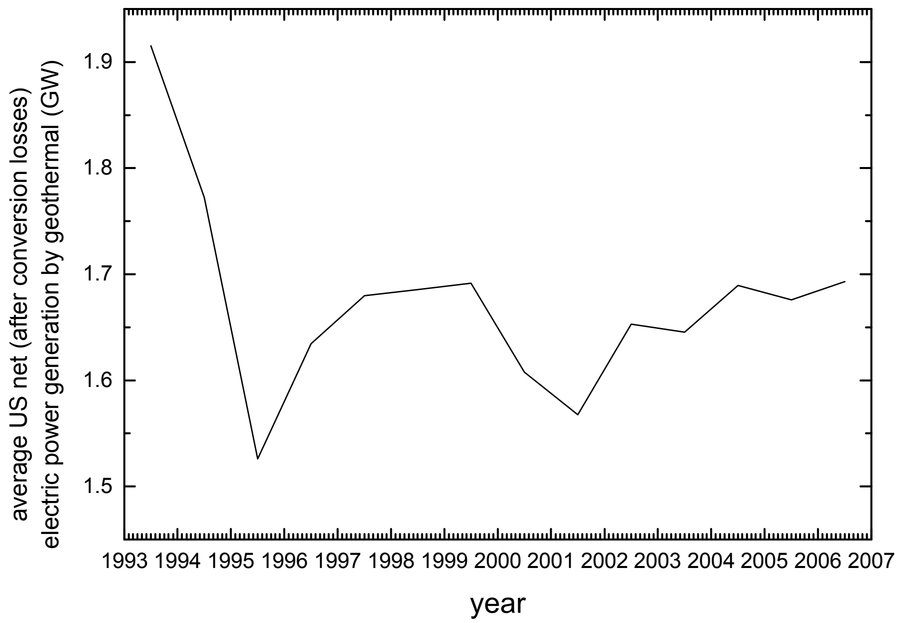
But generally, we see from the above figure that for every kilometer of depth, the rock temperature rises about 20 C. Now, this tells us something right away about geothermal energy, that if one's aim is to generate electricity, as we'll see later that generally means making steam, which requires temperatures near 100 C. So, in order to generate electricity, you can't just plunk down a well anywhere and send water down to turn into steam by absorbing the heat.

Most of us are familiar with geysers such as in Yellowstone park where due to geothermal energy steam actually escapes from the surface. Actually, some of the first geothermal electric generation attempted to use steam escaping from the surface to power a turbine/generator. This failed in most attempts due to the corrosive nature of the steam due to various chemicals present naturally. Rather, one attempts to find a *geothermal reservoir*, which is where a field of underground water (in which similar to an oil field the heated water exists in pores of the rock) is heated to near 100 C, but remains liquid due to pressure:



The heated water exists as liquid until it reaches the generation plant, where the pressure is reduced and the water is allowed to flash into steam, which then turns a turbine.

So, geothermal electric generation is limited to areas where these reservoirs are present. They exist generally where fractures in the continental plates, or where the continental plates meet, allow melted rock or magma to exist nearer the surface. It is difficult then to estimate how much of a resource it is for electric power generation, since of the 44 total terawatts, that is generally spread over the Earth's surface. If one estimates that likely geothermal reservoirs account for 1/1000 of the Earth's surface, the resource is 44 gigawatts. Indeed, geothermal energy accounts for approximately 9 gigawatts of electric power worldwide. Here is a plot of geothermal electric power generation in the United States:



One sees that it accounts for only a small fraction of the ~ 460 gigawatts of net electric power generation in the US, and furthermore is not increasing much.

II. Energy sources

4a. Solar energy, Direct-to-Electric conversion

The Sun's energy manifests itself on the Earth in a variety of ways that can be used. Ignoring biological conversion for the moment, these include direct absorption of solar radiation by photovoltaic or thermal collectors, conversion of mechanical motion induced by the absorption of solar radiation by the Earth (generally wind, waves, or ocean currents), or conversion of potential energy induced by absorption of solar radiation by the Earth (hydroelectric power). These conversion mechanisms are basically in the order of their availability at any point on the earth, which matters to how and to what extent they can be converted. That is, capture of radiation itself can occur basically anywhere on Earth, while conversion of wind or wave energy only works well in certain locations, and hydroelectric conversion at even fewer locations. Here in the preface to this section we will attempt to quantify the overall availability of each source. Then, in the individual sections the effective availability will be derived.

As we learned in the introduction, the power output of the Sun is $4\text{x}10^{26}$ watts. At the orbital position of the Earth, that power intensity is given by

$$P = \frac{4x10^{26}}{4\pi R_{orbit}{}^{2}} = \frac{4x10^{26}}{4\pi(1.5x10^{11})^{2}} = 1400 \quad \frac{\text{watts}}{\text{meter}^{2}}\,. \qquad \text{(II.2.0.1)}$$

As the Earth presents a cross-sectional area equal to $\pi R_{radius}{}^{2}$, the amount of power from the Sun that is intercepted by the Earth is equal to

$$W_{\text{sun, intercepted}} = P\pi R_{radius}{}^{2} = (1400)\pi(6.4x10^{6})^{2} = 180{,}000 \text{ terawatts.} \qquad \text{(II.2.0.2)}$$

The Earth's albedo or power reflectance is 0.37, so the amount of the Sun's power captured by the Earth is

$$W_{\text{sun, captured}} = (1-0.37)W_{\text{sun, intercepted}} = 110{,}000 \text{ terawatts.} \qquad \text{(II.2.0.3)}$$

Of this amount of solar radiation captured by the Earth, some is absorbed in the atmosphere. Calculating the absorption of light in the air is fairly complicated, and amounts to about 20 %. **Thus, the complete availability of solar radiation at the surface for photovoltaic or thermal conversion (ignoring space-based collection) is 90,000 terawatts.**

Photovoltaic or Solar Thermal-to-Electric Collectors-

Photovoltaic solar panels which convert light directly into electricity will be discussed in detail later, but generally commercially available panels have ~ 15 % conversion efficiency. So in principle if the earth could be coated with photovoltaic panels, 13,500 terawatts of electricity could be produced. That has clearly not happened, and as seen in the chart at the beginning of the Nuclear section, solar electric generation is still around 100 megawatts in the US. Besides photovoltaic panels, Solar Thermal-to-Electric collectors use mirrors to concentrate sunlight to high intensities, for example to generate steam which drives a steam turbine/generator (which will be generally discussed in a later section) to make electricity. There are several of these "solar towers" in the US , called Solar Energy Generating Systems (SEGS):

These plants in the Mojave desert use mirrors to concentrate sunlight on a fluid pipe producing steam which runs a turbine-generator, and have been producing several tens of megawatts since the 1980's.

Of the 110,000 terawatts that is not reflected back into space, all is reradiated out into space as thermal radiation, so that the Earth's temperature is constant. The thermal radiation of the Earth can be estimated by treating it as a Blackbody thermal source. If one takes an average surface temperature of 13 C., or 286 K, one can calculate the thermal radiation emitted at the surface using Blackbody radiation theory. This theory requires knowledge of the emissivity of the Earth, which relates the radiation emitted to the temperature as a function of material. The emissivity of water is 0.95. The emissivity of vegetation is nearly the same as water due to its high water content. The emissivity of snow is about 0.98. The emissivity of sand is 0.76. Probably an average number of about 0.9 is good. Then,

$$\begin{aligned} W_{\text{Earth, radiated at surface}} &= 0.9\sigma T^4 4\pi R_{Earth}{}^2 = \\ (0.9)5.67x10^{-8}(286)^4 4\pi(6.4x10^6)^2 &= 180,000 \end{aligned} \quad \text{terawatts.} \qquad \text{(II.2.0.4)}$$

As we've seen a small amount of this is due to internal heating of the Earth (44 terawatts) and can be ignored.

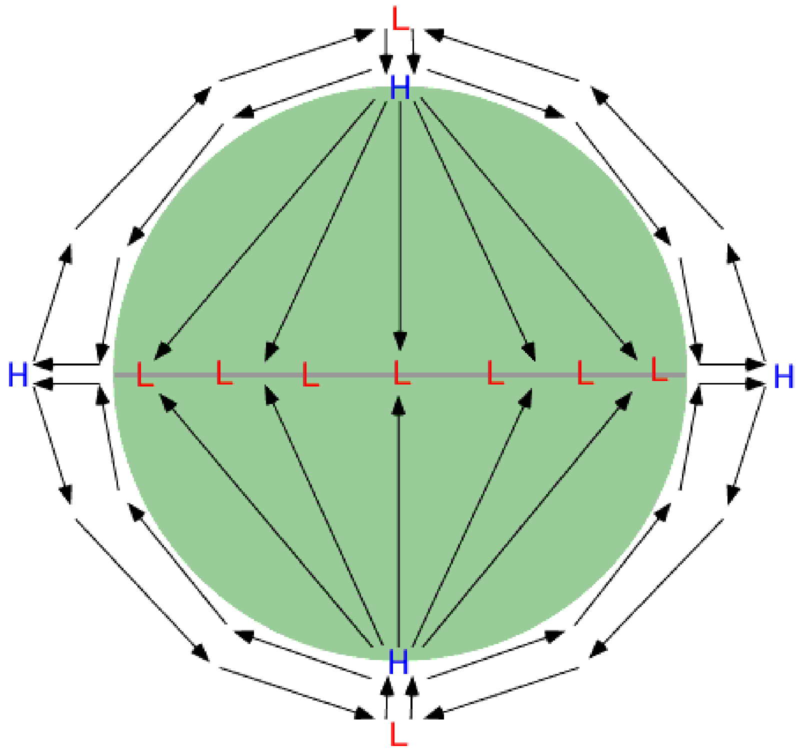
So, what's going on here? Well clearly, the Earth is not cooling at the rate of 70,000 terawatts (note: it would be if the atmosphere was not there, and the Earth would be a lot colder; this is the greenhouse effect). Rather, the difference between these numbers must be being absorbed by the Earth's atmosphere. In addition, the atmosphere is heated by its direct absorption of solar radiation. Thus,

$$\begin{aligned} W_{\text{atmospheric heating}} &= W_{\text{Earth, radiated at surface}} - W_{\text{sun, captured}} + 0.2W_{\text{sun, captured}} \\ &= 90,000 \end{aligned} \quad \text{terawatts.} \qquad \text{(II.2.0.5)}$$

Wind Energy-

This power absorption by the atmosphere drives wind energy, and wind drives ocean waves (ocean currents are more driven by ocean heating). Now, not nearly all of this 90,000 terawatts winds up as wind power. As seen in on the chart at the beginning of the Nuclear section, wind does generate close to 10 gigawatts in the US, and is rising rapidly.

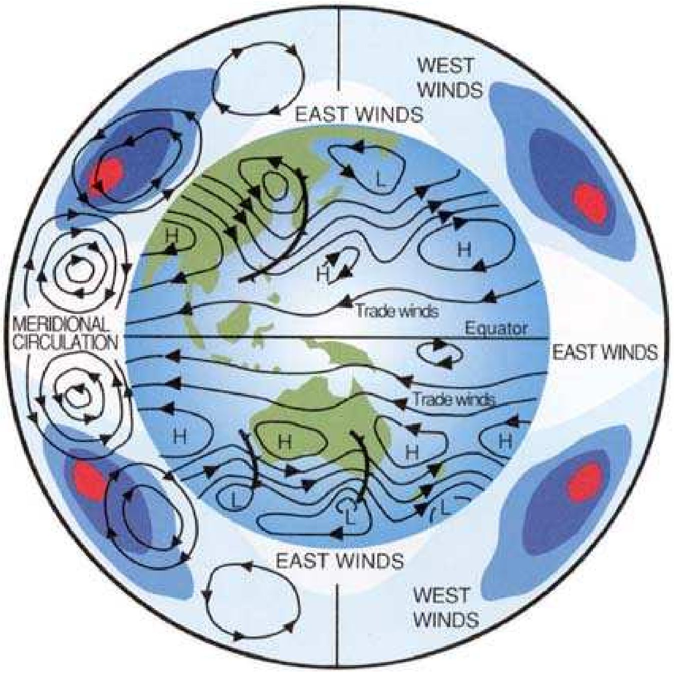
To see how much wind electricity can be made globally, we use an approach here of calculating the total energy in the wind at any given time, as we had done in homework 1 for the energy in the rotation of the earth. Because, looking globally, wind is really an energy resource that is tapped by windmills. While wind is continually regenerated by solar energy, if the rate of tapping the energy stored in wind exceeds the rate of replenishment by solar energy, clearly weather would be affected. So, let's calculate how much energy is in wind at any given time. To understand wind, let's look at a simplified model of global heating and cooling:



Since the equator is heated more than the poles, air rises there, flows along the upper atmosphere, then cools and falls near the poles. This cool air flows along the surface back toward the equator, closing the loop.

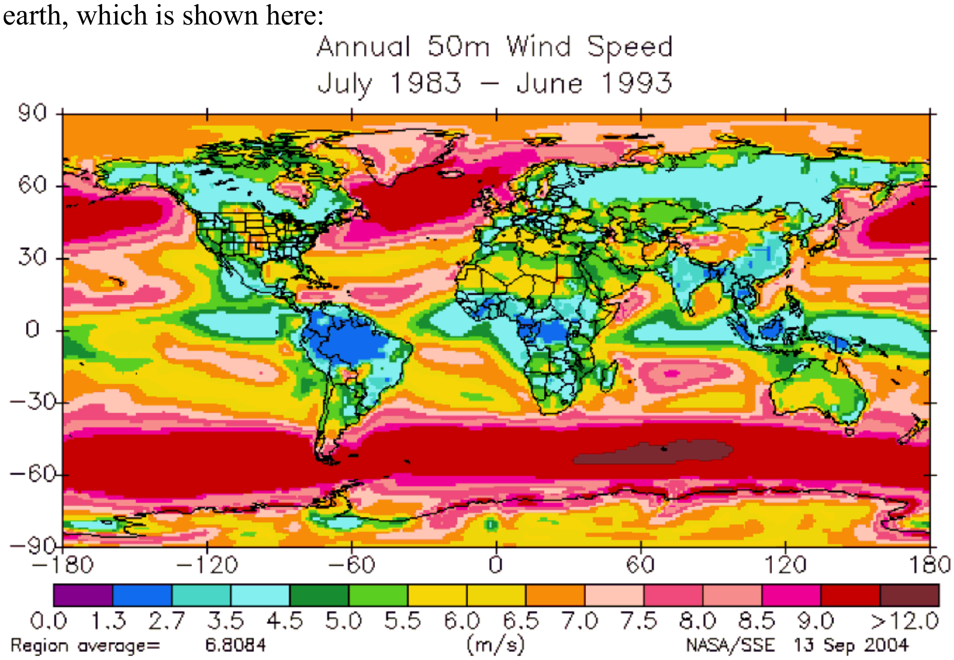
The overall wind patterns are complicated by the fact that the Earth is a sphere, and that it rotates. But, generally, one can think of it as a loop or loops of air in motion. Thus, it has an amount of stored energy. When we place a windmill in the wind, we tap a very small amount of this stored energy. Ignoring mankind's currently puny efforts, we can think of wind as a flow that is driven by the solar heat absorbed. If there were no energy loss mechanisms, that drive would continually make the wind go faster and faster. The fact that wind speeds have reached generally steady state is due to the balancing of frictional losses in the wind loops and the power driving the wind.

As an aside, here is what the general global wind patterns look like when the Earth's spherical shape and rotation are taken into account:



What happens is that three cells are generally set up in each hemisphere. The rotation of the earth causes surface winds to generally blow from east to west near the equator, and from west to east in latitudes corresponding to the US. This is why weather always seems to come from west to east in the US.

Getting back to our estimate of wind resource availability, we see that it is more appropriate to think in terms of a global energy availability (like when we calculated the energy in the rotating Earth) than a power availability. Clearly, if we were to extract more than a certain amount of the energy in the Earth's winds we would cause some problems with our weather. Anyway, the total energy in the Earth's winds can be estimated from a consideration of the total mass of the atmosphere, which is about 5×10^{18} kilograms, and examining wind velocity on the earth, which is shown here:



Note that wind speed is much greater on the oceans where there are no obstructions. Now, the earlier figure on the mass of the atmosphere is the total amount of air. We will consider within

80 meters of the surface, where generally windmills can reach (not considering kites and other schemes proposed to tap upper winds). The density of the atmosphere varies exponentially with height, losing half its density by about 5600 meters elevation. Thus,

$$\rho_{atmosphere} \propto e^{-z/8000}, z \text{ in meters.} \qquad \text{(II.2.0.6)}$$

Thus, the total mass of atmosphere within 80 meters of the surface is

$$m_{80meters} = m_{total} \frac{\int_0^{80} e^{-z/8000} dz}{\int_0^{\infty} e^{-z/8000} dz} = m_{total} \frac{-8000e^{-z/8000} \Big|_0^{80}}{-8000e^{-z/8000} \Big|_0^{\infty}} = m_{total} \frac{-e^{-80/8000}+1}{1} = 0.01 m_{total}$$

=5x10^{16} kilograms. (II.2.0.7)

Since generally we can only put up windmills on land or near land, we reduce this to the 30 % of the globe covered by land to

$$m_{80meters,land} \cong 1.5x10^{16} \text{ kilograms.} \qquad \text{(II.2.0.8)}$$

On land, it appears that the average wind speed is 5 meters/second. Now, in this calculation, since energy goes as velocity squared, we want the average of velocity squared. This will favor higher speeds, so that its average is greater than 5^2. For example, if we have three wind speeds of 0, 5, and 10 m/s, the average velocity squared will be (25+100)/3 = 41. Let's use 50 m2/s2 as the average velocity squared on land. Then,

$$E_{\text{near land surface winds}} \cong \frac{1}{2} m_{80meters,land} \left\langle v_{surface}{}^2 \right\rangle = \frac{1}{2}(1.5x10^{16})50 = 4x10^{17} \text{ joules.} \qquad \text{(II.2.0.8)}$$

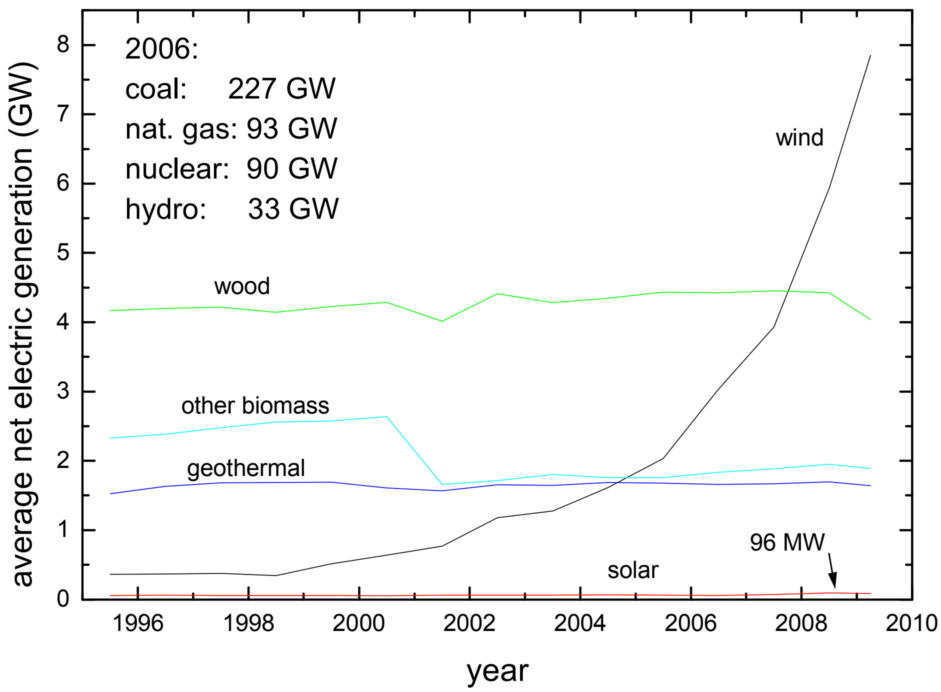
As we did for things like tapping the energy in the Earth's rotation, to calculate an ultimate resource we have to estimate how much can be tapped without causing problems. Put another way, if we put up windmills, they obstruct the wind, slowing it down, and if we reduce global wind speeds appreciably that is probably not good. Clearly, we cannot tap those 4E17 joules every second; we would suddenly absorb all land surface wind energy. So, clearly, the resource is much less than 4E5 terawatts. Let's think on a daily cycle of the Sun warming and cooling the atmosphere, causing wind. If we tap 20 % of the wind's energy every day, that would equate to a power of

$$W_{\text{wind available}} = E_{\text{global land surface winds}} \frac{0.2}{24x3600} = 1 \text{ terawatt.} \qquad \text{(II.2.0.9)}$$

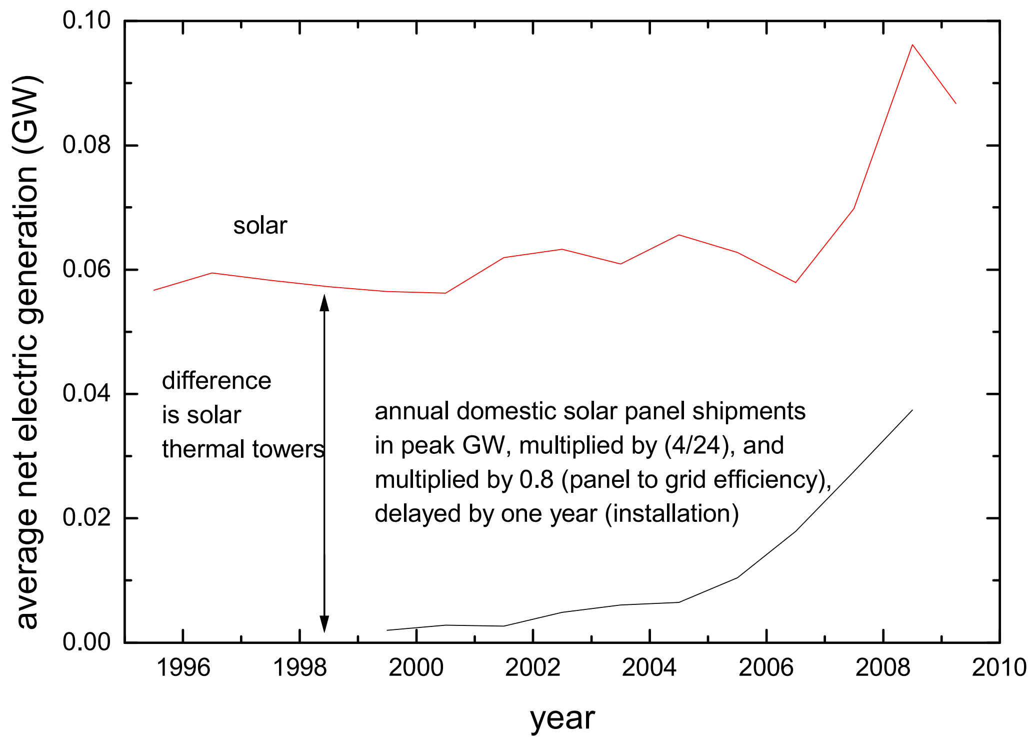
This estimate is two orders of magnitude less than the estimate of a Stanford group (http://www.stanford.edu/group/efmh/winds/global_winds.html), which estimated the global wind resource as 72 terawatts. However, that estimate was "bottom up," in the sense that they calculated wind power flux at points on the earth, and added them up. Clearly, we can't do that, as it would stop all wind, which would likely lead to trouble. Currently, wind generates about ~ 20 gigawatts of electricity worldwide, and is increasing rapidly. It will be interesting to see whether this becomes a problem as it increases to the above value. Probably, the resource availability is somewhere between the bottom-up and top-down estimates of 1 and 72 terawatts, and a good estimate is probably that the **global availability of wind power on land is 10 terawatts.**

The estimate of total hydroelectric power resource is not possible from a calculation of solar energy absorbed by the water in the ocean, as much of water vapor raised from the surface simply falls back as rain on the ocean. Rather, a simple calculation would be from the average height of the world's lakes, and their replenishment rate by precipitation. Rather than attempt this calculation here, on the EIA website it states that total electrical generation by hydroelectric power in the world was 2.9 trillion kWh per year, or 2.9E15 Wh/(365.25x24 hours) = 330 gigawatts average power generation. Total resource is estimated as (http://www.planete-energies.com/content/renewable-energies/hydroelectric-power/future.html) 14 trillion kWh per year, or **global availability of hydroelectric power is 4.6 terawatts.**

Finally in this introductory section, we'll take a look at how solar and wind power is developing in the US. Showing the chart presented at the beginning of section II,

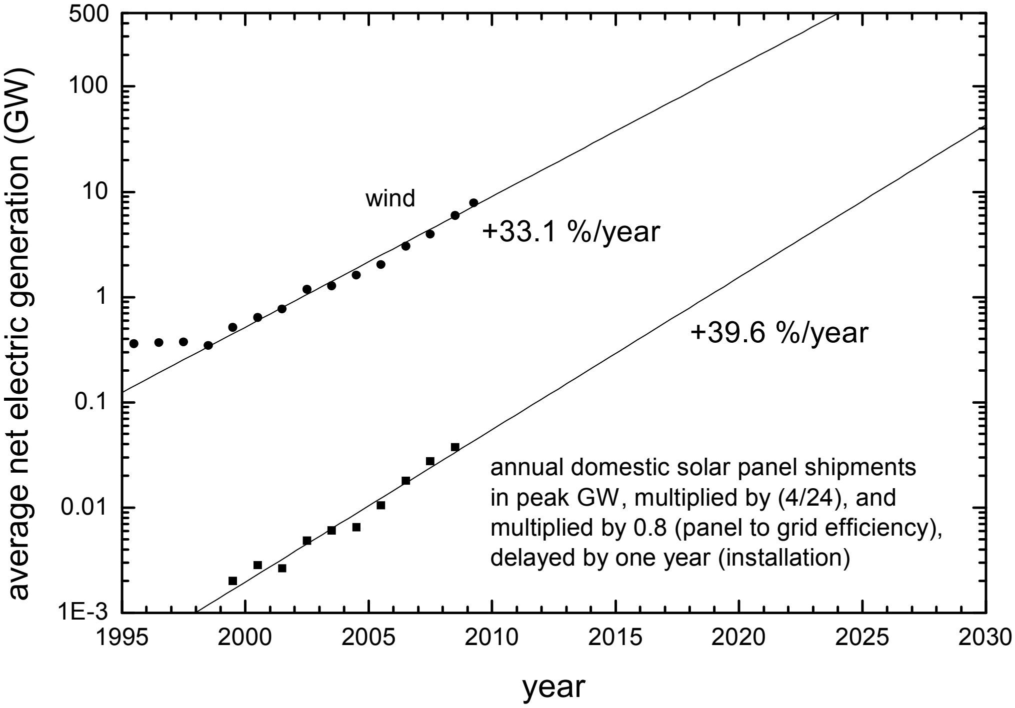


we see that wind is much larger than solar. Expanding the solar chart (note that the red curve is the same in both charts):



It shows that solar-electric generation seems fairly constant over time. But, actual increase of solar *photovoltaic* generation (the type of panels on people's houses) has been much larger than indicated. The reason is that, as stated, SEGS solar tower generation of about 60 megawatts has been going on fairly constantly for the last 20 years, and it is only recently that photovoltaic panel deployment has stepped up. Actual solar panel generation is not listed separately at www.eia.doe.gov, but we can infer it, by plotting the annual domestic solar panel shipments, found at www.eia.doe.gov/cneaf/solar.renewables/page/solarphotv/solarpv.html . There, shipments are listed in peak gigawatts (actually kilowatts, but I converted), that is, what the panel is rated to produce in full sun. The sun does not shine fully all the time. On average, it shines fully 4 hours/day (taking into account cloudy days). So, above, the peak power deployed is multiplied by 4/24. Further, there is loss in the DC-AC converting electronics to get the power to the grid, so it is further multiplied by 0.8.

So, it would appear that much of actual generation was the SEGS generation, and only now is the panel production showing up precipitously on the chart. If one plots this, one obtains:



This and the above indicates that solar generation should begin increasing at 40 %/year now. Note that even at this rate, it will be less that 10 GW by 2020.

The reasoning for the increased adoption of wind compared to solar can perhaps be got from calculating the average power/area in the two. For solar, the average electrical power per unit area is the peak solar power/area (1000 W/m2), times the average fraction of full sunlight (4/24), times the efficiency of the panel (15 %), or

$$P_{ave,solar} = 1000x(4/24)x0.15 = 25$$ W/m2.

For wind, from the introduction the power/area is given by the energy/volume ($\frac{1}{2}\rho v^2$) times the velocity, or

$$P_{wind} = \frac{1}{2}\rho v^3$$.

To get the average power/area in wind, the average of velocity cubed must be taken. For example, if we have three wind speeds of 0, 5, and 10 m/s, the average velocity cubed will be (125+1000)/3 = 375 m3/s3 as the average velocity cubed on land. The density of air at sea level is 1.2 kg/m3:

$$P_{ave,wind,5m/s} = \frac{1}{2}\rho < v^3 >= 0.5x1.2x375 = 225$$ W/m2 (before conversion to electricity).

The conversion efficiency of a windmill is a complicated formula of the blade design, generator efficiency, etc. Here, we'll take a commercial product specification (http://www.altestore.com/mmsolar/others/Company_Brochure02-2005.pdf) and use that to compute the efficiency. From that product brochure, the Whisper 500 produces 3000 watts for a wind speed of 10.7 m/s. Given the rotor diameter of 4.5 m, that product subtends an area of 3.14(2.25)2 = 15.9 m2. From the formula for wind power/area, then, at 10.7 m/s, the wind power incident upon that windmill is 0.5x1.2x10.73 x15.9 = 11,700 watts. Thus, the efficiency is 3000/11,700 = 26 %. Note that this is a relatively small windmill; larger windmills may have greater efficiency.

The windmill efficiency depends upon wind speed, but here we will assume that for a given site, the windmill is designed to produce the highest efficiency for the wind speeds at that site, and we will use 26 %. As mentioned, a larger windmill will produce higher efficiencies, but this is balanced by lower efficiencies at wind speeds other than optimum. Thus, the converted windmill power/area is

$$P_{ave,wind,5m/s} = \frac{1}{2}\rho < \mathrm{v}^3 > \eta_{windmill} = 0.5x1.2x375x0.26 = 59$$ W/m2 (after conv. to electric).

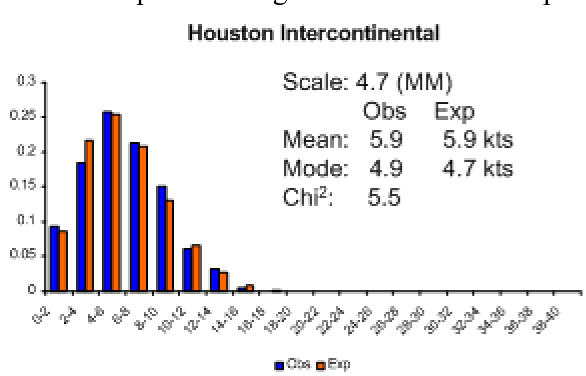
Thus, we see that for sites with an average wind speed of 5 m/s [5x0.00062 miles/(1/3600 hours) = 11 miles per hour], wind average power/area is 2.3 times that of solar. So, if the cost is proportional to area (windmill rotating blade area vs. solar panel area), wind is 2.3 times cheaper for such a location. This does not take into account the tower.

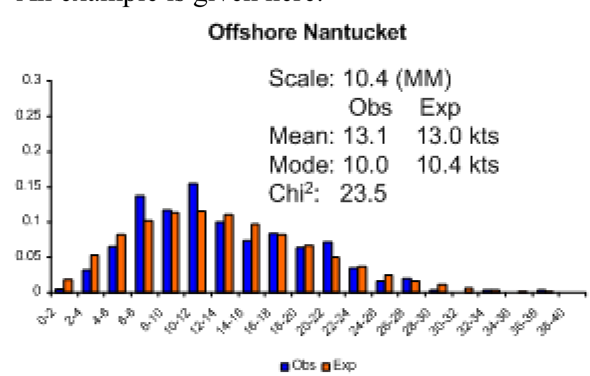
However, if the location has, for example, 2 meter/second average wind velocity (4.5 mph), then the average cubed wind speed is (8+64)/3=24 m3/s3,

$$P_{ave,wind,2m/s} = \frac{1}{2}\rho < \mathrm{v}^3 > \eta_{windmill} = 0.5x1.2x24x0.26 = 4$$ W/m2, (after conv. to electricity).

and so for that location wind has much less average power/area than solar. So, wind is far more site dependent. If a utility can chose a windy site, it is far more effective that solar. But, generally, for home use (unless you live in a very windy area), solar is better.

We can perform a more sophisticated calculation of electricity generated vs. average wind power. To be perfectly correct, we would use a wind speed distribution function, that plots the number of speed readings over time vs. wind speed. An example is given here:

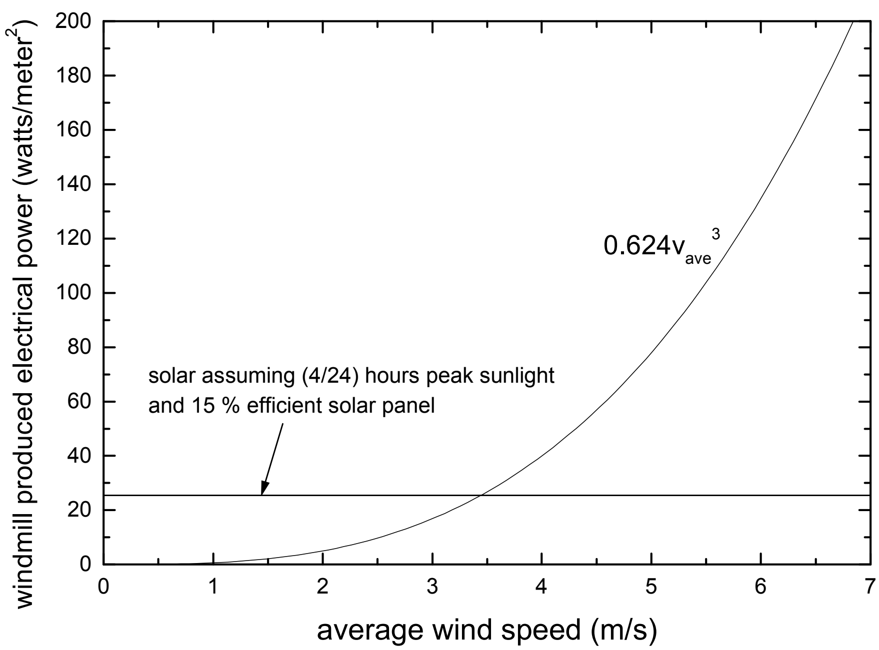




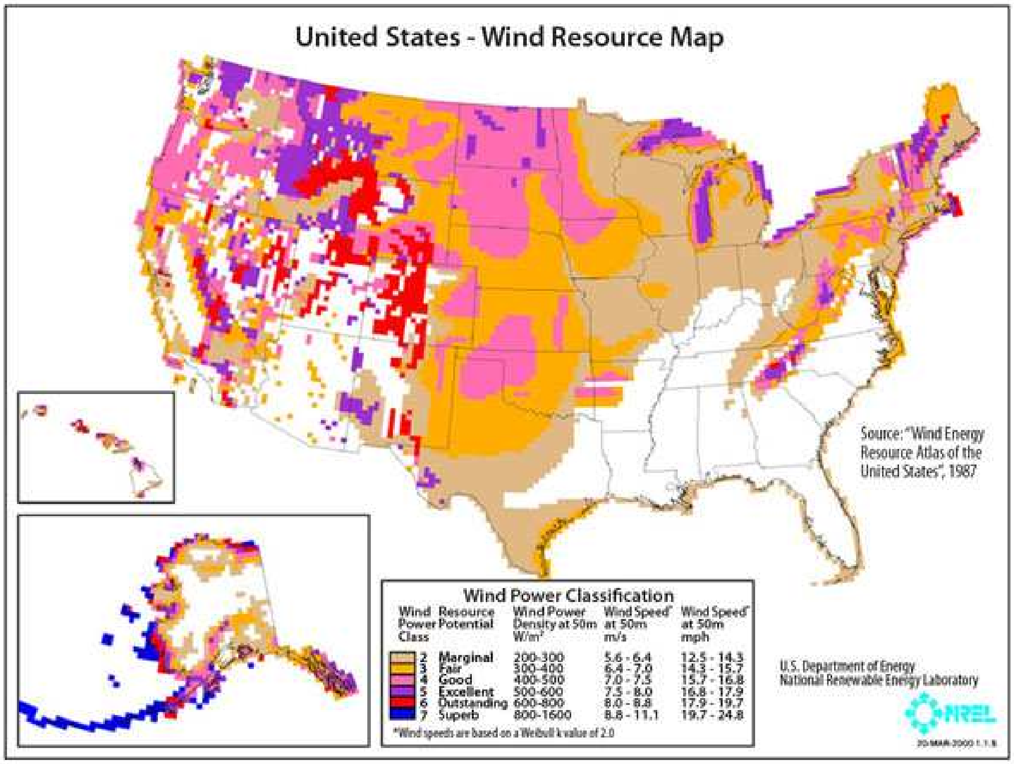
Fitting these distributions to a formula can involve some complicated mathematics; to keep it simple we will just assume that the distribution has a "flat top" from 0 to twice the average speed. Then, the average electrical power is given by

$$P_{ave,wind} \cong \frac{1}{2}\rho\eta_{windmill}\mathrm{v}_{ave}{}^{3}\int_{0}^{2}x^{3}dx = \frac{1}{2}\rho\eta_{windmill}\mathrm{v}_{ave}{}^{3}\frac{x^{4}}{4}\Big|_{0}^{2} = 2\rho\eta_{windmill}\mathrm{v}_{ave}{}^{3}.$$

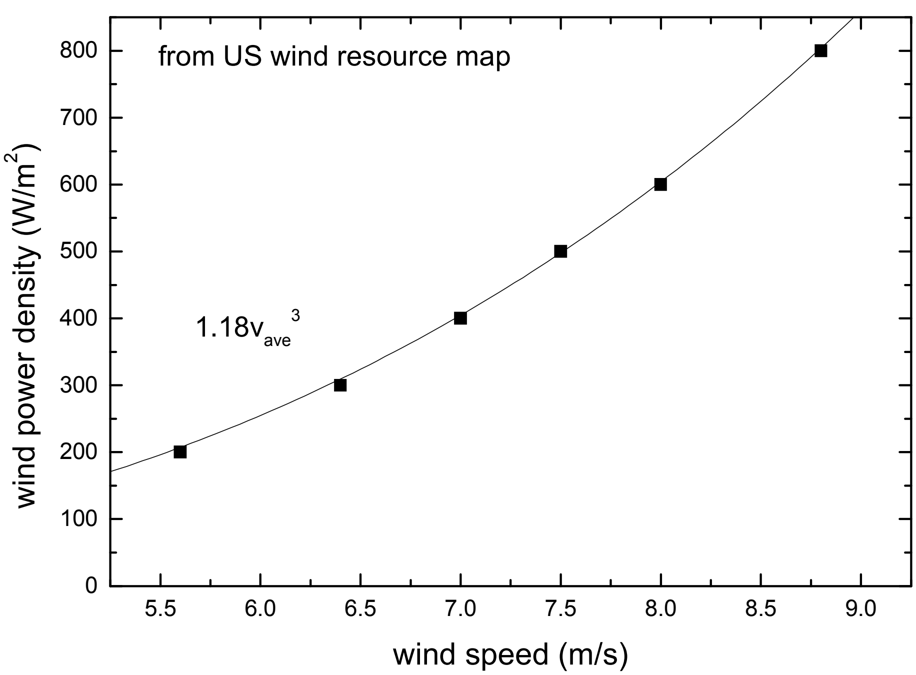
Thus, the power/area vs. average wind speed is given by



This can be compared with average wind speed in the US:



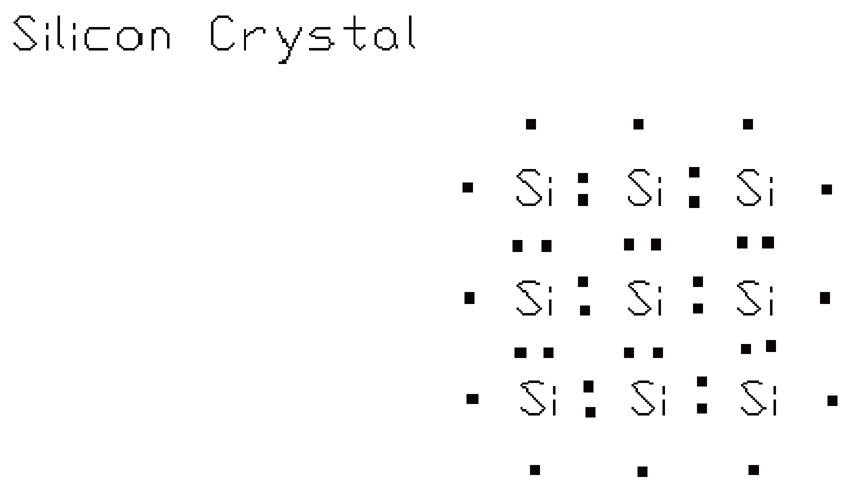
Note this map also calculates wind power and gives values about 2 times that calculated above; I think they have neglected the efficiency of the windmill (which makes it about a factor of 4 higher) and also assumed a tighter wind speed distribution (that makes it about a factor of 2 lower).



Energy Systems, Photovoltaics Appendix
Part A, operation of solar cells in the dark

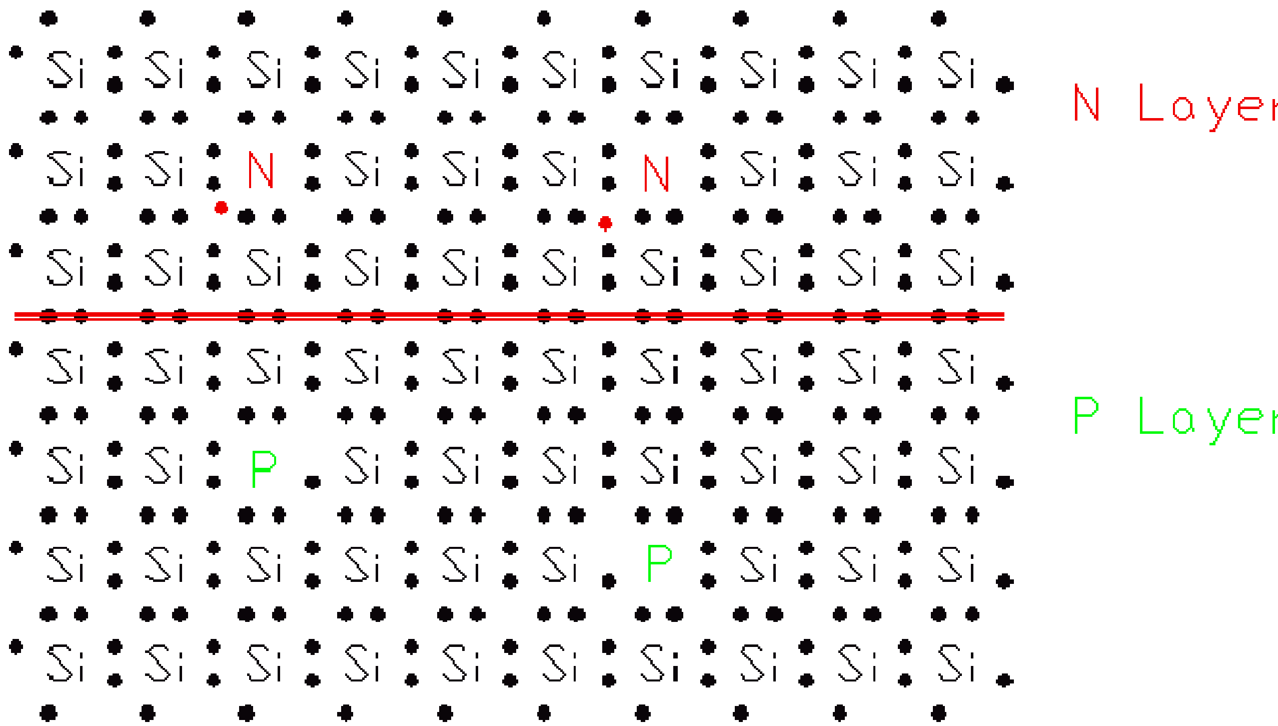
How does a solar cell work? A solar cell is an electronic device that produces electric power (current and voltage) when illuminated. To understand how a solar cell works in the light, one must first understand how it works in the dark. Like any electronic device, that means understanding how its current varies with the voltage applied to it. A wire with some electrical resistance simply has a linear relationship between applied voltage and current, that is, the higher the voltage, the higher the current; additionally for a wire this relationship does not depend upon the polarity of the applied voltage. But, for a solar cell, both are different, the device's current vs. voltage is nonlinear, and also depends upon polarity.

A solar cell is what is called a p-n diode, so-called because it contains a junction between p-type material and n-type material, which are terms referring to the type of electrical conductivity of the material. It is formed from a semiconductor, which intrinsically has no conduction; to make the material p or n requires adding a dopant to the material. This can all be understood from an examination of the microscopic bond structure of the underlying material of the solar cell, which for most solar cells is silicon:



One sees that since silicon is a group IV atom, having 4 valence electrons, it naturally forms completed bonds with four neighboring silicon atoms. <u>Now, for pure silicon, all the valence electrons are incorporated into the bonds. Thus, pure silicon cannot conduct electricity.</u> That is strictly true only at absolute zero temperature; at room temperature there's a small probability that some electrons will be thermally excited from the bonds so they can conduct.

Now, if we dope the silicon crystal with a very small percentage group V atoms on one side, and group III atoms on the other, those sides become n and p type, respectively:



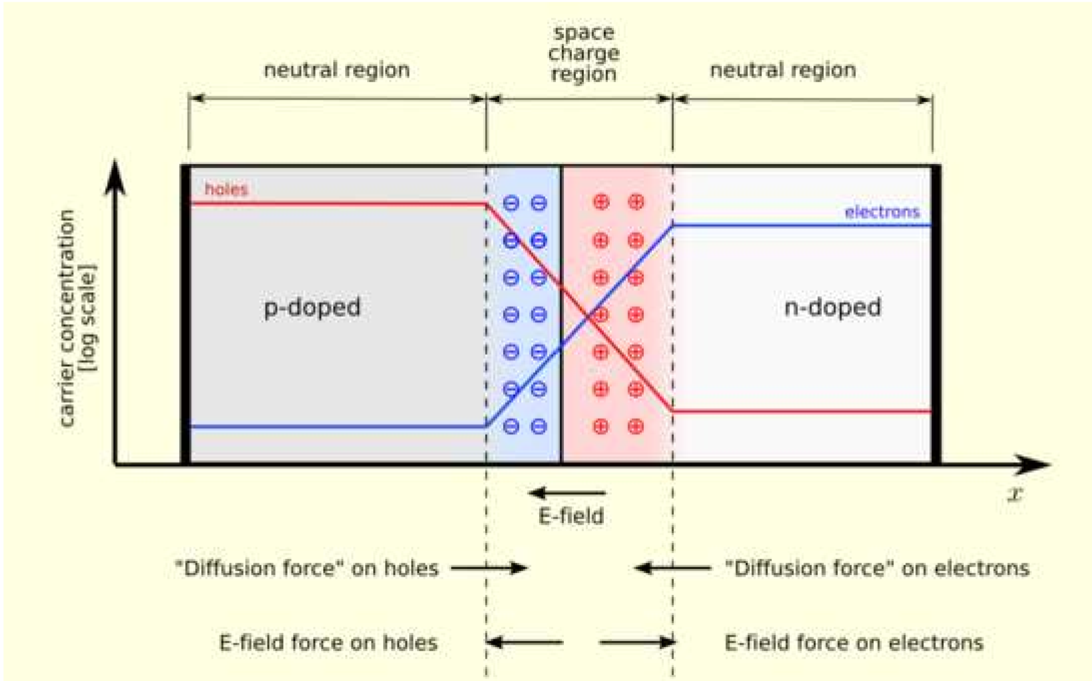
One sees that in the n layer, the nitrogen atoms (group V) contribute an extra valence electrons to the bond. This extra electron can easily escape from the bond and conduct electricity.

In the p layer above, the artist means to state a P type atom, which is group III (phosphorous is group V). Just replace the P's with B's (for boron, a group III atom).

In the p layer, the boron atoms have a missing valence electron. This "hole" can move around the crystal. Imagine a pool table that is filled with pool balls. Remove one of the balls. Now, move the "hole" around. The "hole" does not actually move, but the other pool balls move around, making it look like the hole is moving around. For all practical purposes, then, the hole acts like a positive charge, having the same absolute charge value as an electron. So, n-type refers to the material have negative charge carriers, and p-type means it has positive charge carriers.

In a typical diode, the doping level, that is, how many group III or V atoms are put in, is about at 10 ppm (parts per million). So, this means the underlying silicon must be pure to levels much lower than this, generally lower than 1 ppm. This purity requirement can be a limiting factor in solar cell manufacturing.

Okay, now that we have a solar cell, a pn junction, how does it work in the dark? Well, all those mobile electrons on one side and holes on the other don't just stay in those layers. They move, and so some of the holes in the p layer go into the n layer, and some of the electrons go from the n layer into the p layer. Now, when a mobile electron leaves its dopant atom, it leaves behind a positively charged dopant atom (since that dopant atom requires 5 valence electrons to be neutral). Vice versa for the holes, they leave behind negatively charged dopant atoms. This leads to a *space charge layer*, that is, a layer of the n-type layer that is positively charged, and a layer of the p-type layer that is negatively charged:



In the picture, holes leave the p-type side until sufficient negatively charged p dopant atoms are left that attract them back. The same happens for the electrons leaving the n-type side. Thus, the electrons and holes move to opposite sides until a sufficiently thick space charge region develops that prevents further movement due to the electric field that develops.

Now, what happens when we apply a voltage to the two sides of the diode? If we apply a negative bias to the p-side (positive bias to the n-side), then, nothing much happens since we're helping the space charge layer inhibit current flow. So, for that polarity, negligible current flows.

When we apply a positive bias to the p-side (negative bias to the n-side), we do get current since we're working against the current-inhibiting action of the space charge layer. To understand how much current flows vs. voltage, we must first understand something about energy distributions of the mobile charge carriers vs. temperature.

When there is no voltage, carriers are still moving back and forth across the junction, it's just that they balance. The reason for this is that the carriers have a distribution of energies:

$F(E)=\exp(-E/kT)$

Here k is Boltzmann's constant, and T is the temperature. All this equation is saying is that, at a given temperature, the thermal kinetic energy of the carriers goes down exponentially with energy. The same is true for air molecules in this room, some move slowly, some move faster, and as we go up in energy the number moving with that energy goes down exponentially.

So, at zero applied bias there are still some electrons that can move from left to right and vice versa, and they balance:

$I(V=0) = A[\exp(-Eb0/kT)-f]$

Here, Eb is the barrier energy due to the space charge layer electric field that is preventing electrons from flowing from n to p, and preventing holes from flowing from p to n. f is the flow of residual electrons from p to n and holes from n to p. Since at zero bias we have zero current (in the dark),

$$f=\exp(-Eb0/kT),$$

$$I(V=0) = A[\ \exp(-Eb0/kT)-\exp(-Eb0/kT)\ ].$$

Now, when we apply a bias, the barrier energy for electrons to flow from the n side to the p side is reduced (since we are working against the space charge electric field). But, the flow of electrons from the p side to the n is unchanged, since there was no barrier to that (it just depended upon how many residual electrons there were in the p side). The same happens for holes, in the reverse direction. Thus, the current is given by

$$I(V) = A[\ \exp(-Eb/kT)-\exp(-Eb0/kT)\ ],$$

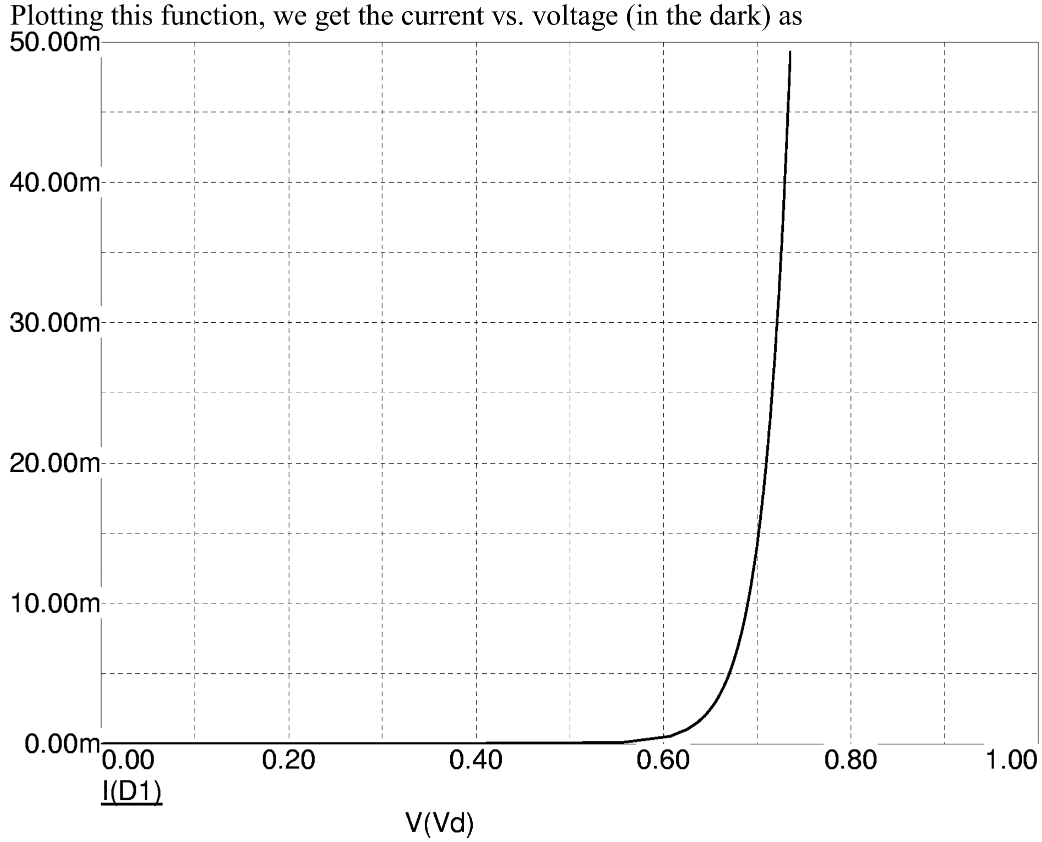
where $Eb<Eb0$. The formula for Eb is easy to understand, since the applied voltage reduces the energy barrier by an amount that is equal to the energy acquired by an electron passing through a voltage V, which we know from the course introduction is eV, where e is the charge of an electron. Thus,

$$Eb=Eb0-eV, \text{ and}$$

$$I(V) = A[\ \exp(-\{Eb0-eV\}/kT)-\exp(Eb0/kT)], \text{ or}$$

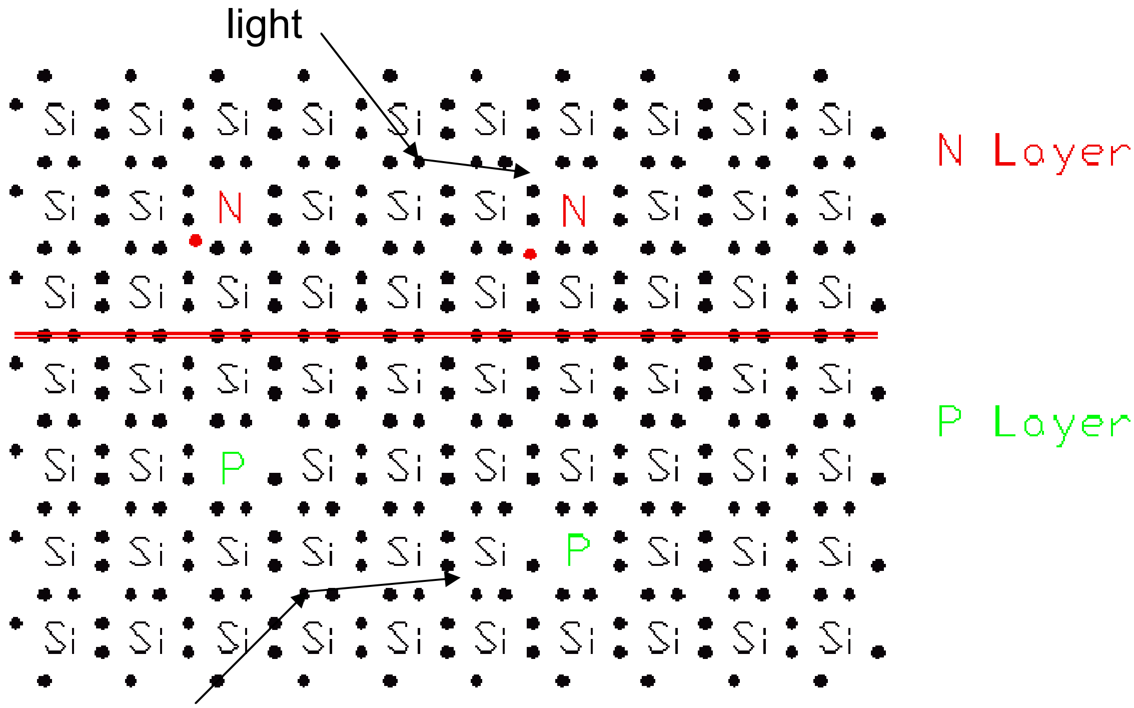
$$I(V) = A\exp(-Eb0/kT)[\exp(eV/kT)-1].$$

Plotting this function, we get the current vs. voltage (in the dark) as

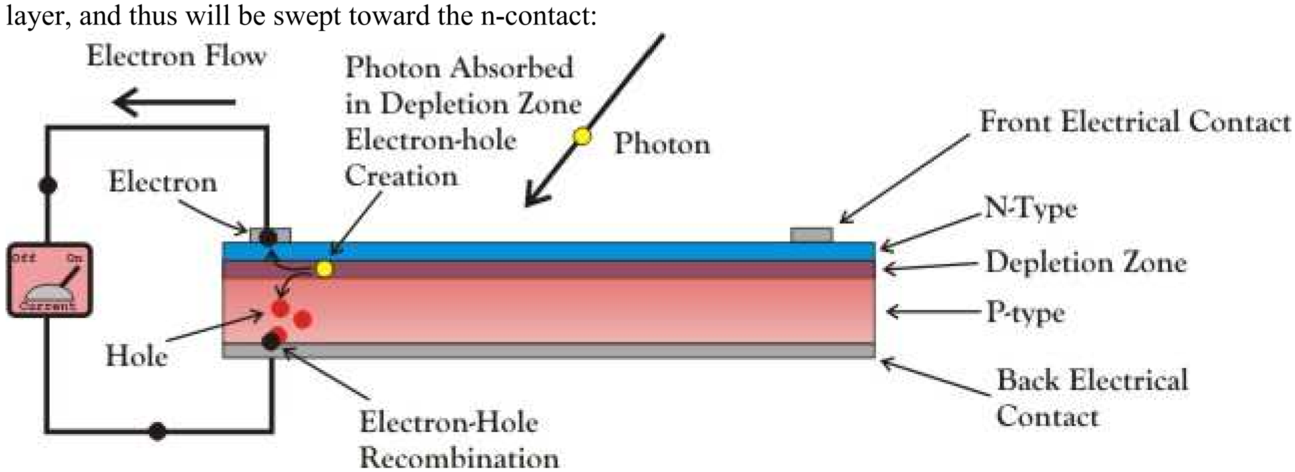


Energy Systems, Photovoltaics Appendix
Part B, operation of solar cells in the light

Now, when light hits the solar cell, the light energy may be imparted to valence electrons, essentially making them mobile:



Thus, light may create an excess of mobile electron, and holes, since when the light knocks the electron off the bond, it leaves behind a hole that can move. The light-generated holes will be repelled by the positive space charge in the n-layer, and thus will be swept toward the the p-side contact, and the light-generated electrons will be repelled by the negative space charge in the p-layer, and thus will be swept toward the n-contact:

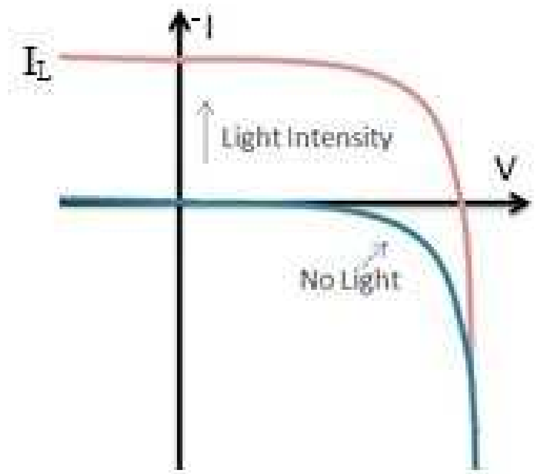


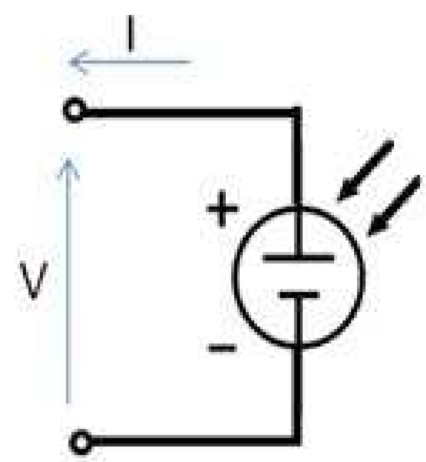
Now, the important things to realize here is: (1) the movement of these photogenerated electrons and holes *is in the opposite direction to the normal flow of electrons and holes in the dark*. Remember, from the previous section, that we get current flow in a pn junction in the dark when a positive bias is applied to the p-layer, thus pushing holes from p-to-n (and vice versa for electrons). The reason again is that the flow of electrons and holes in the dark occurs due to a reduction of the built-in electric field, that allows them to flow. So, in the dark, the flow of carriers is against the field (occurring due to the "pressure" of excess holes on the p side and excess electrons on the n side). Now, when we bring light in, it generates excess carriers that go in the direction of the electric field, so opposite to the dark current. The second thing to realize is: (2) this flow of photogenerated electrons and holes *is independent of the applied bias.* That is, since the flow of photogenerated electrons and holes is caused by <u>any</u> amount of built-in field, they don't care if it is reduced (in forward bias) or strengthened (in reverse bias).

So, the light simply adds a current in the direction opposition to the dark current, and we can modify our diode current vs. voltage equation simply by adding a light-generated term:

$I(V) = A\exp(-Eb0/kT)[\exp(eV/kT)-1] - IL$.

Plotting this function (actually it's negative, or upside down compared to the dark curve shown previously), we get





Here, we've actually plotted –I. The reason is that, when used as a solar cell, the diode of course supplies current, is not fed it.

Note that the solar cell **can provide both voltage and current**, if operated not at I=0 or V=0. This is directly because the photogenerated carriers produce current regardless of the voltage across the diode. The power, again, is current times voltage, so we want to maximize their product, and that is done near the "knee" of the curve. The equation for power is Vx(-I), or

$W(V)=V\{Ip- A\exp(-Eb0/kT)[\exp(eV/kT)-1]\}$.

Here, if the solar cell is charging a battery, V is the battery voltage. Note that the maximum voltage the solar cell may provide is determined by the voltage at which current drops to zero, or

$0=Ip-A\exp(-Eb0/kT)[\exp(eVmax/kT)-1]$,

$Ip= A\exp(-Eb0/kT)[\exp(eVmax/kT)-1]$,

$Vmax=(kT/e)\ln\{Ip/[A\exp(-Eb0/kT)]+1\}$.

Thus, a solar cell cannot charge a battery with a voltage greater than Vmax. In practice, this problem is solved by placing more than one solar cell in series connection, adding their voltages, until it suffices to charge the battery.

The maximum power supplied by the solar cell, of course, does not occur at Vmax, since there is no current then. Rather, Vmax is sized slightly larger than the battery voltage. Look in the above plot, and you see that as we lower the voltage from Vmax, the current goes up rapidly. For voltages lower than the "knee" the current does not rise, so the maximum power occurs right near the "knee". Since this "knee" voltage is near Vmax, the maximum power can be written as

$W_{max}=fI_LV_{max}$,

where $f<1$, and typically is 0.8. f is the "fill factor" of the solar cell current-voltage curve, is typically determined by detrimental effects not included in this idealized analysis, that are beyond the scope here.

Homework 7 (due 10/21):
A solar panel consisting of 36 solar cells in series has a Vmax of 22 volts in full sunlight at a temperature of 25 C. The barrier energy in the cells is 1 eV. How does Vmax change with temperature? Compare with the specification of a real solar panel you find on the web.

II. Energy sources

4. Solar energy.

b. Biomass/biofuels

Solar energy is stored in chemical form by photosynthesis within plants. Indeed, as we've learned this chemical storage of solar light is the precursor to coal at least, and almost certainly with exceptions by a few scientists, oil and natural gas as well.

In the utilization of plants for energy, they are called biomass. In 2005, 3.3 quads of biomass energy was used in the United States, out of the ~ 104 quads total energy consumption. Of this, 2.1 quads was wood, and 1.4 quads was the burning of wood to fire electric power generators. Only 0.3 quads was biofuels, or plant matter converted into liquid fuel, and this consisted nearly entirely of corn converted into ethanol.

As can be seen by the previous paragraph, biomass can be burned directly for space heating or to fire an electric generator, or can be converted into liquid fuel. This is entirely analogous to coal being burned (not so much for space heating anymore) to fire an electric generator, or converted to liquid fuel. And the argument made previously in the coal-to-liquids section is entirely analogous that it is far more efficient both in terms of energy and lowered CO2 emissions to do the former. More on that later, but for now we'll just consider biomass an energy source for burning, and calculate its total resource base as we've done for other sources.

Biomass as a total resource base can be estimated based upon understood figures for the amount of energy that can be grown per year per area using several plant types. Ignoring the plant's utility for converting into liquid fuel, the most efficient plant in terms of energy growth per year is switchgrass, a woody reed, although certain fast growing trees such as willow are close. Although quoted figures vary widely, it is reasonable to expect switchgrass production of about 15 tons, or 14,000 kilograms per acre per year. Note this is the weight of the harvested switchgrass after drying (ever try to burn something wet?). The harvested **switchgrass** then has an energy content of about 20 gigajoules per ton. Note, this equals **21,000 BTU/kilogram**, similar to lower grade coal, which makes sense as we've seen that coal is basically compressed plant matter. Multiplying by the weight per year per year, we get that the energy production is $21{,}000 \times 14{,}000 = 3 \times 10^8$ BTU per acre per year.

The total area of the United States is about 2.3 billion acres. The amount of this which is arable, or upon which plants can be grown for harvest, is quoted variably, but roughly averages about 20 %, or 460 million acres. Of this amount, if half is retained to grow food (enough ?), that leaves 260 million acres which can produce energy crops. Multiplying this by 3×10^8 BTU per acre per year, we obtain **78 quads per year total biomass resource base before subtracting energy inputs**.

This sounds good, but is not the whole story as energy is required to plant and harvest. Analyzing these energy inputs is difficult and results in the large variability of resource estimates. Furthermore it varies widely with crop as different plants require different amounts of fertilizer, water, etc. Finally it varies widely with location as some locations require more fertilizer and irrigation than other. According to http://www.eia.doe.gov/neic/speeches/howard101807.pdf, in 2006 the EIA estimates direct (not including fertilizer) energy use on farms as 0.9 quads or about 1 % of total energy use in the country. Fertilizer energy use is estimated at 0.5 quads, yielding 1.4 quad total energy use:

component	Energy use on US farms in 2006
fertilizer	0.5 quads
diesel	0.45 quads
gasoline	0.15 quads
electricity	0.12 quads
propane	0.08 quads
natural gas	0.08 quads

other	0.02 quads
total	**1.4 quads**

As most of agricultural production in the United States is directed toward food at the present, we can try to estimate energy output of farms based upon the number of people we are able to feed, which is about twice the total population (food is a main export for the U.S.). As discussed in the introduction, it takes about 100 watts to power a human, so if we assume 500 million humans are powered by US farm production, that's 50 gigawatts, or 1.5 quads per year. This production is much lower than the resource base because we don't eat all of the plant, but only the good parts. Note that to get the good parts that we like to eat, there is about a one-to-one conversion of the energy components of the above table into food energy. So agriculture amounts roughly to a direct conversion of energy into food.

To get the total energy production in biomass, we have to assume a ratio of the amount of the energy in the rest of the plant compared to the good parts. Just based upon looking at a corn stalk, it would appear that about 3 times its mass is present in the stalk and leaves compared to the corn ears (this is really rough). But, the stalk and leaves have less energy content. Therefore, let's assume that twice the energy exists outside the good part, or **current biomass production by agriculture is about 3 quads per year**. Note this is less than the currently total used biomass quoted above as most of that is wood. We'll assume here that we are not going to start cutting down our forests for energy.

Thus the agricultural inputs required is about 50 % of energy produced. So, in the above total resource base or 78 quads per year, about half of this would be required to plant and harvest. Thus, **the net biomass resource in the United States is about 39 quads per year**.

Now we get to biofuels, or the conversion of this resource base into liquid fuel. The efficiency of this conversion is complicated by the fact that much of the technology, particularly for converting the stalks and leaves (cellulose) is under development. And, it's generally agreed that the current use of the good parts such as the corn ears is not very efficient and probably will not solve our energy problems significantly.

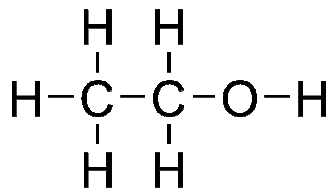
We can do a similar efficiency estimate as done for coal-to-liquids, though, assuming the cellulostic conversion techniques are developed, by noting that in going from cellulose to liquid fuel, energy is concentrated. From above, the energy density in dried switchgrass is 21,000 BTU/kg. Ethanol has about 25,000 BTU/kg. However, ethanol as a fuel is not very useful, as it has a tendency to absorb water and corrode pipelines. A long term solution would be conversion to diesel, which as we've seen has an energy content of about 42,000 BTU/kg. As the energy density is doubled we might expect an ultimate energy conversion of 50 %. This may be optimistic. Thus assuming this conversion efficiency, the **net biofuel resource in the United States is about 20 quads per year**.

As covered in the coal-to-liquids section, use of biofuels to power internal combustion engines, rather than burning the biomass to generate electricity and power electric vehicles, suffers from the biomass-biofuel conversion efficiency (~ 0.5), and the reduced efficiency of the internal combustion engine compared to electric generator/motors (0.2/[0.32x0.8] = 0.78), for an overall net reduction of 0.5x0.78 = 0.39, which is the price paid for the luxury of using a liquid fuel car compared to an electric car. Thus for biofuels, 1/0.39 = 2.6 times more energy must be used, and 2.6 times more CO_2 is emitted into the atmosphere, compared to electric generation and electric vehicles.

Energy Systems, bio-energy appendix

Ethanol-

Ethanol, a fuel or fuel additive for gasoline motors (as well as the main component of alcoholic beverages), is C_2H_6O, although to be clear about what it is you must look at the chemical formula this way:



One sees that it is like ethane except instead of a hydrogen atom on one end, there is –OH. It is produced by taking glucose (sugar) and fermenting it:

$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$

We see that fermentation of sugar to make ethanol also produces carbon dioxide. This is an exothermic reaction so produces energy (the energy came from the sun in the photosynthesis that produced the glucose). Fermentation is commonly performed with the use of yeast, a type of fungus, that consumes glucose and produces ethanol and carbon dioxide as waste products. So basically, the yeast consumes the glucose as food, but whereas when we consume glucose in the presence of oxygen the products are water and carbon dioxide, which have no energy availability, yeast produces ethanol instead of water, and the "waste" product still has energy content. So basically,

$C_6H_{12}O_6$ (aq) + 6 O_2 (g) → 6 CO_2 (g) + 6 H_2O (l) (when we eat glucose [aerobic respiration])

$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$ (when yeast eats glucose [anaerobic respiration])

So, ethanol production is performed by a biological intermediary. As an interesting side not, ethanol fermentation is responsible for the rising of bread dough. Yeast organisms consume sugars in the dough and produce ethanol and carbon dioxide as waste products. The carbon dioxide forms bubbles in the dough, expanding it into something of a foam. Nearly all the ethanol evaporates from the dough when the bread is baked, though.

When you ferment glucose to produce ethanol, the vessel containing the yeast and glucose feedstock is designed such that the carbon dioxide is allowed to escape, but oxygen is prevented from coming in. The reason is that oxygen will cause the aerobic reaction above, producing water instead of ethanol.

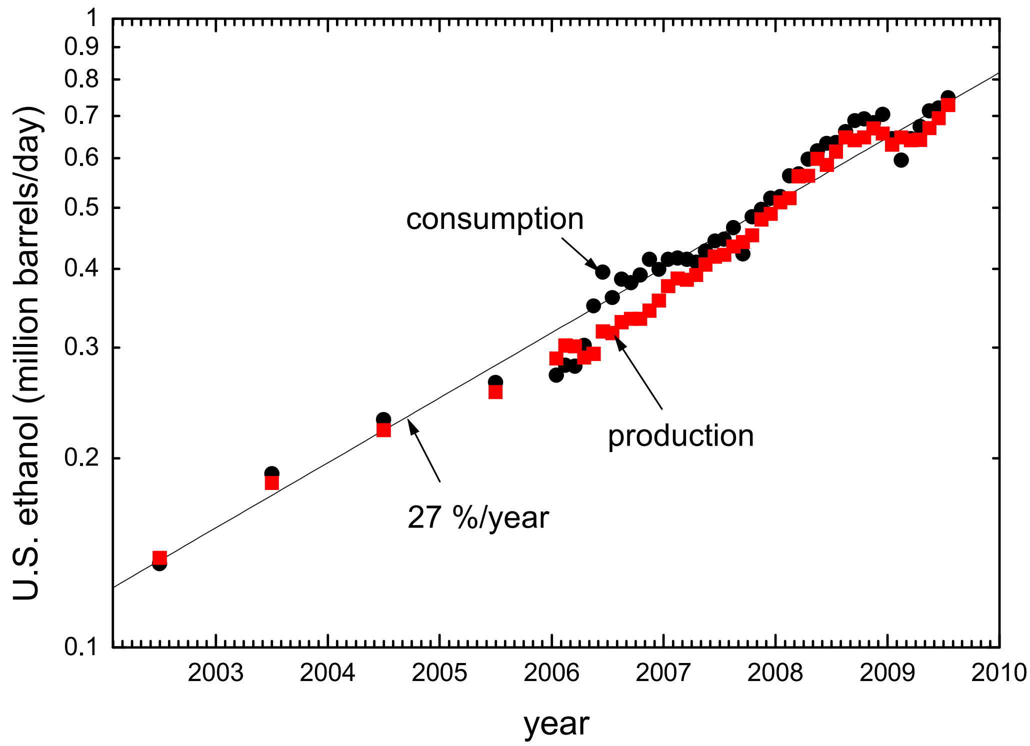
The burning of ethanol as fuel (or metabolism) is through the presence of oxygen as any other fuel, or

$C_2H_5OH + 3\ O_2 \rightarrow 2\ CO_2 + 3\ H_2O(l) + 14.3$ eV.

Since an ethanol molecule weighs (12x2+5+16+1)x1.66e-27 = 7.64E-26 kg, the energy content of ethanol is then 14.3x1.6e-19/7.64E-26 = 2.99E7 joules/kg, or 28,400 BTU/kg. Recall that alkanes in the range from $5<n<15$ had an energy content of about 43,000 BTU/kg, so ethanol is significantly lower. This perhaps makes sense, as ethanol results from one level of digestion already occurring in the yeast.

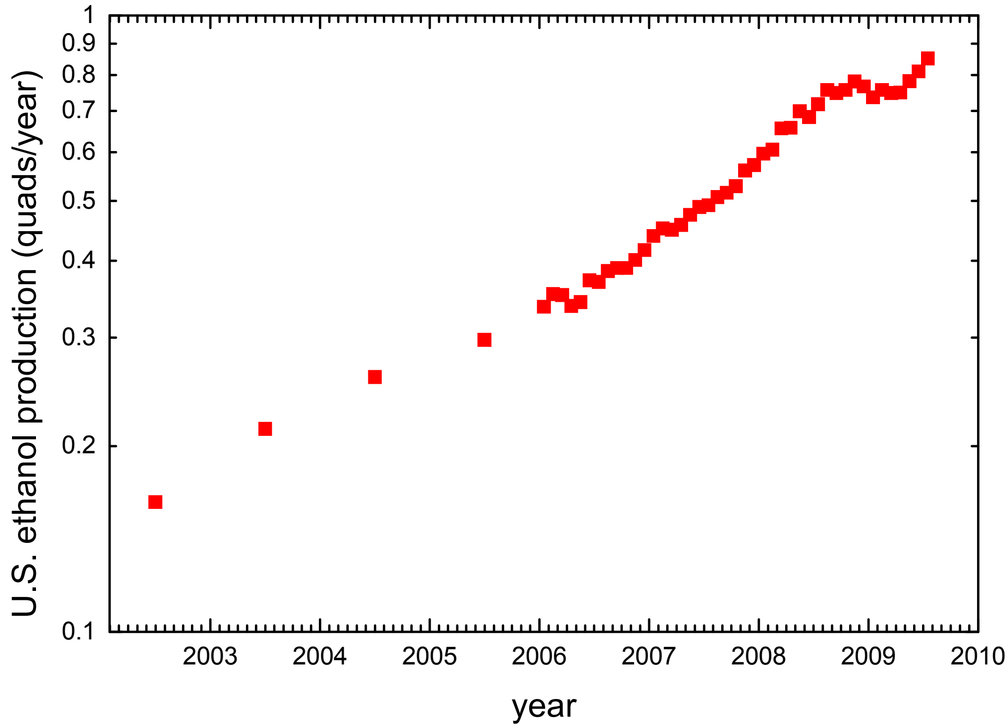
Since the energy content of ethanol is lower than alkanes, their use in fuels will result in a reduction of, for example, miles per gallon in cars, roughly by an amount proportional to the reduction in energy content per gallon. Since the mass density of ethanol is 0.79 g/cm3, and gasoline is about the same at 0.7 g/cm3, the volume energy density reduction is similar to the mass energy density reduction.

The use of ethanol as fuel, typically as a ~ 10 % percentage with standard gasoline, has seen dramatic increase in the last few years:



One sees that, apart from a gap in consumption-production in 2006 (which was made up for from imported ethanol), consumption has roughly equaled domestic production. Consumption has increased by placing a larger percentage in standard gasoline. When you fill up at the pump, the ethanol content may be as high as 10 %, after which it can cause problems with standard gasoline engines. Since consumption of gasoline is about 9 million barrels/day, ethanol consumption is rapidly approaching that limit, after which increased use must be via flex-fuel vehicles, which can take higher percentages.

Using an energy content of 28,400 BTU/kg, and a mass density of 0.7 kg/liter or 2.99 kg/gallon, one comes up with a volume energy content of 85,000 BTU/gallon. It is usually quoted as 76,000 BTU/gallon, since in the above calculation the reaction proceeded to liquid water, but in a car, the water in the exhaust is still vapor. Using 42 gallons/barrel, then, the energy content in a barrel of ethanol is 3.2 million BTU. We can then redraw the ethanol production curve in quads/year:



And thus, ethanol production is approaching 1 quad/year, or about 1 % of US energy use. Note in the class energy chart it is shown as 0.1 quad/year, but that was for 2001.

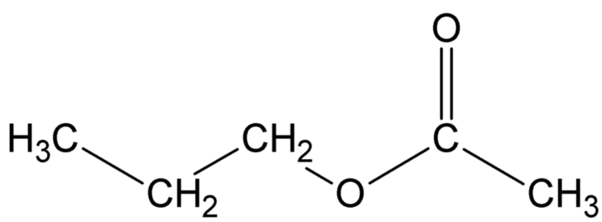
The most contentious aspect of ethanol is whether, after counting all the energy that goes into making it, additional energy is recovered. That additional energy comes of course, from the solar energy used to grow the feed stock. That is to say, after all the diesel (to run the tractors, etc.), fertilizer (formed from natural gas), etc., non-solar energy inputs, does one recover more energy in the burning of the ethanol? Estimates of ethanol's energy returned on energy invested range from below 1 (less recovered than invested), to usually accepted values of 1.5-2 for corn-derived ethanol (if one counts the animal feed left over from the process), to 7-9 for sugar cane derived ethanol. To a certain extent, since the efficiency of the internal combustion engine is less than 20 %, this question could be moot. But, how it matters is in determining whether it is more effective to use the diesel and natural gas that went into the ethanol production directly, rather than through the ethanol. This is a difficult question to answer, as the major fuel input is the fertilizer, that was formed from natural gas, which is generally not used directly as a vehicle fuel. So, even if the ethanol resulted in a one-for-one conversion of natural gas and diesel energy into ethanol energy, one could argue that as it is easier to use ethanol as it is a liquid fuel, that this has been a fair exchange. Ultimately, the question will be answered through economics, as certainly if one makes money while producing ethanol, after having purchased all the fuel (and everything else) that goes into it, it's likely energy has been recovered. That logic is currently confounded by a $0.45/gallon federal subsidy of ethanol. Opponents of ethanol have argued that if it makes sense to do, the subsidy should be lifted.

Finally, much of the hope for ethanol as a future fuel rests upon the ability to produce it, not just from glucose, but from the woody parts of the plant, or the cellulose. There are two ways this could be done: (1) the cellulose is first converted to glucose, usually projected to be done by the introduction of enzymes or acids that break the long-chain cellulose molecules into simple sugars, followed by fermentation is before, or (2) basically by steam reforming of cellulose to produce syngas, essentially similar to coal-to-liquids.

Construction of pilot scale lignocellulosic ethanol plants requires considerable financial support through grants and subsidies. On 28 February 2007, the U.S. Dept. of Energy announced $385 million in grant funding to six cellulosic ethanol plants. This grant funding accounts for 40% of the investment costs. The remaining 60% comes from the promoters of those facilities. Hence, a total of $1 billion will be invested for approximately 140 million gallon capacity. This translates into $7/annual gallon production capacity in capital investment costs for pilot plants (this would work out to $.35/gal over the 20-year life of a facility); future capital costs are expected to be lower. Corn to ethanol plants cost roughly $1–3/annual gallon capacity, though the cost of the corn itself is considerably greater than for switchgrass or waste biomass.

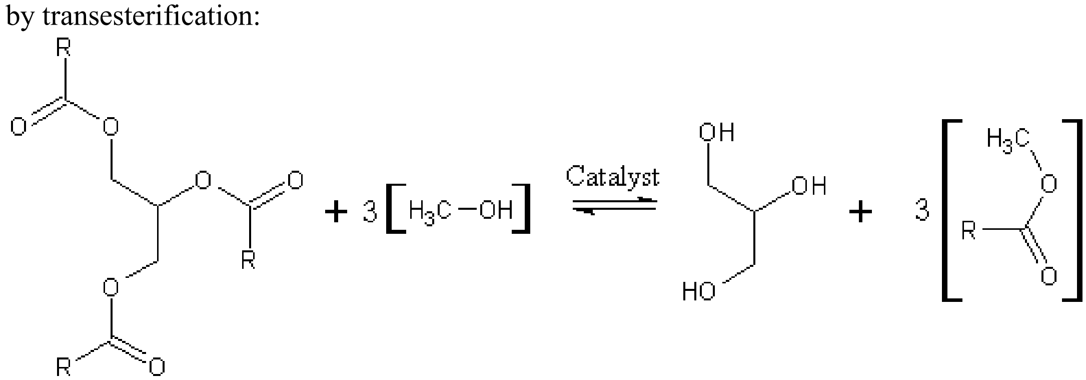
<u>Biodiesel-</u>

Biodiesel is not the same chemical as "diesel" from petroleum which we have seen is an alkane molecule, but rather is an alkyl ester, such as propyl:



One sees that propyl is basically like propane, except the end hydrogen has been replaced the oxygenated structure shown. Biodiesel can consist of methyl, ethyl, or propyl esters, which refers to the number of carbons in the alkane-like chain.

Biodiesel is made from vegetable oil, which is produced directly from the seeds and nuts of certain plants such as soybeans or palm nuts. Vegetable oil is a triglyceride, which means it is a long chain hydrocarbon having three fatty acid molecular groups. Vegetable oil can be used as a fuel directly (by modification of a diesel vehicle to pre-heat the vegetable oil to make it less viscous), but for a standard diesel vehicle it must be made less viscous by converting to biodiesel by transesterification:



Triglyceride Methanol (3) Glycerol Methyl Esters (3)

As such, production of biodiesel consumes both triglyceride (vegetable oil) and methanol. Methanol itself is wood alcohol, and can be produced by heating wood in a test tube (so there is no oxygen). Note: do not drink! But, it is most commonly produced from natural gas (methane), by the production of syngas as we have previously discussed in gas-to-liquids:

$CH_4 + H_2O \rightarrow CO + 3\ H_2$

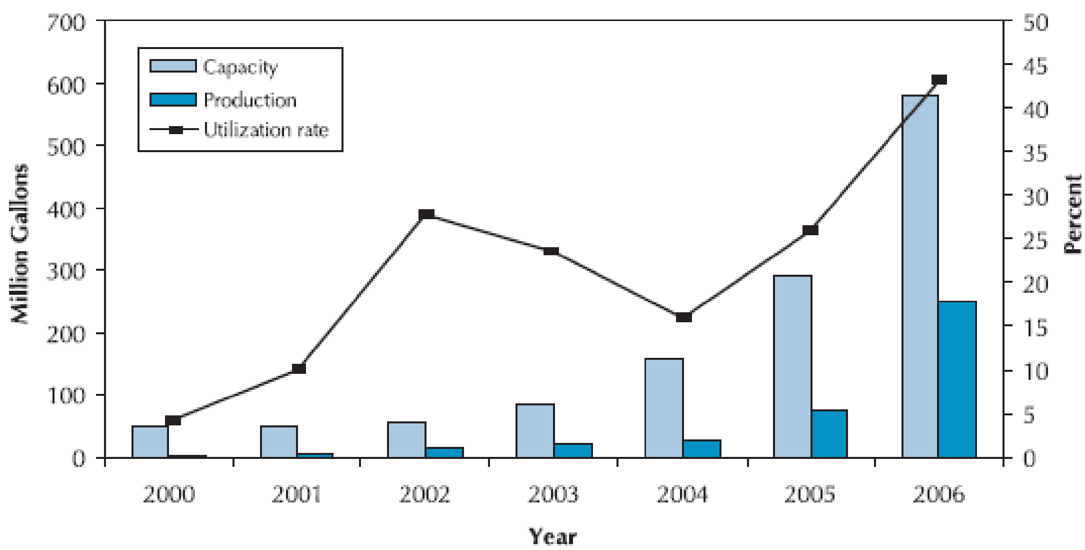
which, after adjusting the amount of CO to H2 via certain reactions, can be reacted to produced methanol:

$CO + 2\ H_2 \rightarrow CH_3OH$.

Thus, in a sense biodiesel is not 100 % bio, in that it currently it consumes natural gas via the methanol used to produce it. Of course, methanol could be produced from biomass via syngas production, by for example steam reforming, but currently it is much cheaper to produce syngas from natural gas.

One notes that to be a biofuel purist, one would use pure vegetable oil, which, as noted, requires vehicle modification to preheat the oil. But, this can be efficiently done by using the waste heat generation from the vehicle. One does need battery power to "preheat" the vegetable oil before the engine warms up.

Biodiesel production is shown here:



Source: National Biodiesel Board.
Note: Capacity given is on September 1 of each year.

Figure 1. U.S. biodiesel production and installed capacity for 2000 to 2006

Production rates in 2006 were ~ 250 million gallons per year, or dividing by 365, and 42 (gallons per barrel), about 16,000 barrels/day. Thus, biodiesel production rates are only ~ 5 % that of ethanol.

III. Energy conversion and efficiencies

1. Laws of thermodynamics.

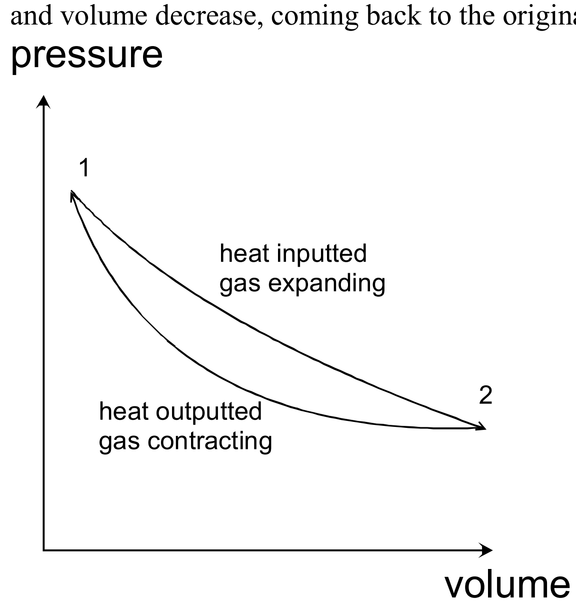
So far we have covered energy sources. In all cases except photovoltaics, wind/waves/tidal, and hydroelectric, the source of energy was really a source of heat. That is, whether it is oil, coal, natural gas, or biomass/biofuels, the source must be burned to release the energy as heat. In the case of nuclear, again, the source is a source of heat.

This heat must be converted to the movement of something whether it be a turbine or a piston/driveshaft, and the thing that performs this conversion is an *engine*, and the movement of the something is called useful *work*, and the rules that determine how much of the heat can be converted into work is called *thermodynamics*. Of course, we're interested in converting all the heat into work, but that doesn't happen, and as can be seen by the spaghetti chart, we're currently converting about 37 % of source energy into useful energy, just taking the outputs on the right and dividing by the inputs on the left. This is not exactly the heat/work conversion efficiency, as there are other losses in the system, but as there are non-heat inputs such as hydroelectric, it's around the heat/work efficiency.

Here well cover the ultimate heat/work efficiency theories to get an idea of what is possible. Although this section is called the laws of thermodynamics, I don't want to get hung up on that as it seems to make things more mysterious than they really are. All the first law says is that energy is conserved, which, duh, and all the second law says is that you can't convert all of the heat into work, which again, duh.

Heat/work conversion efficiencies must be analyzed in terms of specific engines, and the most efficient is the Carnot engine. You can prove it is the most efficient, but we'll save that for later. In the Carnot engine, a gas is contained in a cylinder which has a piston in it, so that when the gas expands the piston is pushed and work is done. The Carnot engine is not an internal combustion engine (we'll cover that below) in that the heat comes from outside the cylinder. This is sort of difficult practically, so our analysis is somewhat a theoretical exercise, but it as it provides the highest work/heat efficiency, we must go through it.

Heat/work conversion efficiency in engines is often analyzed in terms of diagrams of pressure of the gas vs. the volume of the cylinder. As heat is added the gas expands and both pressure and volume increase as the piston is pushed upwards. We could not make an engine if the piston just kept going up, it must come back down in a part of the cycle where the pressure and volume decrease, coming back to the original pressure and volume:



From the introduction, we know that work is the integral of force times distance, and force is pressure times area, so we know that the work done by the expanding gas is

$$W_{\text{expansion}} = \int_1^2 Ap(z)dz = \int_1^2 p(z)dV \ . \qquad \text{(III.1.1)}$$

On the contracting part, since the motion of the piston is in the opposite direction, the work is negative (the piston is doing work on the gas, similar to the midterm problem). Thus, we say the work done on the piston is

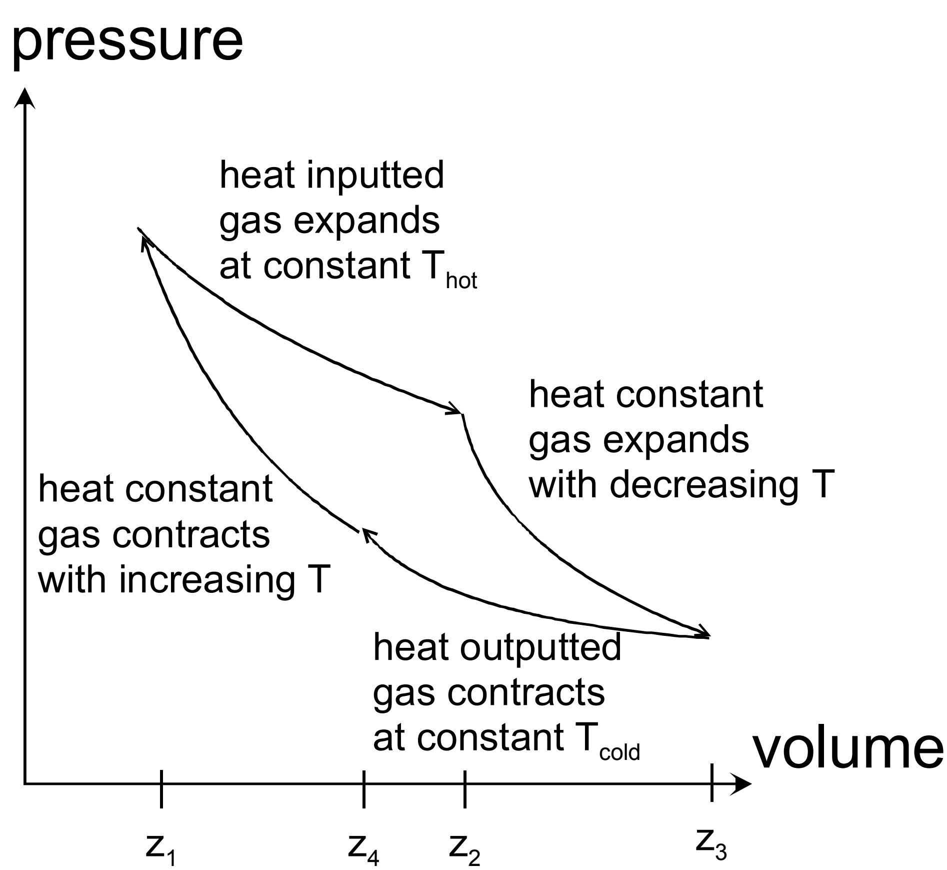
$$W_{\text{contraction}} = \int_2^1 Ap(z)dz = -\int_1^2 p(z)dV \ . \qquad \text{(III.2)}$$

As the above integrals are the net work on the piston, and these integrals are the areas under the respective curves, the **net work is the area enclosed by the plot**:

$$W = \oint pdV \ . \qquad \text{(III.3)}$$

Thus we see that if on the p vs. V diagram, the contraction path follows the same path as the expansion path, no net work is done.

The Carnot cycle is shown here:



We can analyze this assuming that the gas is an ideal gas. Then, along the paths with constant temperature, (remember, $pV \propto T$ for a gas with a constant number of molecules),

$$pV = \text{constant}, p(z) \propto \frac{1}{V} \propto \frac{1}{z}, \quad \text{paths 1-2 and 3-4.} \qquad \text{(III.1.4)}$$

We can now analyze the efficiency. At point 1,

$$pV = \beta T_{hot} \qquad \text{(point 1),} \qquad \text{(III.1.6)}$$

where β is a constant in the cycle dependent upon the total number of gas molecules in the cylinder, which does not change. Thus, from 1 to 2, the temperature does not change, and thus

$$p = \frac{\beta T_{hot}}{V} = \frac{\beta T_{hot}}{Az}, \qquad \text{from 1 to 2, and} \qquad \text{(III.1.7)}$$

$$W_{12} = \int_1^2 p(z)dV = \int_{z_1}^{z_2} \frac{\beta T_{hot}}{Az} dV = \int_{z_1}^{z_2} \frac{\beta T_{hot}}{Az} A dz = \beta T_{hot} \ln(\frac{z_2}{z_1}). \qquad \text{(III.1.8)}$$

Now, since the gas is at a constant temperature, this work done by the gas as it is expanding must equal the heat inputted during this part of the cycle. Thus,

$$Q_{input} = W_{12} = \beta T_{hot} \ln(\frac{z_2}{z_1}). \qquad \text{(III.1.9)}$$

Likewise, the negative work done from 3 to 4 equals the heat lost from the system (it does not return to the heat source, but is "lost" from the entire system):

$$\Delta W_{34} = \int_3^4 p(z)dV = -\int_{z_4}^{z_3} \frac{\beta T_{cold}}{Az} A dz = -\beta T_{cold} \ln(\frac{z_3}{z_4}). \qquad \text{(III.1.10)}$$

This negative work represents heat leaving the gas and lost, so that is

$$Q_{lost} = -W_{34} = \beta T_{cold} \ln(\frac{z_3}{z_4}). \qquad \text{(III.1.11)}$$

Now, by the conservation of energy, the difference between the heat inputted and the heat lost must be the work done on the piston:

$$W = Q_{input} - Q_{lost} = \beta T_{hot} \ln(\frac{z_2}{z_1}) - \beta T_{cold} \ln(\frac{z_3}{z_4}). \qquad \text{(III.1.12)}$$

The efficiency of the engine equals the work done divided by the heat inputted:

$$\eta = \frac{W}{Q_{input}} = \frac{\beta T_{hot}\ln(\frac{z_2}{z_1}) - \beta T_{cold}\ln(\frac{z_3}{z_4})}{\beta T_{hot}\ln(\frac{z_2}{z_1})} = 1 - \frac{T_{cold}\ln(\frac{z_3}{z_4})}{T_{hot}\ln(\frac{z_2}{z_1})}. \qquad \text{(III.1.13)}$$

Now, it turns out we can determine a relationship between z_3 / z_4 and z_2 / z_1 from the rules of an ideal gas. From 2 to 3, the gas does not change heat content, but changes temperature. While this sounds contradictory, it is not, as the same gas at the same temperature, but at different volumes, has different heat content. The reason for this can be summarized by understanding that the increased volume presents a larger surface area with which to transfer heat. Since the container is at the same temperature, the heat content must increase with the surface area to keep the system in thermal equilibrium. Thus, the heat content goes with temperature times surface area, and since surface area goes as the square of the linear dimension of the container, and volume goes as the cube, the heat content goes as temperature times volume to the 2/3 power. Thus, at constant temperature,

$$\text{heat content of ideal gas} \propto TV^{2/3} \propto (pV)V^{2/3} \propto pV^{5/3}. \qquad \text{(III.1.14)}$$

Thus, from 2 to 3, $pV^{5/3}$ is constant. Since at point 2,

$$pV = \beta T_{hot}, \qquad \text{(point 2)} \qquad \text{(III.1.15)}$$

then at point 2 also,

$$pV^{5/3} = \beta T_{hot}(Az_2)^{2/3}. \qquad \text{(III.1.16)}$$

Now, since from 2 to 3 the heat content of the gas is constant, we have that

$$p_3 V_3^{5/3} = (p_3 V_3)V_3^{2/3} = \beta T_{cold}(Az_3)^{2/3} = \beta T_{hot}(Az_2)^{2/3}. \qquad \text{(III.1.17)}$$

Thus, we see that during a part of the cycle when the heat content of the gas does not change, $Tz^{2/3}$ is constant. Thus we also have that

$$T_{hot} z_1^{2/3} = T_{cold} z_4^{2/3}. \qquad \text{(III.1.18)}$$

Examining III.1.17 and III.1.18, we see that

$$\frac{z_2}{z_3} = \frac{z_1}{z_4} = (\frac{T_{cold}}{T_{hot}})^{3/2}. \qquad \text{(III.1.19)}$$

Rewriting this, we have that

$$\frac{z_2}{z_1} = \frac{z_3}{z_4}. \qquad \text{(III.1.20)}$$

Now examining equation III.1.13, we have that

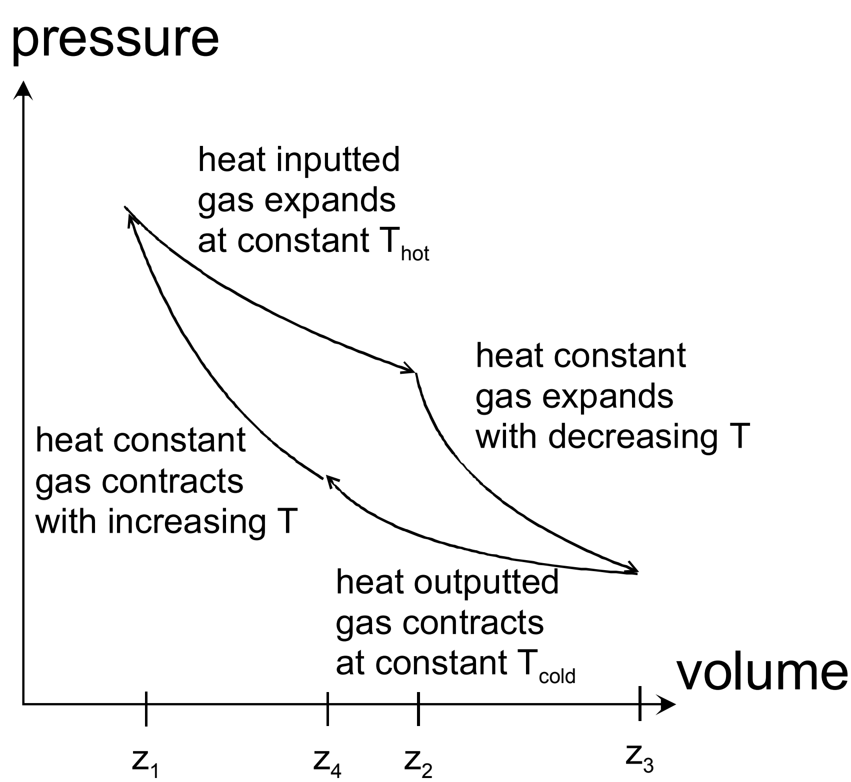
$$\eta = 1 - \frac{T_{cold}\ln(\frac{z_3}{z_4})}{T_{hot}\ln(\frac{z_2}{z_1})} = 1 - \frac{T_{cold}\ln(\frac{z_3}{z_4})}{T_{hot}\ln(\frac{z_3}{z_4})} = 1 - \frac{T_{cold}}{T_{hot}}. \quad \text{(III.1.21)}$$

Thus, we have that the efficiency depends upon the ratio of the hot and cold temperatures of the cycle. Indeed, a real Carnot engine would first bring a reservoir at T_{hot} into perfect thermal contact with the engine, absorb heat at that temperature, then isolate the engine so that no more heat transfer occurred until the gas had cooled by expansion to T_{cold}, then bring a reservoir at T_{cold} into perfect thermal contact to absorb waste heat from the system, then isolate the engine so that the gas would continue contracting, then bring it into perfect thermal contact with the hot reservoir to start the cycle again. The greater the difference between the cold and hot reservoirs, the larger the efficiency is. For no difference, efficiency is zero and no work can be extracted.

While the Carnot engine is not real and more a theoretical exercise, it illustrates the principle that extracting work from heat requires being able to move the system from hot to cold to hot, etc. Since in practical terms the "cold" reservoir is at room temperature (or higher), we see that to get the most efficiency, we want as high a temperature as possible from our source of heat

APPENDIX

Equation III.1.12 may not be perfectly clear, since you may not believe the statement "the difference between the heat inputted and the heat lost must be the work done on the piston." We can find III.1.12 another way. Let's confirm in the Carnot cycle that the work done from 2-3 is cancelled out by the negative work done from 4-1:



Recall that, from 2 to 3, $pV^{5/3}$ is constant. Since at point 2,

$$pV = \beta T_{hot}, \qquad \text{(point 2)} \tag{III.1.a.1}$$

then at point 2 also,

$$pV^{5/3} = \beta T_{hot}(Az_2)^{2/3}. \tag{III.1.a.2}$$

Then from 2 to 3,

$$pV^{5/3} = p(Az)^{5/3} = \beta T_{hot}(Az_2)^{2/3}. \tag{III.1.a.3}$$

and

$$p = \frac{\beta T_{hot} z_2^{\ 2/3}}{Az^{5/3}} \tag{III.1.a.4}$$

and

$$W_{23} = \int_{z_2}^{z_3} pdV = \int_{z_2}^{z_3} \frac{\beta T_{hot} z_2^{\ 2/3}}{Az^{5/3}} Adz = \int_{z_2}^{z_3} \frac{\beta T_{hot} z_2^{\ 2/3}}{z^{5/3}} dz = -(3/2)\frac{\beta T_{hot} z_2^{\ 2/3}}{z^{2/3}} \Big|_{z_2}^{z_3}$$
$$= (3/2)\beta T_{hot}[1-(\frac{z_2}{z_3})^{2/3}] \tag{III.1.a.5}$$

Likewise, from 4 to 1,

$$W_{41} = \int_{z_4}^{z_1} pdV = -\int_{z_1}^{z_4} \frac{\beta T_{hot} z_1^{\ 2/3}}{Az^{5/3}} Adz = -\int_{z_1}^{z_4} \frac{\beta T_{hot} z_1^{\ 2/3}}{z^{5/3}} dz = (3/2)\frac{\beta T_{hot} z_1^{\ 2/3}}{z^{2/3}} \Big|_{z_1}^{z_4}$$
$$= -(3/2)\beta T_{hot}[1-(\frac{z_1}{z_4})^{2/3}] \tag{III.1.a.6}$$

But, in the previous section , we found that

$$\frac{z_2}{z_1} = \frac{z_3}{z_4}, \quad \text{or} \qquad \frac{z_2}{z_3} = \frac{z_1}{z_4} \tag{III.1.a.7}$$

Comparing equations III.1.a.5, 6, and 7,

$$W_{23} = -W_{14}, \tag{III.1.a.8}$$

and no net work is done in the 23 and 14 parts of the cycle. Repeating our findings from the previous section,

$$W_{12} = \int_1^2 p(z)dV = \int_{z_1}^{z_2} \frac{\beta T_{hot}}{Az} dV = \int_{z_1}^{z_2} \frac{\beta T_{hot}}{Az} Adz = \beta T_{hot} \ln(\frac{z_2}{z_1}) . \quad \text{(III.1.a.9)}$$

and

$$W_{34} = \int_3^4 p(z)dV = -\int_{z_4}^{z_3} \frac{\beta T_{cold}}{Az} Adz = -\beta T_{cold} \ln(\frac{z_3}{z_4}) . \quad \text{(III.1.a.10)}$$

Since there is no net work in the 23 and 41 parts of the cycle, the total work done is

$$W = W_{12} + W_{34} = \beta T_{hot} \ln(\frac{z_2}{z_1}) - \beta T_{cold} \ln(\frac{z_3}{z_4}) , \quad \text{(III.1.a.12)}$$

and we have recovered III.1.12.

Repeating the rest of the analysis, since the gas is at a constant temperature during 12, this work done by the gas then must equal the heat inputted during this part of the cycle. Thus,

$$Q_{input} = W_{12} = \beta T_{hot} \ln(\frac{z_2}{z_1}) . \quad \text{(III.1.a.13)}$$

The efficiency of the engine equals the work done divided by the heat inputted:

$$\eta_{Carnot} = \frac{W}{Q_{input}} = \frac{\beta T_{hot} \ln(\frac{z_2}{z_1}) - \beta T_{cold} \ln(\frac{z_3}{z_4})}{\beta T_{hot} \ln(\frac{z_2}{z_1})} = 1 - \frac{T_{cold} \ln(\frac{z_3}{z_4})}{T_{hot} \ln(\frac{z_2}{z_1})} , \quad \text{(III.1.a.14)}$$

And by III.1.a.7,

$$\eta_{Carnot} = 1 - \frac{T_{cold} \ln(\frac{z_3}{z_4})}{T_{hot} \ln(\frac{z_2}{z_1})} = 1 - \frac{T_{cold} \ln(\frac{z_3}{z_4})}{T_{hot} \ln(\frac{z_3}{z_4})} = 1 - \frac{T_{cold}}{T_{hot}} . \quad \text{(III.1.a.15)}$$

Thus, we have that the efficiency depends upon the ratio of the hot and cold temperatures of the cycle. Indeed, a real Carnot engine would first bring a reservoir at T_{hot} into perfect thermal contact with the engine, absorb heat at that temperature, then isolate the engine so that no more heat transfer occurred until the gas had cooled by expansion to T_{cold}, then bring a reservoir at T_{cold} into perfect thermal contact to absorb waste heat from the system, then isolate the engine so that the gas would continue contracting, then bring it into perfect thermal contact with the hot reservoir to start the cycle again. The greater the difference between the cold and hot reservoirs, the larger the efficiency is. For no difference, efficiency is zero and no work can be extracted.

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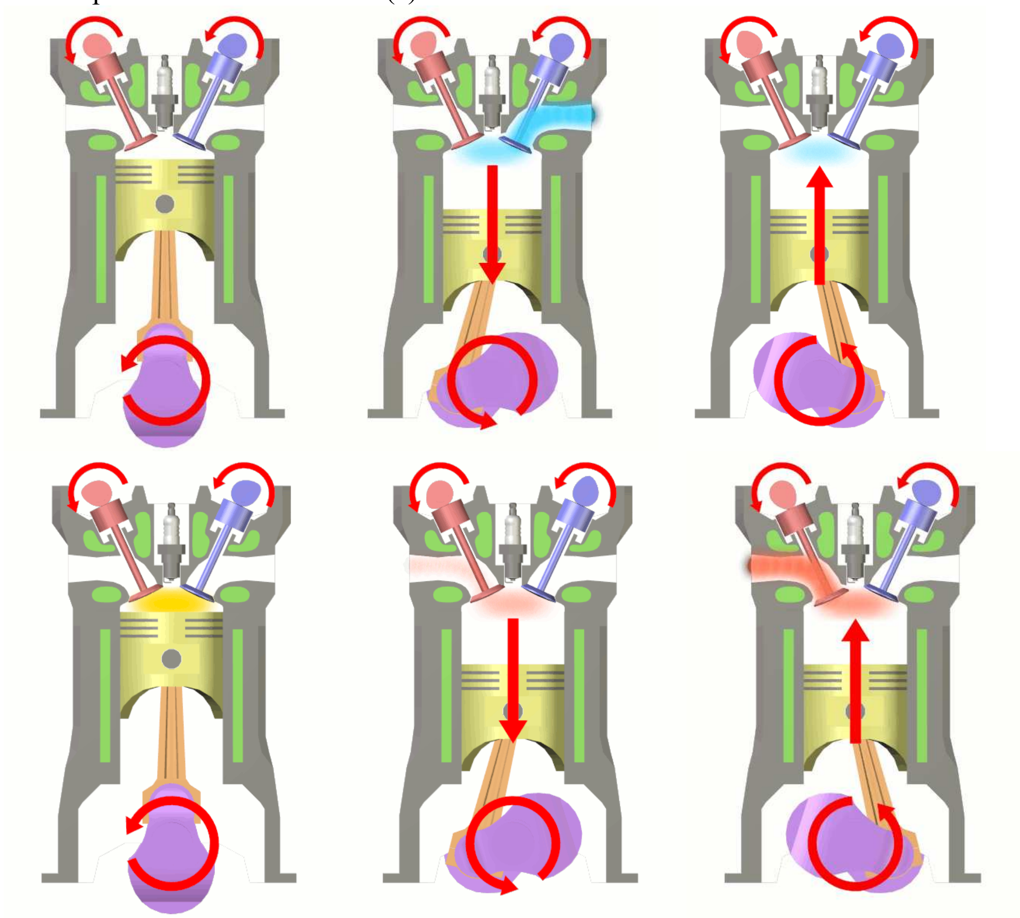
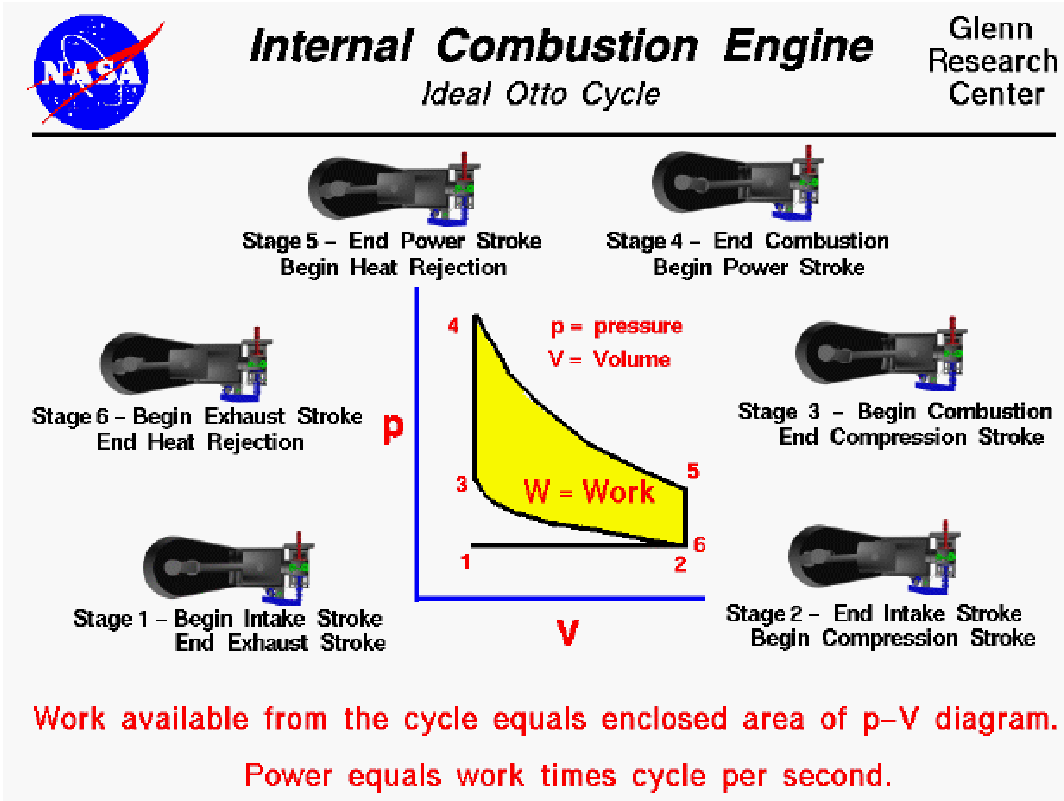
A real engine: the Otto cycle-
The Otto is basically a four-stroke gasoline engine and is the highest efficiency "real" engine based upon internal combustion (?). Here it is shown:



Here is its pressure/volume diagram:



It turns out that the thermal efficiency of the Otto cycle can be expressed in terms of the volumetric compression ratio $R = V_2 / V_1$. That is:

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - 1/(r^{k-1})$$

where k is the specific heat ratio ($= C_p / C_v$).

So we can improve the cycle's efficiency by increasing the compresion ratio. The following figure shows the relation graphically.

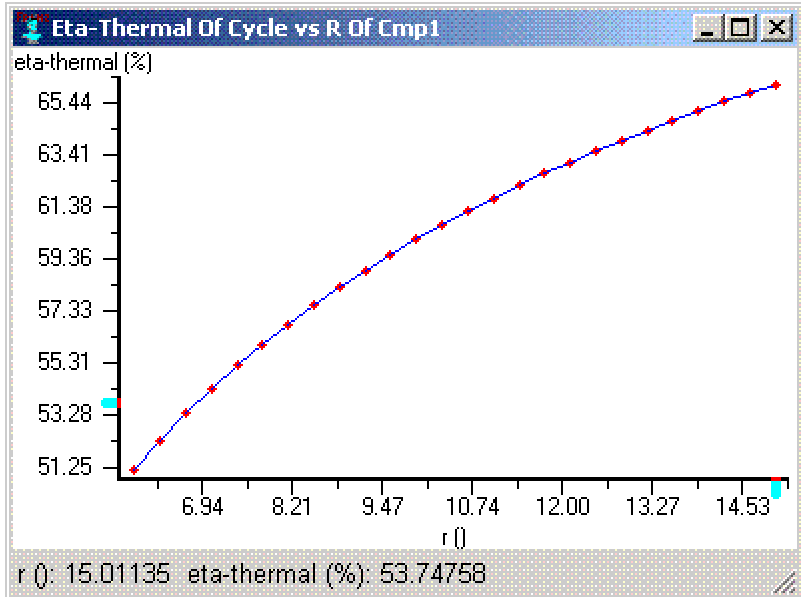


Figure 8: Cycle Efficiency vs. Volumetric Compression Ratio

So, if we were to change the value of *r* to 10, our cycle efficiency would increase to over 60%, which is a significant improvement.

This begs the obvious question: Why not set the compression ratio to something very large to get the highest efficiency? The answer is twofold. First, our compression ratio is limited by mechanical constraints in the system. If the pressure in the cylinder is too high, the chance of breaking the piston, the cylinder, or some other part of the engine. For example, bearings are prone to failure in automobile engines run with overly high compression ratios. The plot below shows the relationship between maximum cycle pressure and the compression ratio.

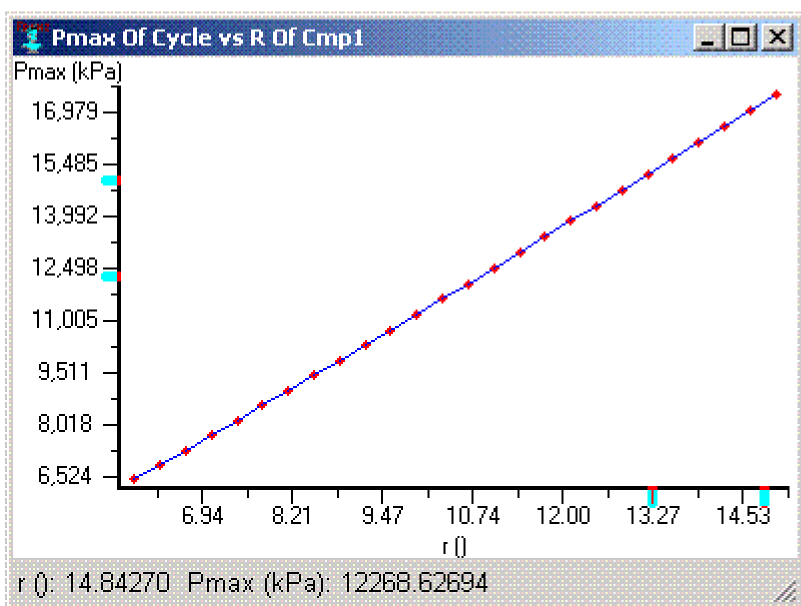


Figure 9: Maximum Cycle Pressure vs. Volumetric Compression Ratio

In taking the compression ratio from 8 to 11, for instance, we have increased the maximum cycle pressure from just under 9 Mpa to almost 12.5 Mpa.

In addition, as we increase the compression ratio, the increased pressure and temperature after the compression process increases the likelihood of *dieseling*, which describes a situation in which the fuel ignites on its own, before the ignition spark is applied. This conflicts with our assumption that ignition (and thus combustion) takes place when the piston is at the isochoric bottom dead center position. In addition, it can actually result in engine damage where the combustion takes place even before the piston has finished getting through the compression process and forces the piston backup before the crank shaft has rotated to the proper position (before it has gone from the orientation shown in figure 3 to the one in figure 4).

In section III.1, we found that, as we can roughly see in the p/V diagram, the efficiency is determined mainly by the ratio of the cycle volumes, which determines the enclosed area of the curve. Without more derivation than that,

$$\eta_{Otto} = 1 - (\frac{V_1}{V_2})^{\kappa}, \qquad \text{(III.1.b.1)}$$

where κ is a constant that depends upon the specific heat of the gas, among other things. Typically, $\kappa \cong 0.4$, so for a typical volume ratio of 1/10,

$$\eta_{Otto,typical} = 0.6. \qquad \text{(III.1.b.2)}$$

Now, this efficiency does not take into account frictional losses in the piston and cylinder. According to the Department of Energy, the average car, taking into account those losses, has a heat to drive shaft efficiency of about

$$\eta_{Otto,typical} = 0.38 \text{ (including frictional losses).} \qquad \text{(III.1.b.3)}$$

For the efficiency of a gasoline engine, from input fuel to shaft turning, we can get an idea from one of our early homework problems,
Homework 2:

1. A home electrical generator is a device with an internal combustion engine that drives a shaft that turns the rotor in a generator. Looking at http://www.lowes.com/lowes/lkn?action=productDetail&productId=124742-24212-005734&lpage=none, we see on that states that at half-load (7500 watts), it has a run time of 10 hours at its fuel capacity of 16 gallons, or in other words, to produce 7500 watts of electrical energy, it consumes 1.6 gallons of gasoline per hour. If the efficiency of its electrical generator is 90 %, what is the efficiency of the internal combustion engine?
ANSWER:
At a consumption rate of 1.6 gallons of gasoline per hour, that is a fuel energy consumption of

1.6x124,000 BTU/hour = 198,000 BTU/hour, which equals

198,400 BTU/hour x 0.29 watts/(BTU/hour) = 57,500 watts input fuel power to generator.

The output power is the input power times the product of the efficiencies of the internal combustion engine and the generator, or

$W_{output} = \eta_{\text{int}\,comb}\eta_{gen}W_{input}$, or

$$\eta_{\text{int}comb} = W_{output} / (\eta_{gen} W_{input}) = 7500 / (0.9x57500) = 0.145$$

The efficiency of the internal combustion engine converting fuel energy to shaft-turning energy is 14.5 %.

This is much lower than the 38 % given by DOE. This can perhaps be explained by incomplete combustion of the fuel.

From

http://www.scribd.com/doc/19466574/Air-Pollution-due-to-IC-engine-emissions

automobile exhaust contains up to 6000 ppm unburnt fuel.

From the combustion equation

$$C_n H_{2n+2} + [(3n+1)/2] O_2 \rightarrow nCO_2 + (n+1) H_2O \text{ ,}$$

for n=8, there are 8 CO2 molecules, and 9 H2O molecules per alkane molecule. This does not take into account the combustion in the presence of standard air, which contains 3.76 molecules of nitrogen per molecule of oxygen; these nitrogen molecules pass through the system generally unaffected. So, for n=8, in addition to the CO2 and H2O molecules, there are 3.76x12.5 = 47 nitrogen molecules. So, complete combustion would result in 47+8+9 = 64 molecules on the right. Thus, if the unburnt fuel is 6000 ppm or 0.006 of the exhaust molecules, it would amount to 0.006x64 = 0.384 molecule per reaction.

Wow! That's a lot. It means that only 0.616 of the fuel is burnt. This would explain a lot though, as if the thermodynamic efficiency of car engines is 60 %, and the combustion efficiency is 62 %, the overall efficiency before frictional losses is 0.6x0.62 = 0.37. Then, adding friction could easily get us to the 0.15 efficiency we calculated from homework 2.

Why would there be so much unburnt fuel? Generally, this is due to two effects: one, incomplete mixing of the fuel and oxygen, and two, not enough oxygen so that fuel is uncombusted. To solve the problem, generally the engine is run oxygen rich, so that a little oxygen passes through to the exhaust. In order to improve the efficiency of an internal combustion engine in a motor vehicle, an oxygen sensor is often used to sense the oxygen content of the exhaust gas, and the air-fuel mixture admitted to the engine is adjusted by the engine management system according to the sensed oxygen level of the exhaust gas.

I think that our generator engine in the homework does not have an oxygen sensor, so probably has more unburnt fuel in the exhaust than an automobile. Also, I think that the 6000 ppm figure above is a worst case. Perhaps 4000 ppm is typical for our generator. Then, the combustion efficiency would be 1-0.256 ~ 0.75 for the generator. Let's say the oxygen sensors on automobiles improve this to 0.9. **Then, we need to revise our estimate of the automobile engine efficiency by (90/75)x15 = 18 %:**

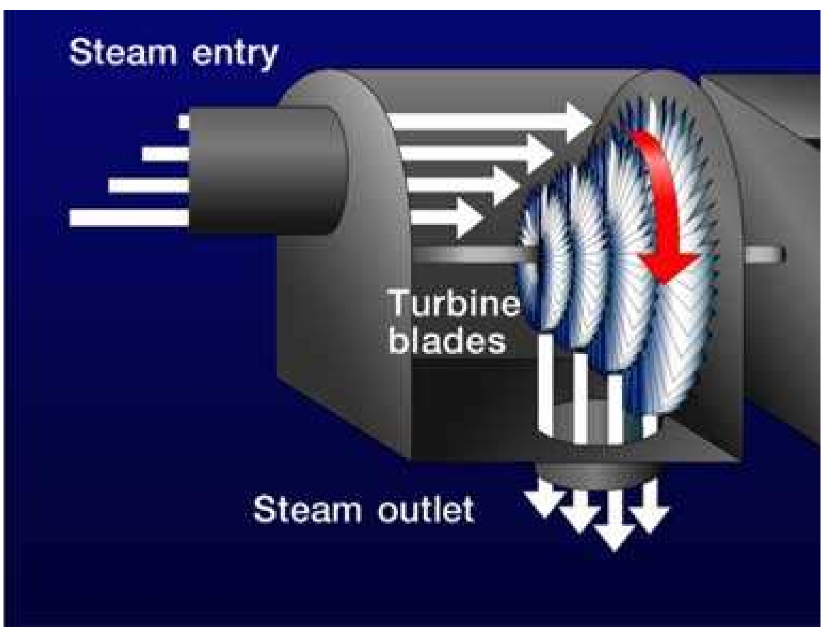
$$\eta_{\text{int}ernalcombustionengine} = 0.18 \qquad \text{(III.1.b.4)}$$

Energy conversion and efficiencies

1. Laws of thermodynamics (conversion of heat to work, typically a turning shaft).

c. The steam turbine.

So far we have discussed generally piston-and-cylinder heat to work engines. Another heat to work engine is the steam turbine, in which burning fuel heats steam, which then flows with great velocity across blades of what is similar to a windmill:



The action of the steam turbine is based on the thermodynamic principle that when a vapor is allowed to expand, its temperature drops, and its internal energy is thereby decreased. This reduction in internal energy is transformed into mechanical energy in the form of an acceleration of the particles of the vapor. This transformation makes a large amount of work energy directly available. In the case of expanding steam, expansion can result in increasing the speed of the steam particles to a rate of almost 2,900 km/hr (1,800 mph). At such speeds the energy available is great, even though the particles are extremely light.

The trick in the steam turbine is to use multiple blade stages, as is shown in the figures. Thus, as energy is drawn from the vapor stream, the blade stages change so as to provide a matched load to most efficiently draw energy from it. A properly designed large steam turbine, such as is usually used to generate electricity, has a heat-work efficiency approximately equal to the Carnot efficiency:

$$\eta_{\text{large steam turbine}} \cong \eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}} . \qquad \text{(III.1.c.1)}$$

As the steam is typically heated to ~ 1500 F, or about 1100 K, and is reduced to around room temperature (~ 300 K). (Note there is a phase transformation from vapor to liquid water, which we will ignore). Thus,

$$\eta_{\text{large steam turbine}} \cong \eta_{Carnot} = 1 - \frac{300}{1100} = 0.73 . \qquad \text{(III.1.c.2)}$$

The actual efficiency of a steam turbine is much lower than this, as we will see in the next section.

III. Energy conversion and efficiencies

2. Conversion of work (a turning shaft) to electricity.

"A moving magnet can make electricity, and electricity can make a magnet move."

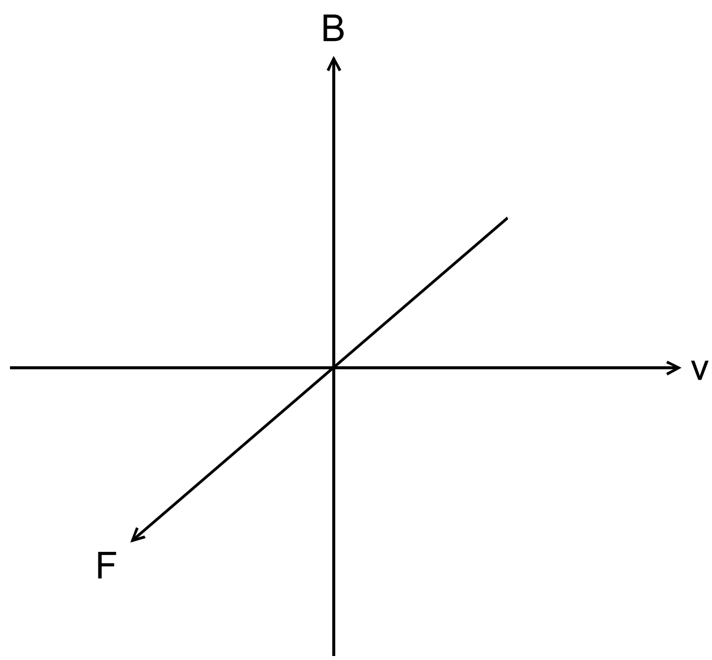
Prof. Goossen, addressing his son's 1st grade class

There, that's it.

Okay, let's do a little more. Most of us (including that 1st grade class) were aware of magnets, and that they induce forces upon other magnets. The also induce forces upon electrons, but only if there is a relative velocity between the magnet and the electrons. This force is given by

$$\mathbf{F} = e\mathbf{v} \times \mathbf{B}, \qquad \text{(III.2.1)}$$

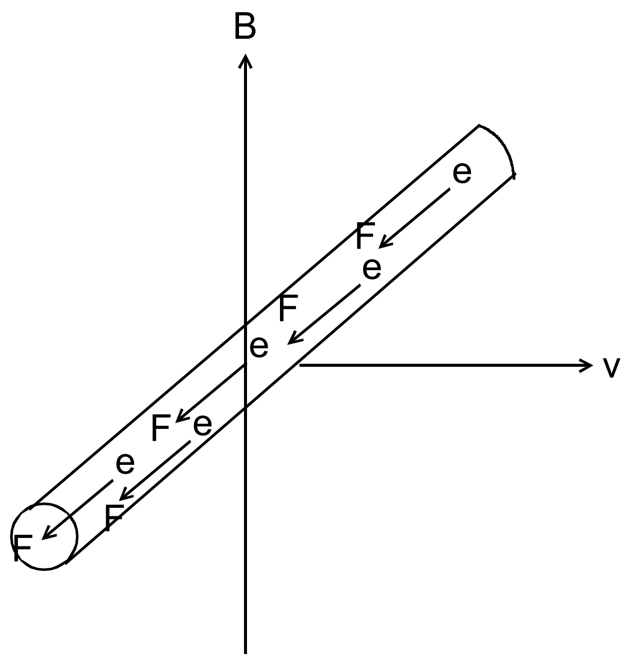
As in the introduction, if you have not had vector calculus, don't panic. What the $\times$ symbol means in III.2.1 is called the cross product of the velocity ($\mathbf{v}$) and magnetic field **B** vectors, which means that the magnitude of the product is greater, the more perpendicular those vectors are, and is greatest when they are exactly perpendicular. Furthermore, what else the $\times$ symbol means is that then the force on the electrons is perpendicular to both the velocity and the magnetic field. So we can draw



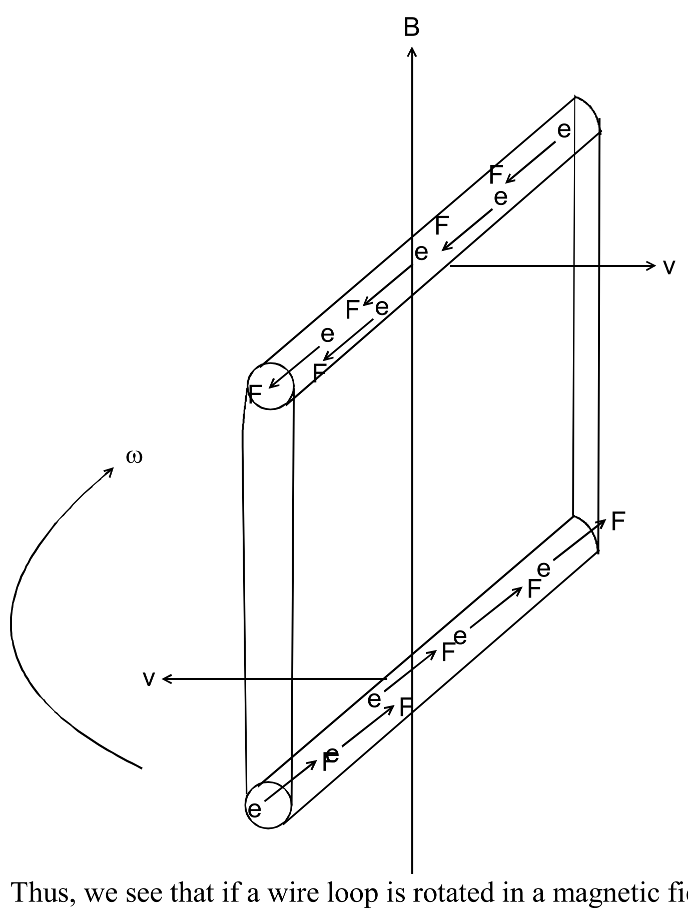
and if we remember to keep the vectors in this direction, rewrite III.2.1 as

$$\mathrm{F} = e\mathrm{vB}. \qquad \text{(III.2.2)}$$

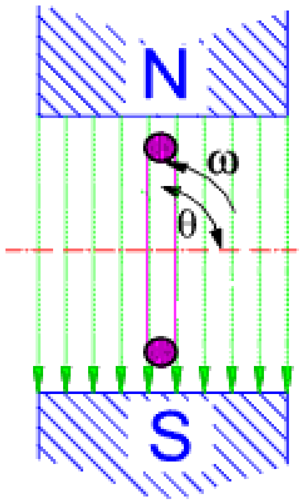
What the figure shows is that an electron going from left to right, in a magnetic field pointing up, will experience a force out of the page. Now, let's replace the electron with a moving wire:

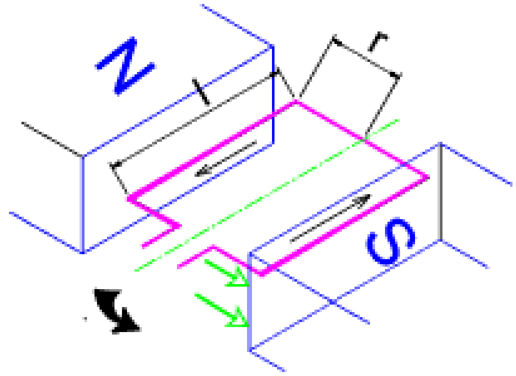


So, we see that wire moving through a magnetic field will have a force applied to its electrons causing them to move through the wire, thus making a current. This figure is incomplete, though, since the wire can't go on forever. It must make a loop:



Thus, we see that if a wire loop is rotated in a magnetic field turned by a steam turbine typically, current will flow through the wire. The two parts of the loop perpendicular to the magnetic field will experience forces on the electrons in the opposite direction, and so a current will form. The current is withdrawn from a break in the loop located near the shaft which turns the loop:





Now, to calculate the current that flows through the loop requires a little more complicated electromagnetic theory than we will go into here, but it is safe to say that the larger the magnetic field, and the larger the area (A) of the wire loop, and the faster the rotation, the more current there will be:

$$I \propto \mathrm{B}A\omega . \qquad \text{(III.2.3)}$$

In fact, the current would be infinite, but for the fact that the wire has resistance to current flow (R):

$$I = \frac{\mathrm{B}A\omega}{R} . \qquad \text{(III.2.4)}$$

In III.2.5, it is acceptable to think of R as a proportionality constant. In general, though, the voltage produced in the loop is given by the current times resistance:

$$V = IR = \mathrm{B}A\omega . \qquad \text{(III.2.5)}$$

Thus, the generator presents a voltage given by III.2.5 to be used by electrical devices. This voltage can be altered through the use of transformers. Typically, the voltage developed at an electrical power plant is several tens of thousands of volts, then is eventually converted down to the 115 volts typically presented at a US outlet.

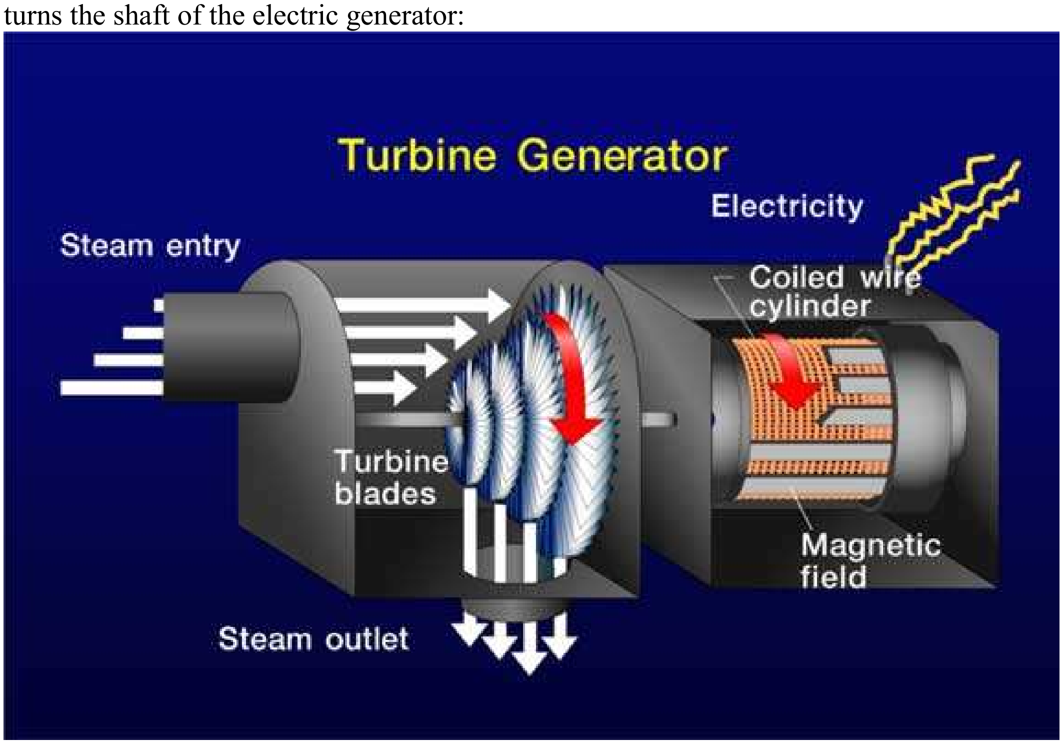
The resistance to current flow in the wire converts a small part of the current into heat. Thus, the conversion of the shaft rotation into electrical power is not perfect. This power loss is the voltage times the current in the wire:

$$W_{lost} = IV = I^2 R . \qquad \text{(III.2.6)}$$

We see that the loss goes as the square of the current. In the delivery of electrical power, that power is the product of current and voltage at any given point in the distribution system. Transformers keep the product of current and voltage the same, but can reduce one while raising the other. Since loss goes as current squared, this favors high voltages in the system wherever possible (and allowed by safety concerns). Since the voltage goes as the size of the magnetic field and wire loop, very large generators are more efficient than smaller ones, and the larger the magnetic field, the better. Hence,

.

Calculating the efficiency of work to electrical generation requires a detailed analysis of the resistances in the generator and the loads on the system. As mentioned typically a steam turbine turns the shaft of the electric generator:



From the energy flow chart in the introduction, the overall efficiency (including distribution losses) is

$$\eta_{electric,overall} = \frac{11}{34.4} = 0.32 \; . \qquad \text{(III.2.7)}$$

This would equal the product of the efficiency of the steam turbine, electric generator, and transmission system:

$$\eta_{electric,overall} = \eta_{\text{large steam turbine}} \eta_{generator} \eta_{transmission} \; . \qquad \text{(III.2.8)}$$

The efficiency of a generator, as for a motor, is about 90 %, as is the distribution system (transformer and wires) Thus

$$\eta_{\text{large steam turbine}} = \frac{\eta_{electric,overall}}{\eta_{transmission}\eta_{generator}} = \frac{0.32}{0.9x0.9} = 0.4 \; . \qquad \text{(III.2.9)}$$

This is much lower than the Carnot efficiency of 73 % found in the preceding section.

Steam turbine efficiency has seen some advances in recent years, but apparently not yet been widely deployed:

New Benchmarks for Steam Turbine Efficiency
By Dr. Alexander S. Leyzerovich,
Consultant
In the 20th century, steam turbines became the most powerful electric power generators available, accounting for more than 50 percent of the world's installed power generation capacity. However, many people, even some power engineering professionals, had come to view steam turbines as a mature technology that would not experience any remarkable achievements in the near future. Indeed, by the late 1980s, the thermal efficiency of new steam turbines had practically stabilized. But the 1990s brought new breakthroughs in steam turbine technology, and technology progress continues today. This progress is primarily the result of two main factors. The first is the development of new heat-resistant high-chromium-percentage ferritic-class steels that enable steam turbines to reach elevated steam temperatures without resorting to austenitic steels. The second is implementation of new advanced approaches to steam path design. Noteworthy as well are advances in developing longer last-stage rotating blades that further decrease exit losses.
The leading producers of large power steam turbines in the world today are European-based multinationals ALSTOM and Siemens AG; GE Power Systems (GE) in the U.S.; Mitsubishi Heavy Industries (MHI), Hitachi and Toshiba Corp. in Japan; Leningrad Metallic Works (LMZ) in Russia; Ansaldo Energia in Italy; Turboatom in Ukraine; and Skoda in Czech Republic.

Latest and Greatest
The advances in steam turbine technology can be better understood by reviewing the design, installation, and commissioning results of several power plants that have recently come on-line. By late 2001, the first operating year's and acceptance tests' data had been processed and partially published for two of the newest power units commissioned in Germany and Japan. These two units are the 907 MW Unit 1 of the Boxberg power plant, operated by Eastern-Germany utility VEAG, and the 1050 MW Unit 2 of the Tachibana-wan power plant, located in Tokushima Prefecture (Shikoku Island) and operated by Electric Power Development Co. (EPDC).

Boxberg Unit 1 went on-line in June 2000 and passed acceptance tests in October 2000. The unit's net efficiency was 42.7 percent and the gross efficiency of the Siemens steam turbine was 48.5 percent. Its steam conditions of 3860 psi and 1013/1078 F do not practically differ from those of other recent-vintage turbines at German power plants.

Figure 1. Siemens steam turbine in use at Boxberg power plant in Germany. Photo courtesy of Siemens.

Tachibana-wan Unit 2 entered commercial operation in mid-December 2000. With a gross efficiency of 49 percent, its MHI steam turbine has been acclaimed the most efficient worldwide. The unit's steam conditions, at 3636 psi and 1112/1130 F, represent the next step in the Japanese steam temperature staircase: 1000/1051 F for Matsuura Unit 1 (1000 MW, 1990); 1000/1099 F for Hekinan Unit 3 (700 MW, 1993); 1051/1099 F for Nanao Ohta (500 MW, 1995); 1099/1099 F for Matsuura Unit 2 (1000 MW, 1997); and 1112/1112 F for Misumi Unit 1 and Haramachi Unit 2 (1000 MW, 1998).
The cited steam turbine efficiency figures provide a benchmark for new units. Meaningful is that both power plants burn solid fuel. It is worth recalling that the best steam turbines put into operation in the 1990s had already reached comparable gross efficiency values:

- **47.4%-**Japan's Hekinan Unit 3, with a rated output of 700 MW and steam conditions of 3480 psi, 1000/1099 F (MHI turbine);
- **47.6%-**Germany's Hessler plant, with a rated output of 720 MW and steam conditions of 3990 psi, 1072/1112 F (ALSTOM turbine); and
- **48.4%-**Japan's Kawagoe Units 1 and 2, with a rated output of 700 MW and steam conditions of 4496 psi, 1051/1051/1051 F (Toshiba turbines).

Of significance is that these units, as well as those at Boxberg and Tachibana-wan, achieved these close efficiency values with the turbines at materially different steam conditions. According to MHI, a steam temperature increase from 1000/1100 F to 1112/1112 F makes a turbine more efficient (heat rate) by about 2.2 percent, that is, its efficiency rises by approximately 1.1 percent. According to German power plant engineers, raising the steam parameters from 3625 psi, 1004/1040 F to 3915 psi, 1085/1112 F should increase turbine efficiency about 1.3 percent. So, closeness of the actual efficiency values for the same capacity class turbines with remarkably different steam temperatures, and with regard to differences in the condenser vacuum (722 mm Hg at Boxberg and 730 mm Hg at Tachibana-wan), feedwater heating, etc., says at least that some of these turbines have noticeable reserves to increase efficiency by reducing losses in the steam path and using more progressive designs.

III. Energy conversion and efficiencies

3. Comparison of efficiencies of fuel/work (internal combustion) and fuel/work/electricity/work (electric vehicle) systems.

This short section addresses an important consideration going forward for our transportation system, whether to convert raw hydrocarbon resources such as coal or biomass to fuel for an internal combustion engine, or to burn the hydrocarbons in power plants to make electricity to run electric vehicles.

Here, we will compare coal-to-liquids/internal combustion, with coal/electricity/electric vehicles. The first, using equation III.1.b.4,

$$\eta_{\text{internal combustion}} = \eta_{coal-to-liquids}\eta_{\text{int}ernalcombustionengine} = 0.42x0.18 = 0.08\,. \qquad \text{(III.3.1)}$$

The second is assuming battery powered vehicles, where batteries must be charged (90 % efficient) and discharged (90 % efficient), as well as the overall electric distribution efficiency of 32 %:

$$\eta_{batteryelectric} = \eta_{electric,overall}\eta_{electricmotor}\eta_{\text{charging circuit}}\eta_{\text{discharging circuit}} = 0.32x0.9x0.9x0.9 = 0.23\,.$$

(III.3.3)

We see that electric vehicles are 3 times as efficient converting hydrocarbon energy into engine power.

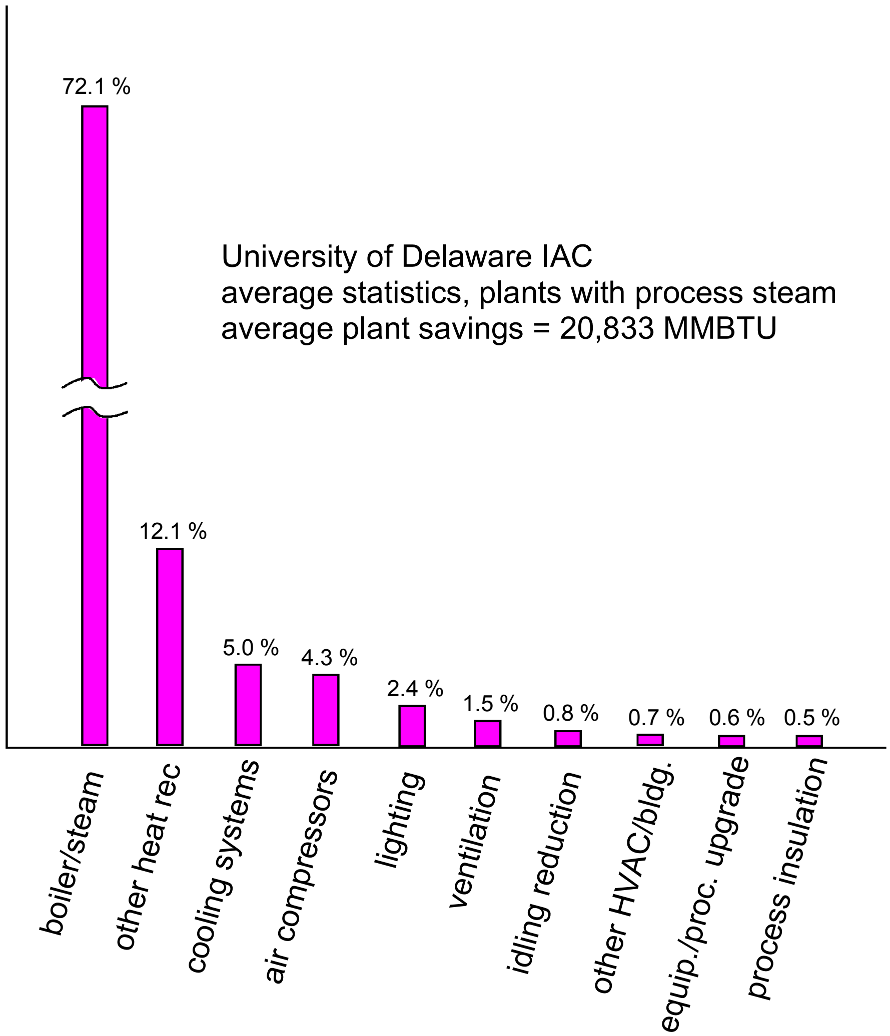
IV. Energy systems

1. Industrial energy efficiencies.

The industrial energy efficiency, from the energy flow chart in the introduction, is 15.2/19 = 0.8. So, it would appear to be quite efficient, but this is clearly incorrect. It is not clear where the "15.2" quad number for useful output comes from. As Director of the University of Delaware Industrial Assessment Center, which performs energy audits of local industries, I know that we average about 15 % savings in the recommendations that we make, so it would appear by this that we can reduce the 19 quad input by 2.9 quads, and still maintain the same output.

That being said, we can explore what efficiencies are available in industrial systems. From the audits we have performed, we find that industrial plants can roughly be divided into two categories, those that use process steam, and those that do not. By "process steam", we mean the use of steam in the industrial process, rather than simply for space heating. You may be familiar with steam space heating systems, consisting of a boiler, a steam pipe distribution system, and steam radiators. Process steam refers to the use of steam, for example, to heat a chemical vat, or, frequently, as a feedstock for the industrial process. An example of the latter is injection of the steam into the chemical vat, incorporating it into the chemical. Thus, the steam is consumed, rather than just providing heat. Another example of this is the making of cardboard. Ever wonder how the curly paper between the cardboard faces is made? Well, just like steam can make your hair curl up, it makes paper curl, and that's how cardboard is made.

For plants with process steam, this chart summarizes the recommendations made by the University of Delaware Industrial Assessment Center:



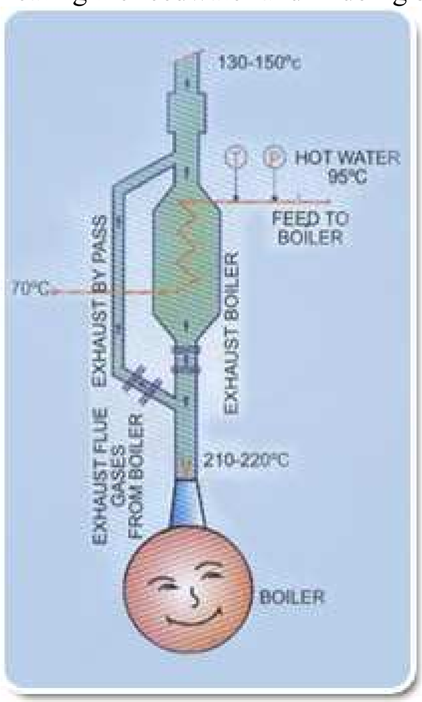
The average savings of a plant with process steam assessed by the University of Delaware IAC is 20,833 MMBTU (million BTU) per plant. The categories are:

- Boiler/steam: this includes all aspects of the boiler and steam systems including for example boiler trimming, boiler heat recovery, boiler replacement with point-of-use hot water systems, and steam systems including leaks and insulation.
- Other heat recovery: heat recovery of systems other than boiler and air compressors.
- Cooling systems: modification of cooling systems including for example variable speed drives on pumps and fans and use of free cooling.
- Air compressors: including modification (e.g., variable frequency drives) of the air compressor itself, but also the compressed air system such as load balancing and idling reduction, and reduction of leaks. This category also includes air compressor heat recovery.
- Lighting
- Ventilation: including energy recovery of vented air, as well as equipment/process changes that reduce venting of conditioned air.
- Idling reduction: identification of process and operational changes that reduce equipment idling.
- Other HVAC/building: Building insulation and HVAC equipment upgrades, as well as the equipment refits that reduce building cooling loads.
- Equipment/process upgrades: Those not in other categories.

- Process insulation: Adding insulation to process equipment to reduce heat loss or cooling load. Note this does not include steam pipe insulation.

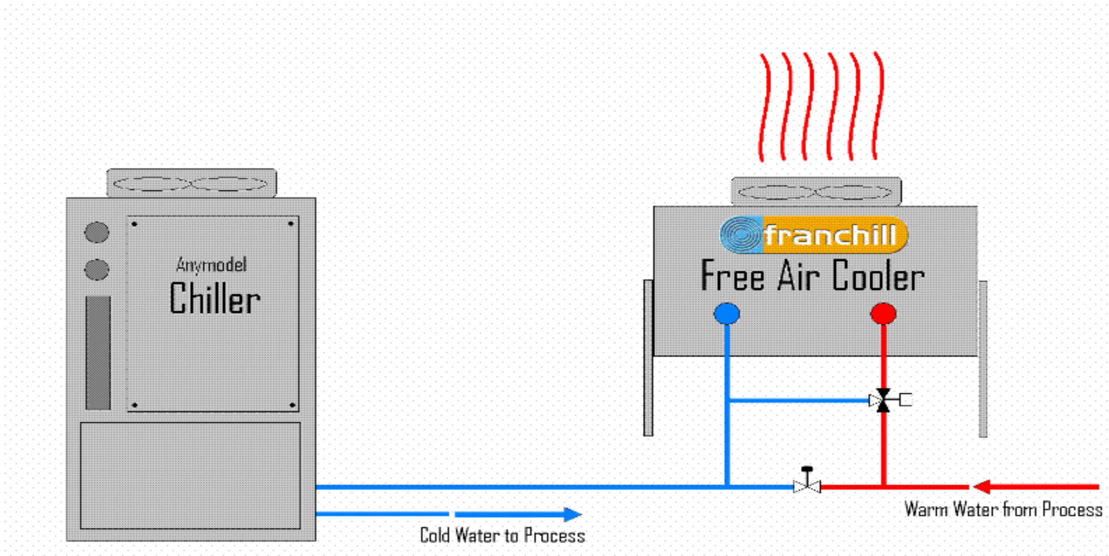
What figure 1 shows quite clearly is that in plants with process steam, the boiler and steam system overwhelmingly dominate the energy savings opportunities, and of course must dominate the focus of any assessment. Furthermore, heat recovery of other process equipment is a rich target. The reason for this, usually, is that there is a place to put the heat, in the boiler. Third, cooling systems represent a large target, which makes sense as if there is process steam, there is frequently process cooling. Finally, as for all plants, the compressed air system is a target.

An example of boiler heat recovery is the routing of the feedwater lines (since the boiler makes steam, it consumes water) through a heat exchanger in the stack (chimney) of the boiler, thus pre-heating the feedwater and in doing so recovering some of the heat that escapes up the stack:



Another example of heat recovery is using the cooling exhaust of an air compressor for space heating. As mentioned earlier in the course, compressed air is used in nearly all industrial plants, for example as air actuated motors in areas where electric motors are not allowed due to the possibility of sparking in a volatile environment. A use you may have seen is at a car mechanic's shop, where it drives the air wrench for removing tire lug nuts. Compressed air is very convenient, but in the act of compressing air, about 85 % of the electrical energy driving the compressor is converted into heat. The reason for this is that air cannot be confined to a smaller volume without introducing significant kinetic energy to the air molecules, which is what heat it. Thus, the compressed air line is usually cooled by a blower before entering the plant. This is naturally producing a large flow of heated air, which can be used in the plant for space heating, offsetting the requirements of the existing space heaters.

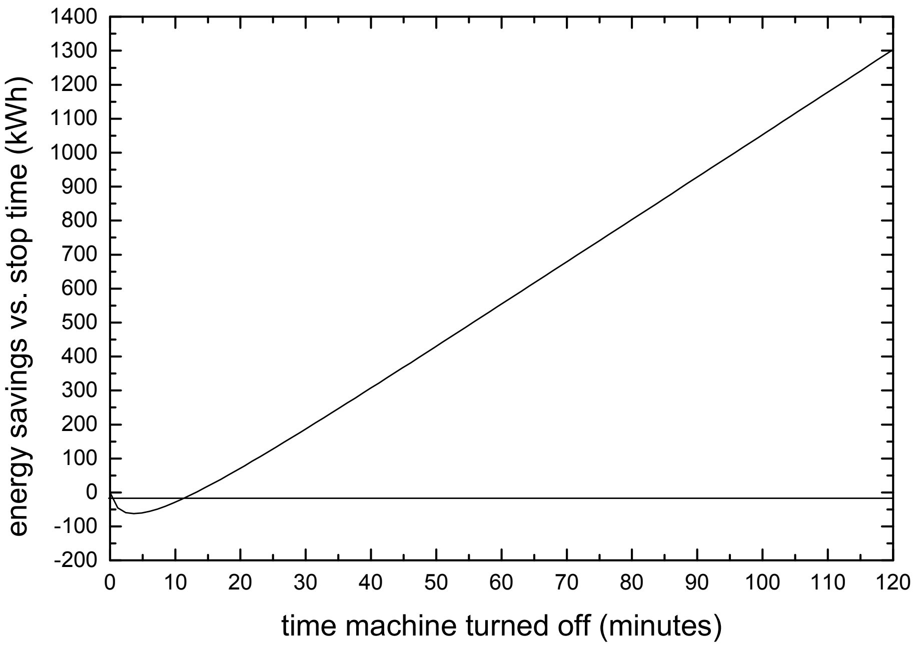
An example of reducing energy in cooling systems is "free cooling". Many plants have cooling systems, for example water cooling lines to keep equipment from overheating. These cooling lines are frequently routed to a "chiller", which is basically a form of air conditioner that cools the water lines instead of air. The chiller is backed up by a cooling tower, that simply blows ambient air across the lines. Especially in winter, this cools the water to ambient "for free", lowering energy requirements on the chiller:



The standard lighting recommendation in industrial settings is the replacement of metal halide (the "upside-down bell" fixtures you may see in gyms) with fluorescent lighting, which is about 40 % more efficient. By the way, a common misconception with fluorescent lighting is that it takes more energy to start the bulb that would be saved by turning it off. Not true. The startup time of a fluorescent light is a few tenths of a second. Thus, unless you're going to be back in the room in less than a second, turn it off. Now, turning the light on and off repeatedly reduces bulb life: the Department of Energy has determined that minimizing total cost (energy and bulbs) that if the room is to be left for more than 15 minutes, the lights should be turned off.

An enormous problem in industrial systems, as well as laboratories, is the venting of heated or air conditioned air. Sometimes venting is required due to the necessity of removal of toxic fumes. However, one example of savings that can be had, that we recommended at a recent plant, was simply placing the vent closer to the equipment venting the fumes. This allowed a reduction in venting requirements. It may sound minor until you think about it some: this simple act saved this relatively small company $20,000 in annual heating costs. If you work in a laboratory, please close your hood sashes when not in use: the energy required to re-condition air inputted to the building to replace that vented equals the energy consumption of 3 average houses!

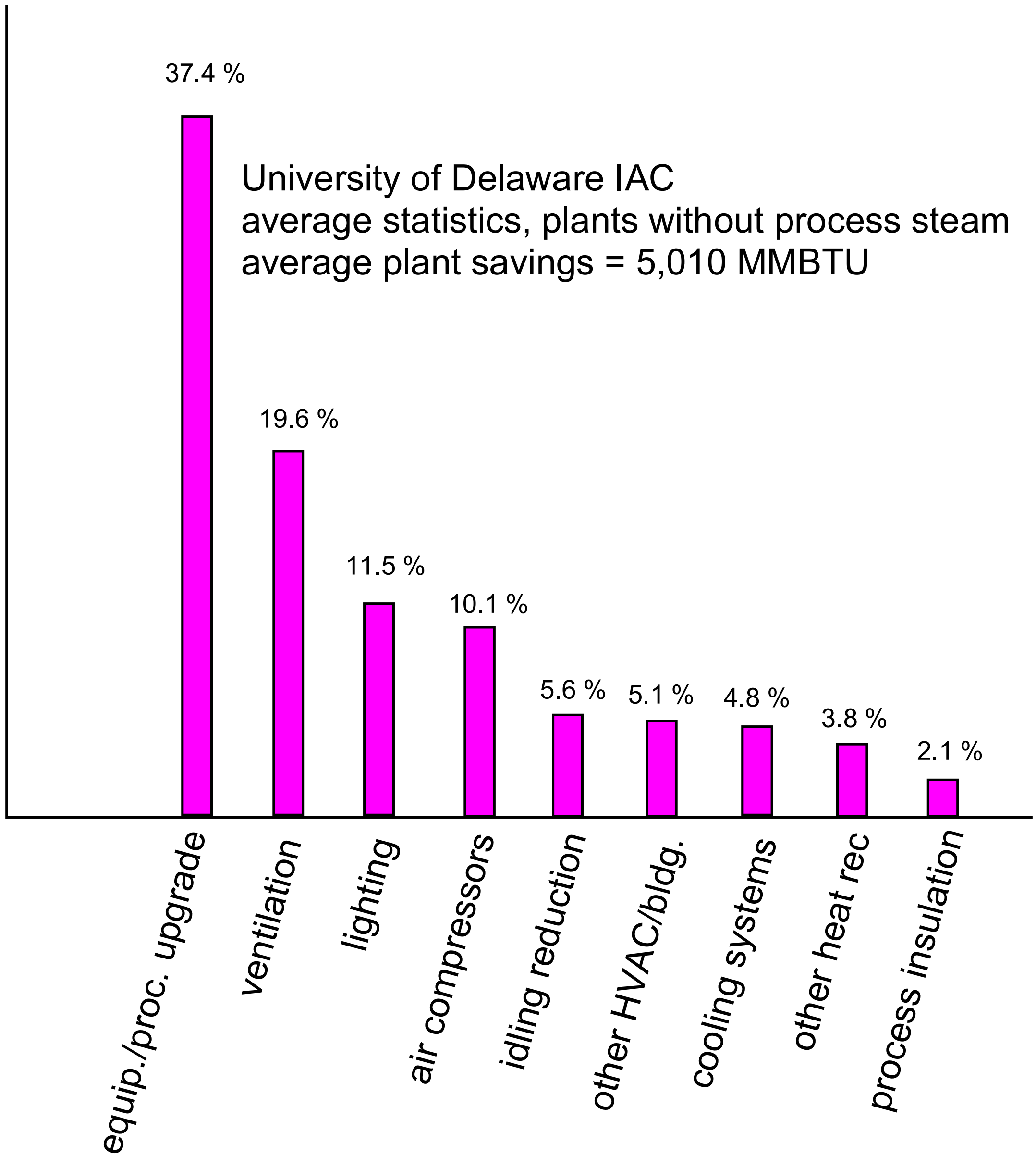
Idling reduction: we were at a plant that left their (large) industrial ovens on during lunch break since they thought it took more energy to heat the oven back up. This is a common misconception many people have in their kitchen. The warm up time of an oven (in the case of the plant, and at home) is about 10 minutes. This graph shows the energy savings of turning it off, vs. the time before it is needed again:



Unless the "off time" is less than the "warm up time", turn the oven off.

Process insulation, such as ovens, is usually only called for if the surface to be insulated is above 150 F. Otherwise, the pay back times of performing the insulation usually exceed 5-10 years.

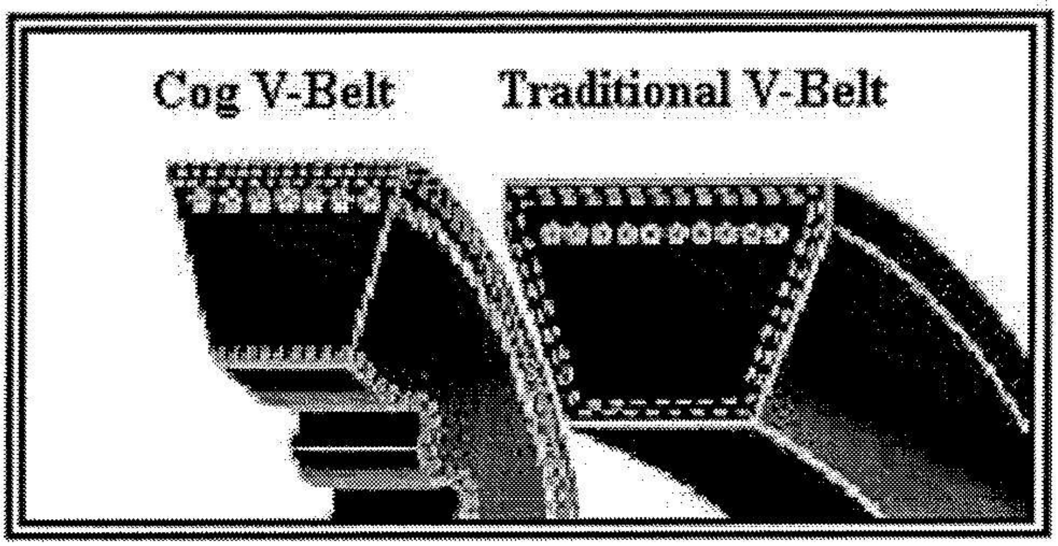
For plants without process steam, the chart goes like this:



One sees that heat recovery issues are not so critical, for two reasons: if there is no process steam, there is generally less heat being generated, and also, recovery of heat in liquid form, that for plants with a boiler could easily be put there and recovered, has no where to go.

Rather, equipment or process upgrades dominate these plants. A typical example of this is the installation of variable speed drives on motors, replacing "throttling" in fluid flow systems. Throttling refers to placing vanes in the pipe to partially block the flow, restricting it to the desired level. But, the pump motor keeps running full on! Of course, that's not smart, but it happens frequently. Rather, installation of a variable speed drive on the pump motor allows it to control the flow, reducing motor power, and the energy it consumes.

Another standard example of equipment upgrade is on motor-driven pumps or fans, using a belt to convey rotation between the motor and the pump or fan, replacing a smooth or "V" belt with a cog belt (having teeth):



This usually requires replacing the pulleys as well, but typically saves ~ 3 % on the motor power, since smooth belts slip. If you ever walk by a motor system with a belt and hear squeaking, energy is being wasted.

Finally, another example of energy savings, is the matching of loads to equipment. Since the energy losses of a piece of equipment are a percentage of it's input energy (not an absolute amount), larger equipment wastes more energy. Thus, opportunities for reducing the size of equipment, when it is oversized compared to the load, should always be sought. Of course, this is more effectively done before the equipment is paid for and installed.

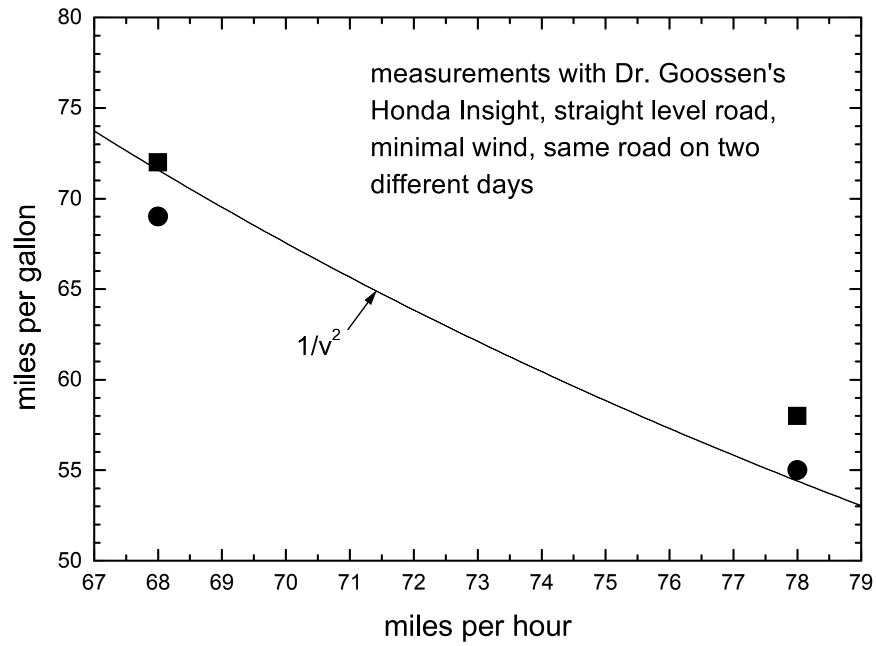
Energy savings in industrial plants is a combination of noting and applying these "standard" recommendations (of which only a fraction are listed here), and also being creative. The starting point of this creativity is determining where energy is being used in the plant. Then, one asks themselves, "how can this same task be done with less energy?"

IV. Energy systems

2. Transportation efficiencies.

Energy usage by road vehicles at constant velocity-

We've already discussed engine efficiency, that is the ratio of turning shaft energy to input fuel energy. Besides that, there is the efficiency losses due to air and road resistance, essentially, heat lost to the air and road. The most straightforward aspect of automobile efficiency is the dependence of miles-per-gallon on speed. At highway speeds, air resistance is the primary limitation, and this results in MPG going as the inverse of velocity squared:



This is a difficult measurement to do! I did it with my on-board MPG meter, being careful to pick a stretch of road with minimal hills about 10 miles long, on days of minimal wind.

We can easily calculate this dependence of MPG on velocity due to air resistance, by considering the force on the vehicle when a "wind" equal to the velocity, is on a stationary vehicle. As we have learned in the course introduction, the power per unit area in wind equals the kinetic energy in wind times the velocity:

$$P_{wind} = (\frac{1}{2}\rho \mathrm{v}^2)\mathrm{v}\,. \qquad \text{(IV.2.1)}$$

Now, if we allow the wind to "push" the vehicle at a constant velocity, the energy imparted equals the force times distance:

$$E_{wind} = \mathrm{F}_{wind}\mathrm{x}\,. \qquad \text{(IV.2.2)}$$

And, the power delivered by the wind equals the time derivative of this:

$$W_{wind} = \frac{dE_{wind}}{dt} = \mathrm{F}_{wind}\frac{d\mathrm{x}}{dt} = \mathrm{F}_{wind}\mathrm{v}\,. \qquad \text{(IV.2.3)}$$

But, this just equals equation IV.2.1 times the effective wind resistance area of the vehicle:

$$W_{wind} = P_{wind} A_{eff} = \frac{1}{2}\rho v^3 A_{eff} \,. \qquad \text{(IV.2.4)}$$

Equating IV.2.3 with IV.2.4, we have that the force on the vehicle due to the wind is

$$F_{wind} = \frac{1}{2}\rho v^2 A_{eff} \,. \qquad \text{(IV.2.5)}$$

Now, the key thing here is that it doesn't matter whether the vehicle is moving or the air is, but just the relative velocity of the two. So we can write

$$F_{\text{air resistance}} = \frac{1}{2}\rho v^2 A_{eff} \,, \qquad \text{(IV.2.6)}$$

where v is really is the difference between the vehicle velocity and the wind velocity. Thus we see why wind can greatly affect the measurement above.

Now, given the force of air resistance, the energy required to move a vehicle at constant velocity is just that force times distance, or

$$E = F_{\text{air resistance}} x = \frac{1}{2}\rho v^2 A_{eff} x \,, \qquad \text{(IV.2.7)}$$

and the power required to keep the vehicle moving is

$$W_{vehicle} = \frac{dE}{dt} = \frac{1}{2}\rho v^2 A_{eff} \frac{dx}{dt} = \frac{1}{2}\rho v^3 A_{eff} \,. \qquad \text{(IV.2.8)}$$

But, this is proportional to the rate of consumption of fuel:

$$W_{vehicle} = \alpha \frac{dG}{dt} \,, \qquad \text{(IV.2.9)}$$

where α is the energy content in a gallon of fuel. This can be rewritten

$$W_{vehicle} = \alpha \frac{dG}{dt} = \alpha \frac{dG}{dx}\left(\frac{dx}{dt}\right) = \frac{\alpha v}{MPG} \,, \qquad \text{(IV.2.10)}$$

where dx/dG is the miles per gallon. Equating IV.2.8 with IV.2.10, we have

$$MPG = \frac{\alpha v}{W_{vehicle}} = \frac{\alpha v}{\frac{1}{2}\rho v^3 A_{eff}} = \frac{2\alpha}{\rho v^2 A_{eff}} \,. \qquad \text{(IV.2.11)}$$

And we see that the miles per gallon goes as the inverse of velocity squared.

So, this is why in the energy crisis of the 1970's, the speed limit was reduced to 55 miles per hour. From 55 MPH to 80 MPH, your car's gas mileage goes down by $(55/80)^2$, or by a factor of 2. If you get 30 MPG at 55 MPH, you will roughly get only 15 MPG at 80 MPH.

We see other factors in equation IV.2.11. The effective area does depend upon the actual area of the vehicle, so naturally the MPG will go down with larger size vehicles. Thus in sport utility vehicles which have a high cross section the highway gas mileage will go down accordingly.

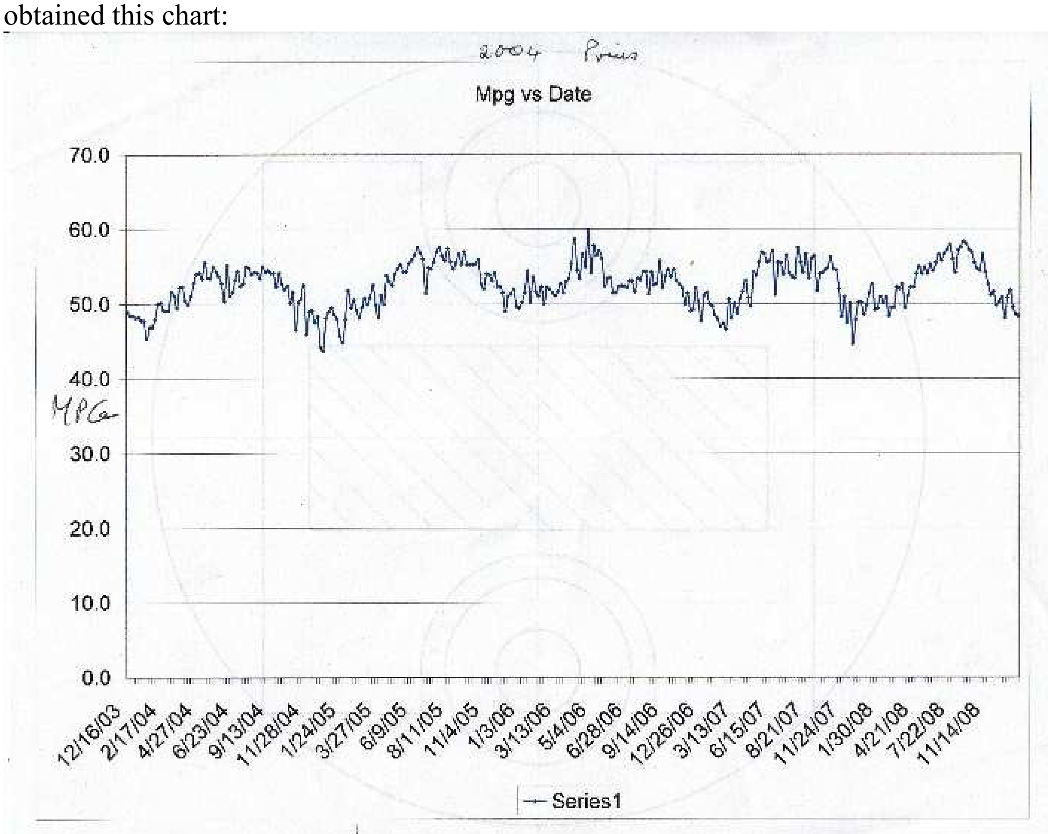
Another factor is the mass density of air. While at first glance this may appear to be a constant, it is not, as we know that by the ideal gas law,

$$pV \propto \rho T . \tag{IV.2.12}$$

Since the pressure of the atmosphere at the surface does not change with temperature, we have that

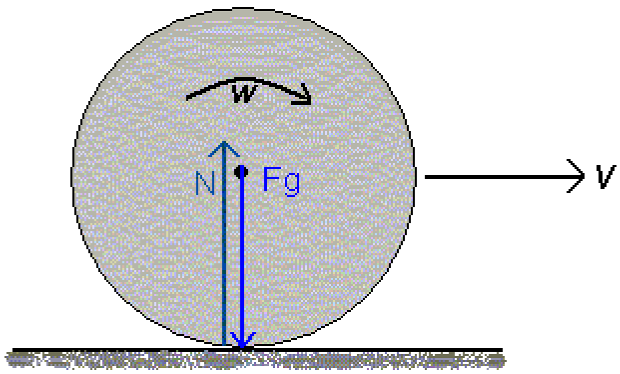
$$\rho \propto \frac{1}{T} . \tag{IV.2.13}$$

Thus, air density goes up in the winter and MPG goes down. Note that this is temperature in Kelvin, so in the winter at a temperature of ~ 20 F (266 K) compared to 90 F (305 K), gas mileage goes down by (266/305)=0.87 or 13 %. I have noted this in my vehicle. Others have as well, a colleague of mine has performed detailed seasonal measurements on his Prius, and obtained this chart:



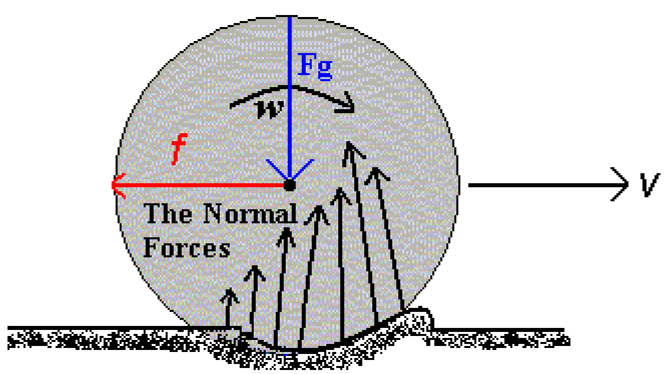
The seasonal pattern is quite evident, with about 15-20 % lower MPG in the winter. Part of this may be due to reduced engine efficiency with lower temperature air intake.

Now, if the vehicle goes slower, MPG does not just keep climbing since there are other forces at work. The primary other force is *rolling resistance*, which is the resistance presented to the vehicle at the tires because they have deformed and are not perfectly circular (it is not the frictional resistance due to the wheel bearings). It is illustrated in these diagrams:



Now, in this image, pure rolling motion has been achieved and the wheel begins to roll forward with a constant velocity, v. Notice that the frictional force is now zero due to the one to one motion at the apparent contact points(no relative velocity).

In the actual case of the rolling wheel, the free-body diagram is much different. Both the wheel and the surface will undergo deformations due to their particular elastic characteristics. At the contact points, the wheel flattens out while a small trench is formed in the surface. The normal force is now distributed over the actual contact area rather than the point just below the center of the wheel.



The actual forces acting on the wheel and the surface. As one can see in this exagerated view, both the wheel and the surface undergo deformation to an extent determined by the elastic properties of the two surfaces.

Thus, rolling resistance exists due to deformation of the tires and due to imperfections in the road surface. The exact physics of rolling resistance is fairly complicated, but all we need to know here is that it is independent of velocity:

$$\mathrm{F}_{\text{rolling resistance}} = C_{tire} m \,, \tag{IV.2.14}$$

where C_{tire} is a factor that goes up as the tires are more deformable (read, having too-low pressure), and *m* is the mass of the vehicle, since a heavier vehicle will deform the tires more.

Now, including the rolling resistance force in equation IV.2.7, we have that

$$E = (\mathrm{F}_{\text{air resistance}} + \mathrm{F}_{\text{rolling resistance}})\mathrm{x} = (\frac{1}{2}\rho \mathrm{v}^2 A_{eff} + C_{tire} m)\mathrm{x} \,, \tag{IV.2.15}$$

and

$$W_{vehicle} = \frac{dE}{dt} = (\frac{1}{2}\rho \mathrm{v}^2 A_{eff} + C_{tire} m)\frac{d\mathrm{x}}{dt} = \frac{1}{2}\rho \mathrm{v}^3 A_{eff} + C_{tire} m\mathrm{v} \,, \tag{IV.2.16}$$

as before this equals

$$W_{vehicle} = \frac{\alpha \mathrm{v}}{MPG} \,, \tag{IV.2.17}$$

and we have

$$MPG = \frac{\alpha \mathrm{v}}{W_{vehicle}} = \frac{\alpha \mathrm{v}}{\frac{1}{2}\rho \mathrm{v}^3 A_{eff} + C_{tire} m\mathrm{v}} = \frac{2\alpha}{\rho \mathrm{v}^2 A_{eff} + 2C_{tire} m} \,. \tag{IV.2.18}$$

Thus, as velocity drops, MPG will reach a limiting value.

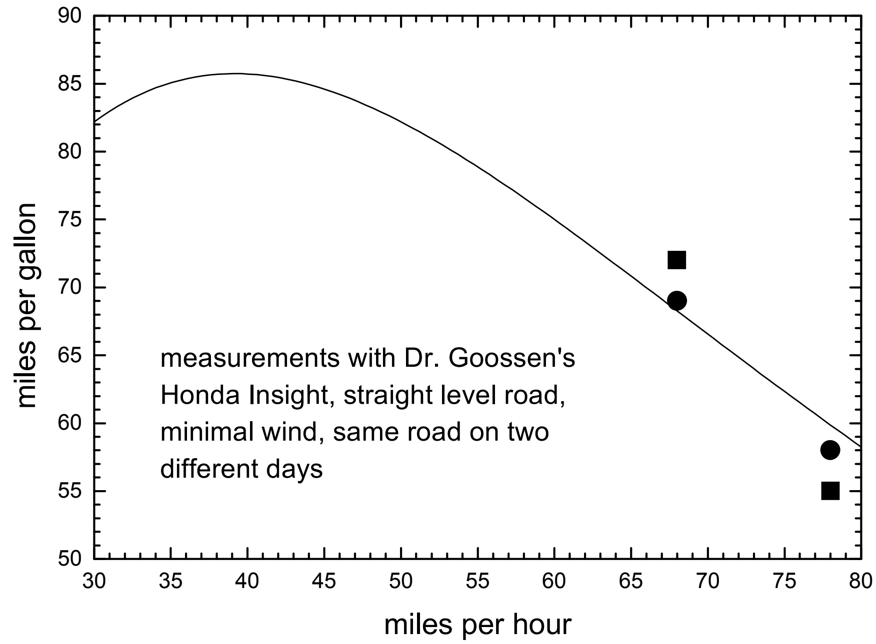
Finally, though, we have to include the heat losses in the vehicle. Here, the difficulty is determining their dependence upon velocity. Certainly there are losses that are independent of velocity, so I will simply incorporate a linear term in IV.2.16,

$$W_{vehicle} = \frac{1}{2}\rho \mathrm{v}^3 A_{eff} + C_{tire} m\mathrm{v} + W_{loss} \tag{IV.2.19}$$

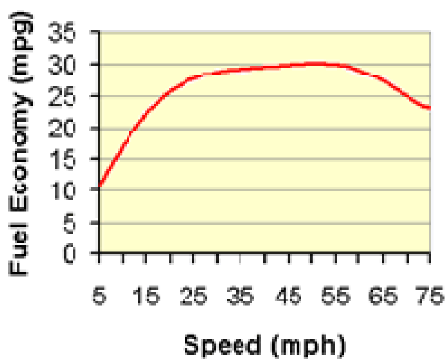
and then

$$MPG = \frac{\alpha \mathrm{v}}{W_{vehicle}} = \frac{\alpha \mathrm{v}}{\frac{1}{2}\rho \mathrm{v}^3 A_{eff} + C_{tire} m\mathrm{v} + W_{loss}} = \frac{2\alpha}{\rho \mathrm{v}^2 A_{eff} + 2C_{tire} m + 2Wloss/\mathrm{v}} \tag{Iv.2.20}$$

Fitting my car's gas mileage to the equation $1/(A\mathrm{v}2 + B + C/\mathrm{v})$, I obtain

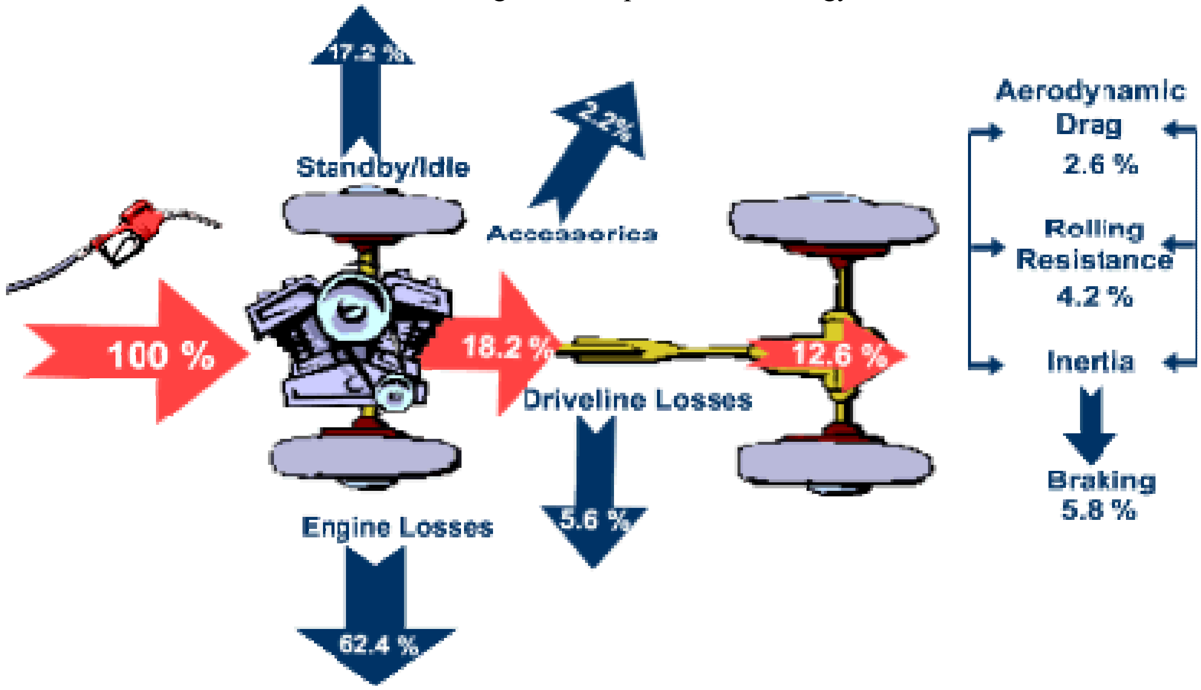


From EPA's web site on fuel efficiency vs. speed, they plot



So the maximum in fuel efficiency is approximately at 45-55 MPH.

Automobile losses broken down according to US Department of Energy:



As we calculated from our homework problem, and taking the difference in combustion efficiency of automobile engines and the generator engine, it appears the Engine Losses of an internal combustion engine are actually about 82 %.

The Standby/Idle losses can now be estimated from the Auto-Stop feature available on hybrids that has a high efficiency starter that allows the engine to be turned off at idle:

Stop-start: Not just for hybrids anymore
Jamie LaReau
and Richard Truett
Automotive News
November 2, 2009 - 12:01 am ET
Stop-start is moving to start.

Today, only hybrids such as the **Toyota Prius** and **Ford Escape** Hybrid use a stop-start system in North America. But that's about to change. Starting in 2010 with the Porsche Panamera, stop-start is coming to vehicles with conventional powertrains.
The system is one of the most economical ways automakers can improve fuel economy quickly, at least for small cars with manual transmissions.
A stop-start system turns the engine off when the vehicle comes to a stop, saving fuel. It restarts the engine when the driver's foot leaves the brake pedal.

Stop-start savings
What it does: Turns off the engine when the vehicle stops, saving fuel; turns engine on again when the driver's foot lifts off the brake.

Some 2010 vehicles with it
• Ford Escape Hybrid
• Porsche Panamera
• Toyota Prius
• More coming from Europe
Some suppliers that make it
• Robert Bosch
• Delphi
• Denso
• Magneti Marelli
• Valeo

Easy packaging
Stop-start uses either an improved starter motor or the alternator to restart the engine, plus software and minor electrical equipment. It's easily packaged, so no changes are needed to the engine or chassis.
The system already is on many European and Japanese vehicles.
The consulting firm IHS Global Insight predicts that by 2010, stop-start will be on 2.4 million vehicles worldwide. That will double to 5 million in 2011 and again to 10 million by 2013.
"We see it being put on everything it can possibly go on easily and cheaply," says Andrew Close, senior powertrain analyst at IHS Global Insight in London. "The more difficult applications -- the automatic transmission and the larger diesel engines -- will come later, toward the 2012 time frame."
In Europe, for example, stop-start is used on BMW's 1- and 3-series cars. BMW's supplier, Robert Bosch GmbH, developed a special fast-acting, high-performance starter motor.
BMW spokesman Tom Plucinsky says stop-start is inexpensive. He says BMW will offer stop-start in North America but has not decided which vehicles will get it.
Fiat will put the technology on every new vehicle to be released in Europe starting next year.
The fuel savings is estimated to be 5 to 7 percent on the European driving cycle. But stop-start's benefits in the United States will be slightly less. The American driving cycle involves more heavy acceleration and freeway driving, reducing the fuel savings to around 2 percent.

Thus, it appears Standby/Idling losses are only 2 % (US).

Accessory losses of 2 % are probably accurate. Thus, the overall losses of the internal combustion engine in automobiles, to the drive shaft, are

82 % (engine losses) + 2 % (idling) + 2 % accessories = 86 %.

Advanced vehicle engines-

Hybrid vehicles-
“Hybrids” have both an electric and gasoline motor that augment each other, with the battery charging to power the electric motor coming from the gasoline motor, and additionally from generation that occurs in braking. Thus, they are gasoline-fueled vehicles, with an overall increase in efficiency that occurs in that energy otherwise wasted in braking is captured. The electric motor is cunningly located around the drive shaft:

Here we see the gasoline motor, the drive shaft, and the electric motor arranged around the drive shaft so that its power is directly applied without gearing. When braking, the electric motor operates backwards as a generator, charging the battery.

Having the electric motor allows the gasoline motor to be undersized, so that while driving steadily, the electric motor is off, and a small gasoline motor powers the vehicle. Then, when accelerating or going up a hill, the electric motor kicks in to provide added power.

Hybrids can be series or parallel, or series/parallel. "Series" hybrids refer to models in which the electric motor powers the car exclusively, and the gasoline motor is just there to charge the batteries. Parallel, like my Honda Insight, models can have both the gasoline and electric providing torque to the drive shaft, but, cannot operate on the electric motor alone. Series/parallel (note: this is my designation, technically it's a parallel), like the Prius, are the same as the Insight, except the electric motor can exclusively power the car. This leads to the possibility of a plug-in hybrid, where the battery may be separately charged by plugging it in. These are supposed to come out soon, with the battery then being able to supply about 40 miles travel under a single charge.

One of the great efficiencies of the parallel hybrid is that the electric motor acts as the starter for the gasoline engine, which much greater force than a standard gasoline starter. Thus, hybrids may turn off the gasoline engine completely when they come to a stop, since the electric motor starter can easily restart the engine. This results in great savings due to the lack of idling.

My Insight, which is no longer sold since it is a two-seater and there was a lack of sales because of that, is clearly the MPG champ. The EPA rating is 66/60 highway/city, and I easily achieve that, even going much faster than 55 mph (I typically drive 70 on the highway). There is a continuous meter that shows instantaneous MPG and average MPG from when the car began life. My lifetime average meter reads 63.6 MPG. I haven't asked, but believe anecdotally that the Prius, with the average driver, is in the low 40's, but you could see if you looked at the average MPG meter. The reason the Insight is better is simply that it is smaller, being only a two-seater, having lower mass and lower aerodynamic drag.

Electric vehicles

These are any vehicle that must be plugged in, and may be hybrid (plug-in hybrid), or pure electric. The attractiveness of the electric vehicle is that electric motors are typically 85-95 % efficient, compared to the 18 % of internal combustion. One must consider that there is "hidden" energy cost in that the efficiency of the electric power plant must be considered. This "hidden" energy cost shows up in the dollar cost of electricity on a pure energy basis. Consider that electricity costs ~ \$0.2/kWh, and gasoline ~ \$3/gallon. In a gallon of gasoline there is

124,000 BTU, or 124,000x1055 joules, or 124,000x1055/(1000x3600) = 36.3 kWh. So, gasoline costs ~ \$3/36.3 = \$0.083/kWh equivalent energy, lower than electricity on an energy basis.

But, the electric car is 0.9/0.18 = 5 times more efficient. There is actually an easy way to think about this. If we compare the same *vehicle*, but one with an electric motor and one with an internal combustion engine, then each must have the same drive shaft power. But the "fuel inputs" to each engine are different based upon their efficiencies:

$$\eta_{electric}\eta_{battery}W_{electricity} = \eta_{ICE}W_{ICE} \text{ ,}$$

where we have included the efficiency of charging the battery from the wall outlet. Now, considering that the electric energy costs x per kWh, and the gasoline costs y per gallon or $y/36.3$ per equivalent kWh, we may write that

$$\eta_{electric}\eta_{battery}(\$_e / x) = \eta_{ICE}[(\$_g /(y / 36.3)] \text{ ,}$$

we can write the ratio of the costs of driving the electric vehicle to the gasoline vehicle as

$$\$_e / \$_g = 36.3x\eta_{ICE} /(y\eta_{electric}\eta_{battery}) = 8.07(x / y) \text{ ,}$$

having plugged in 18 % for the ICE and 90 % for the electric motor and for the charging of the battery. Thus, at \$3/gallon gasoline, and \$0.2/kWh,

$$\$_e / \$_g = 8.07(0.2 / 3) = 0.54 \text{ ,}$$

and at current energy prices it is about half the cost to drive an electric vehicle, for the same vehicle performance. Now, this does not take into account that the electric vehicle may have to have somewhat higher drive shaft power to take into account the weight of the battery. From below, for Li-Ion batteries, the weight may be several hundred pounds, or about 10 % of the weight of the vehicle. Very simply, the formula above could be multiplied by 1.1 to take this into account.

In absolute terms, if we have a gasoline vehicle that gets 30 MPG (0.033 gallons/mile = 1.21 equivalent kWh/mile), and we replace the gasoline engine with an electric motor,

$$(kWh / mile)_{electricity} = \eta_{ICE}(eq.kWh / mile)_{ICE} /(\eta_{electric}\eta_{battery}) = 0.18(1.21) /(0.9x0.9) = 0.27 \text{ .}$$

At \$0.2/kWh, the electric vehicle costs \$0.054/mile to operate, while at \$3/gallon, the gasoline vehicle costs 0.033x3 = \$0.10/mile.

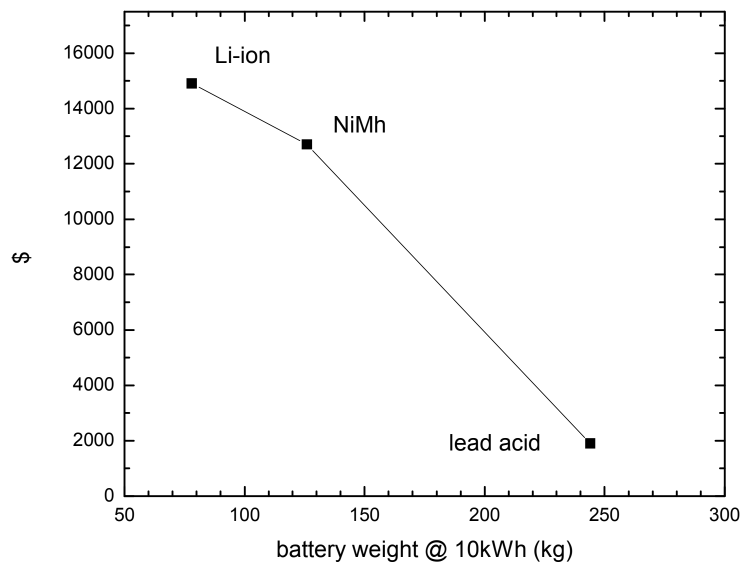
Now, I googled "electric" and "miles per kWh" and most sites postulate ~ 1/3 kWh per mile, so this analysis appears accurate.

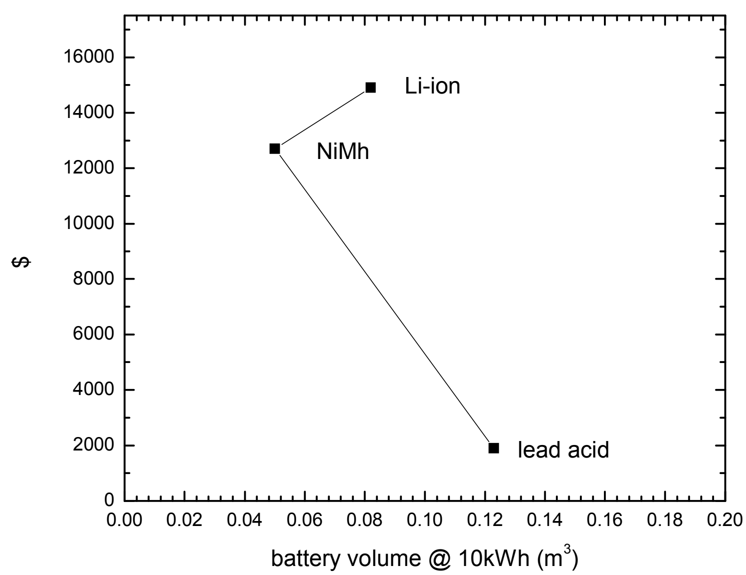
So, the conclusion is, economically it is a win economically to drive an electric vehicle. Now, the battery pack, as discussed below, adds a high cost to the vehicle. Not to mention, where does the cabin heat come from in the winter? I value that "waste heat" of the internal combustion engine in the winter, it's "recovered". An electric vehicle would have to have an electric heater, adding to the battery consumption.

Generally, it is considered to put lithium batteries in electric cars as they have the lowest weight per energy storage (numbers from commercially available batteries):

battery type	watt-hours	kg	meter^3	kg @ 10kWh	m^3 @ 10kWh	$ @ 10 kWh
lead-acid	12240	299	0.151	244	0.123	1900
NiMh	432	5.44	0.00218	126	0.05	12700
Li-ion	888	6.95	0.00729	78	0.082	14900

However, it can be seem from the right column that the price is much higher than for standard lead-acid batteries. The price per energy density can be plotted:





Compressed natural gas vehicles-

As discussed in the section on natural gas, these exist today, and vehicle consumption of natural gas is climbing. They are basically an internal combustion engine using natural gas as a fuel. Current natural gas prices to the consumer are about $20 per million BTU. Since a gallon of gasoline contains 116,000 BTU, at $3 per gallon, gasoline costs ~ $25 per million BTU. Thus, the costs are similar. As mentioned in the section on natural gas, a CNG vehicle can only travel about a quarter the distance of a gasoline engine.

Compressed air vehicle-

Not to be confused with a CNG vehicle, here there is a compressed air tank that supplies it to drive a motor. I personally do not think much of this as we have seen in the section on industrial efficiency that when compressing air about 85 % of the input electrical energy is lost as heat. This compares with 10 % heat loss when charging a battery.

Flywheel vehicle-

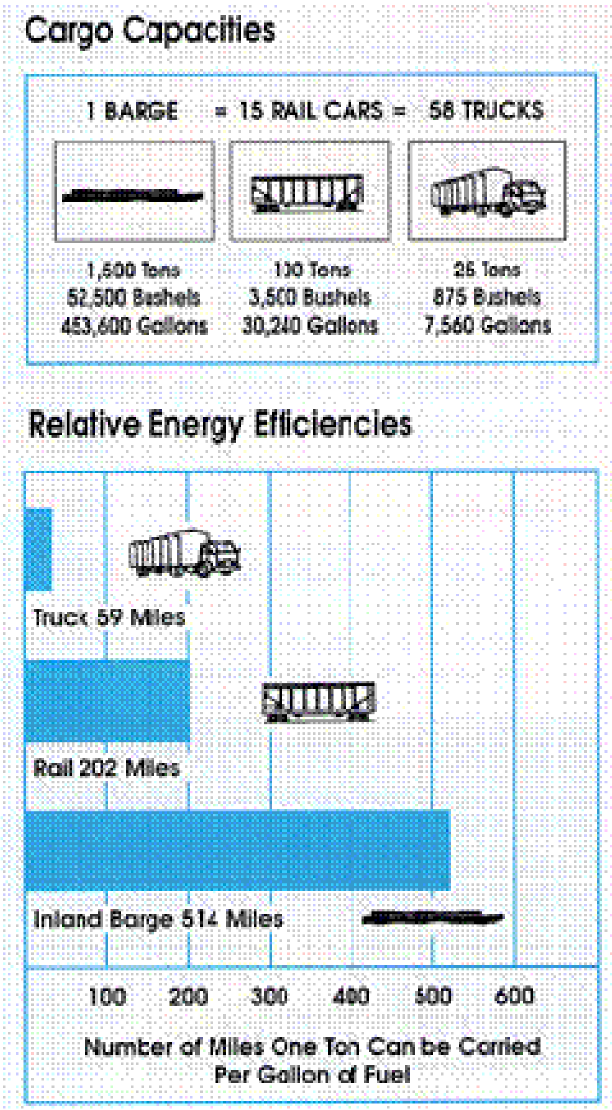
This is an electric vehicle where a flywheel is used to store energy instead of a battery. Current flywheels can have energy storage of several hundred kilojoules/kilogram. This is comparable with lithium ion batteries. The drawback appears to be cost.

Hydrogen vehicles-

Much has been said of the "hydrogen economy" a large aspect of which is the hydrogen vehicle. Since there is no hydrogen in the earth to be mined, it must be made. How it is made is typically by reforming of natural gas, so by this route we're back to a natural gas economy, not hydrogen. But, it can be made through electrolysis of water (just stick the leads of a 9 volt battery in water and you'll see it bubble), so hydrogen is touted as an energy carrier when mined energy source run out and all we have are nuclear, wind, solar, etc., to generate electricity. Essentially, it is a fuel that can be made from electricity. While there are many aspects to a hydrogen economy including hydrogen distribution (can't go through pipelines) and storage (compressed or cryogenic), here we'll simply calculate the cost on a per million BTU basis. Electrolysis is about 75 % efficient in converting electrical energy into stored energy in the hydrogen. Since 293 kWh equals 1 million BTU, it takes 293/0.75 = 390 kWh to make a million BTU of hydrogen. If the price of electricity is $0.2/kWh, then the cost of hydrogen is $78 per million BTU. This compares with $25 per million BTU for $3/gallon gas. Thus, for hydrogen to be cost competitive (as a fuel, not counting the other costs of distribution and storage), gasoline would have to be above $9/gallon.

<u>Efficiency of other modes of transportation-</u>

While cars and trucks dominate the transportation of people and goods in our country, shipping by rail and boat are substantially more efficient:


Cargo Capacities
1 BARGE = 15 RAIL CARS = 58 TRUCKS
1,500 Tons
52,500 Bushels
453,600 Gallons
100 Tons
3,500 Bushels
30,240 Gallons
26 Tons
875 Bushels
7,560 Gallons
Relative Energy Efficiencies
Truck 59 Miles
Rail 202 Miles
Inland Barge 514 Miles
100
200
300
400
500
600
Number of Miles One Ton Can be Carried Per Gallon of Fuel

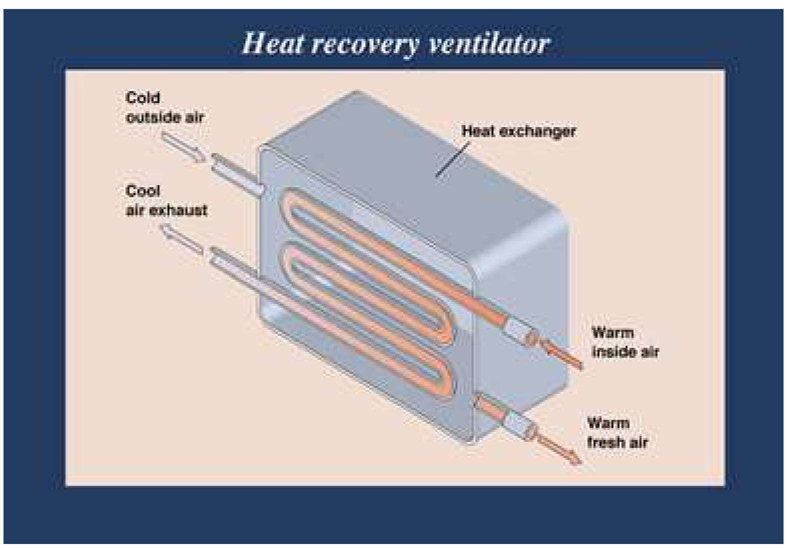
IV. Energy systems

3. Residential and commercial energy use (focus on heating ventilation and air conditioning).

The most energy used in residential and commercial areas is heating. This can be seen from the energy flow chart, which show that of the 19.3 quads going into residential/commercial, 8.3 is from natural gas, and 2.2 is from petroleum, which is mostly heating oil and propane, and both are used for almost exclusively for heating, either cooking, water heating, or space heating. Of heating applications of natural gas and petroleum, about 80 % is space heating. In addition, from the introduction, about 10 % of electrical use in residential systems is for space heating, and can probably be applied for residential/commercial systems, leading from the chart to an additional ~ 0.8 quads for space heating. The total used for space heating is then 0.8x(8.3 + 2.2) + 0.8 = 9.2 quads, or 48 % of the total energy use in the residential/commercial area!

From the introduction, 16 % of electrical use in residential systems is air conditioning, and applying that same fraction to residential/commercial, that is 1.3 quads, or 7 % of total energy use. Thus 48 + 7 = 55 % of residential/commercial energy use is to either heat or cool the air in the building.

Part of this total is due to the necessity to ventilate the buildings with outside air that must be cooled or heated. Usually in commercial buildings to maintain indoor air quality, primarily with regard to carbon dioxide, about 20 % of the air in the building is replaced every hour with outside air, and that air must be heated or cooled. To save the energy that would be lost upon ventilation, a heat exchanger can be made part of the ventilation unit:



There are other ways that ventilators can be constructed that extract the heat from purged air to vented air, and many are incorporated into heating and air conditioning units.

Apart from intelligent ways of venting air without losing the energy, the basic ways of saving heating and air conditioning energy is through insulation to avoid heat loss in the winter or heat input in the summer, and weatherization or sealing of the building to avoid outside air infiltration.

Insulation-

Insulation is basically anything that refers to reducing the heat flow through the solid envelope of the building. It takes many forms including the fiberglass blankets placed in attics and air spaces between multiple panes or windows. All are characterized by a resistance to heat flow called an R-rating.

Heat flow through a material is governed by a simple equation,

$$Q = \frac{\sigma A}{t}(T_{inside} - T_{outside}) = \frac{A}{R}(T_{inside} - T_{outside}) . \qquad \text{(IV.3.1)}$$

Here t is the thickness of the solid material and A is area. For example, a wall of a building of thickness t and area A characterized by a thermal conductivity σ experiences a heat flow given by this equation. Insulating materials are usually characterized by R-value which is proportional to thickness. Thus the heat flow or loss goes up linearly with area and temperature difference, and inversely with R-rating. Note that insulation is far more important in winter than summer as the temperature difference between outside and inside is much larger in winter.

The R-rating of a material depends upon the specific materials, for example, for metals it is far lower than for glass, and upon the air trapped in the material that basically cannot contribute to heat conduction. This is the same principle of jackets we where that are puffed up with air spaces. From equation IV.3.1, the units of R are degrees-area/power. Usually material are rated in English units or Farhenheit-square feet/(BTU per hour). Here is a list of the R-rating of various materials in those units:

Material	Thickness In Inches	R-Value
Concrete	1.0	0.30
Gypsum	1.0	0.60
Wood	1.0	0.91
Tectum	1.0	2.00
Inside Air Film	N/A	0.92
Outside Air Film - Summer	N/A	0.25
Outside Air Film - Winter	N/A	0.17
Vapor Retarders	N/A	0.00
BUR Gravel	N/A	0.34
BUR Smooth	N/A	0.24
Fiberboard	1.0	2.78
Perlite	1.0	2.78
Phenolic Foam*	1.0	8.30
Fiber Glass	1.0	3.90
Polyisocyanurate	1.0	5.56
Polyisocyanurate Composite	1.5	4.17
Polystyrene Bead Board	1.0	3.57
Polystyrene Composite Board	1.5	3.32
Polystyrene - Expanded (EPS)**	1.0	3.85
Polystyrene - Extruded (XEPS)***	1.0	5.00

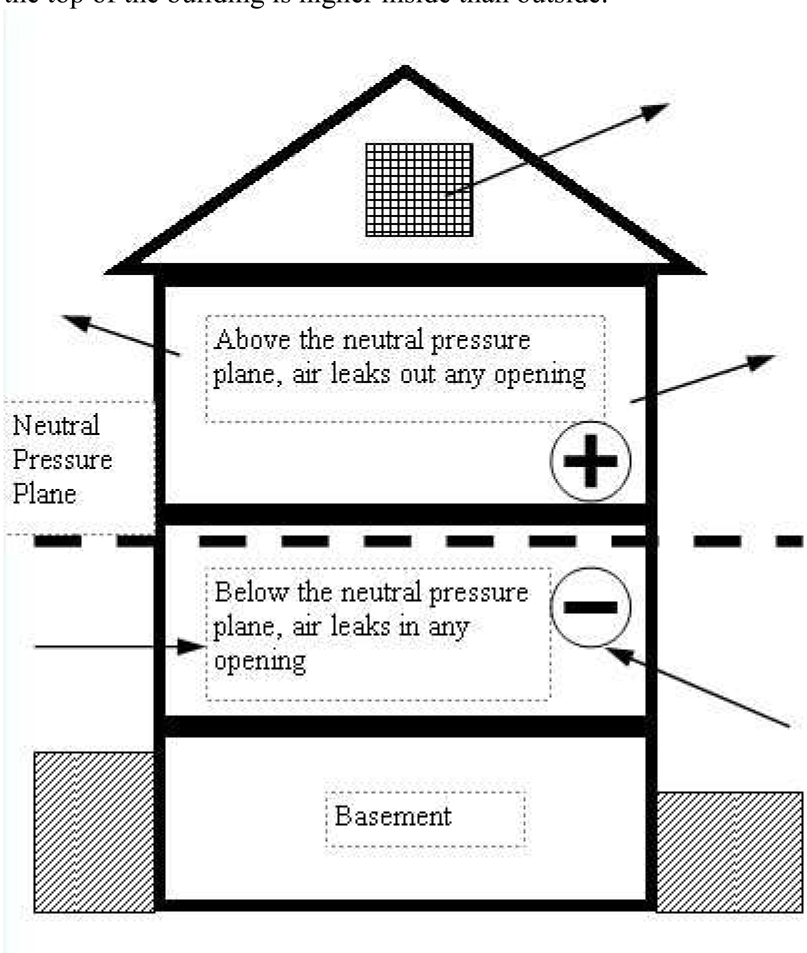
Sprayed Polyurethane Foam****	1.0	6.88
Cork	1.0	3.57

Weatherization or building sealing-

Sealing a building against uncontrolled air flow is of course a way to reduce energy costs, and of course makes sense when considering wind against the building. In addition, though, air will flow into a building even without wind. The reason is due to something called stack pressure, which states that the pressure at the bottom of a column of air will be higher than the pressure at the top, due to the weight of the air. This is simply a restatement of what everyone knows, that air pressure decreases with elevation.

However, the variation of air pressure with elevation will depend upon the temperature of the air, with cold column of air having higher pressure at the bottom. Thus, outside a heated building, the pressure at the base of the building will be higher outside than inside. This pressure differential leads to cold air flowing into the building through any cracks near the floor. It also leads to significant air flow whenever a door is opened. This is why revolving doors save energy, since the building is never fully opened to the outside.

The cold air that enters the heated building must exit, and it doe so because the pressure at the top of the building is higher inside than outside.



This naturally follows from the fact that the column of air inside the building has a lower pressure gradient due to its higher temperature. Note that at a certain elevation in the building pressure inside and out are equal. This means that openings at this level are typically only sensitive to wind infiltration.

The pressure difference between inside and outside is basically proportional to the difference in the inverse of the temperatures:

$$\Delta p \propto \frac{1}{T_{outside}} - \frac{1}{T_{inside}}. \qquad \text{(IV.3.2)}$$

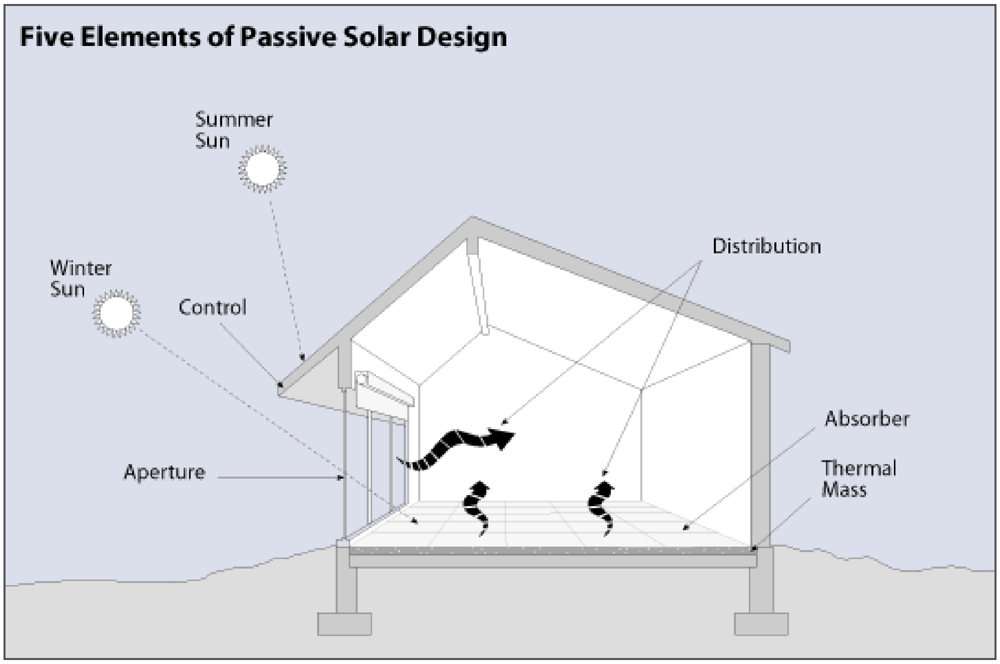
Then to calculate the heat flow requires calculating the air flow and multiplying by the heat capacity of air. Unfortunately calculating air flow from pressure difference is somewhat more complicated than for insulation above, and is not a simple linear relationship.

It is estimated that in residences, several 10's of percent of heating load is due to infiltration. However, as homes do not typically have the type of heat exchanging ventilation units described above, some of this infiltration is actually needed for indoor air quality.

An important thing to realize in the aforementioned "weatherization" of buildings is that what it tells you is the energy lost from the house in the winter, and the energy that enters into the house in the summer, the latter needing to be "pumped out" to maintain the temperature in the building. For the former, the energy lost equals the heating energy required to make it up. But for the latter, the energy needed to "pump out" the energy that leaks in is less that the energy that leaks in. While that may sound counterintuitive at first, the simple fact is that an air conditioner can cool, that is, remove so may BTU of heat from the building, moving that amount of heat energy with a lower amount of electrical energy. The ratio of the energy removal value to the electrical energy value is called the coefficient of performance (COP) of the air conditioner. It does not violate any principle, for example, of conservation of energy that it takes less energy to *move* another amount of energy, as the energy is not being created or destroyed, merely moved. While a complete description requires us to go back to the chapter on thermodynamics, we can simply look at a nearby air conditioner to know the COP. Unfortunately, the heat removal rating is in BTU/hour, so we need to convert, but we know how from the first chapter. A room air conditioner in my house is rated at 8000 BTU/hour, from chapter 1, at 0.29 W/(BTU/hour), that AC can move 8000x0.29 = 2320 watts or joules per second. The nameplate says it consumes 7.3 amps at 115 volts when doing so, or 840 watts of electrical energy. Thus, its COP is 2320/840 = 2.76.

A COP of 2.5-3.5 is typical depending upon the system. Thus, in the summer, when calculating the energy "leakage" into the building, one divides by the COP of the air conditioning system to determine the energy cost.

While we have discussed energy leakage through conduction or air leakage, the so-called "building envelope" issues, the other aspect of heating and cooling are the "building load" issues. This is a combination of the heat sources in the building, and the load due to sunlight on the building and it's absorptive properties. In the winter, of course, it is desirable to have these effects, and windows allowing sunlight in produce solar "heating". However, in the summer, of course, solar heating is not desirable. There is a simple measure to address this, which is the window overhang. Since the sun is higher in the sky in the summer, an overhang or awning can deflect sunlight in the summer while allowing it in during the winter. All it takes is a little geometry:

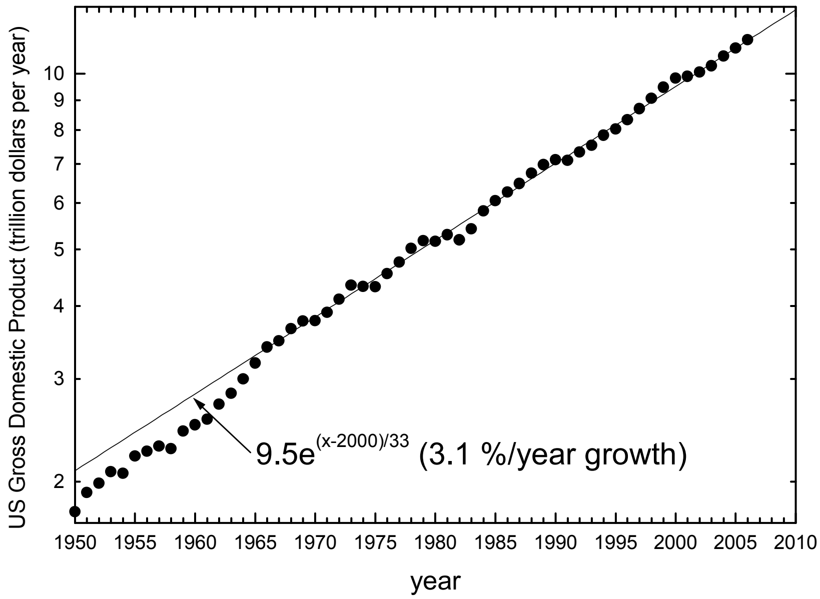


Finally we can discuss the simplest way to reduce heating and cooling energy use, turning down the thermostat in the winter and up in the summer. The Department of Energy has provided a rough guide line that a 1 F decrease in set point in the winter reduces energy use by 5 %. A 1 F increase in the summer reduces energy use by 2 %. This is, of course, due to the COP which here would be 2.5.

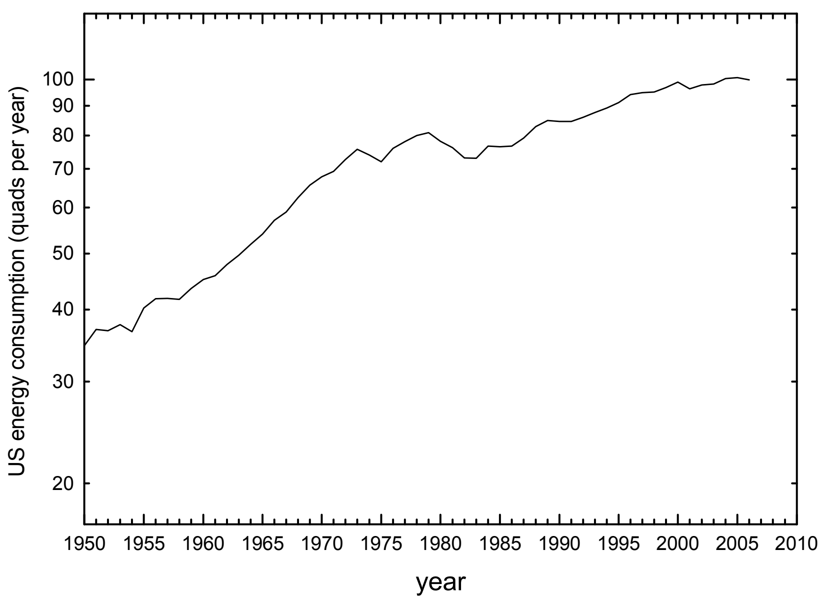
V. Energy and economics

A brief collection of facts to frame a discussion-

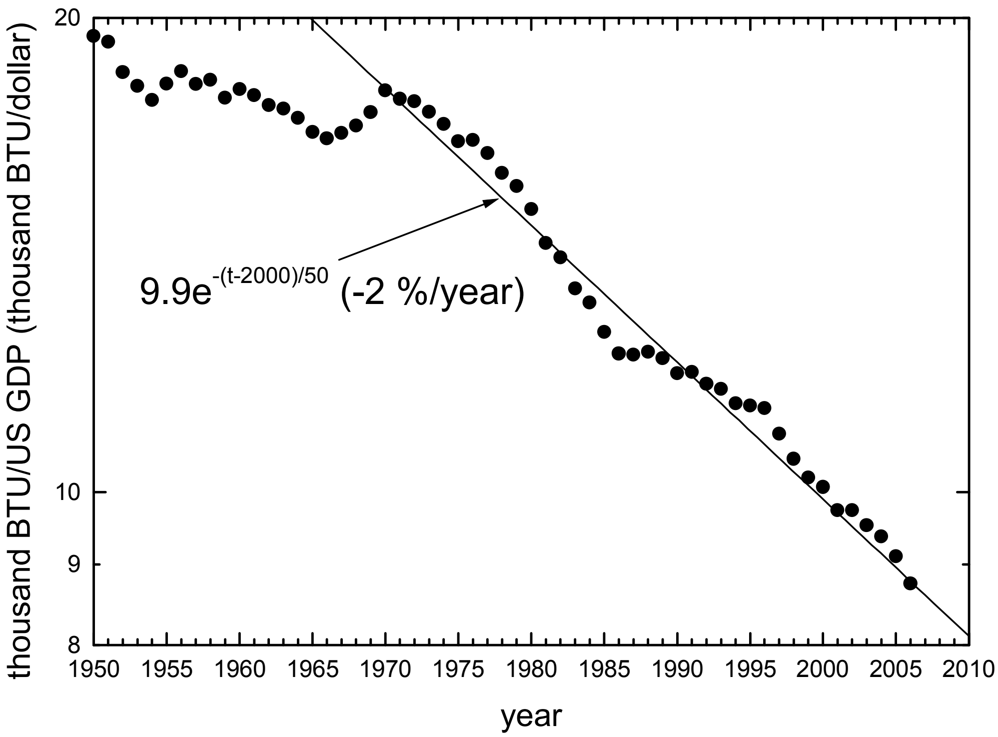
This chart shows the Gross Domestic Product (GDP) of the United States, that is, the total value of all goods and services sold in the United States (including those things sold to people outside the United States), which has been growing fairly constantly at about 3.1 %/year and now is well above 10 trillion dollars per year:



And here is a chart of energy consumption in the United States:



This leads to the often cited plot of energy consumption per dollar produced chart which shows decreasing energy requirements for our economy:

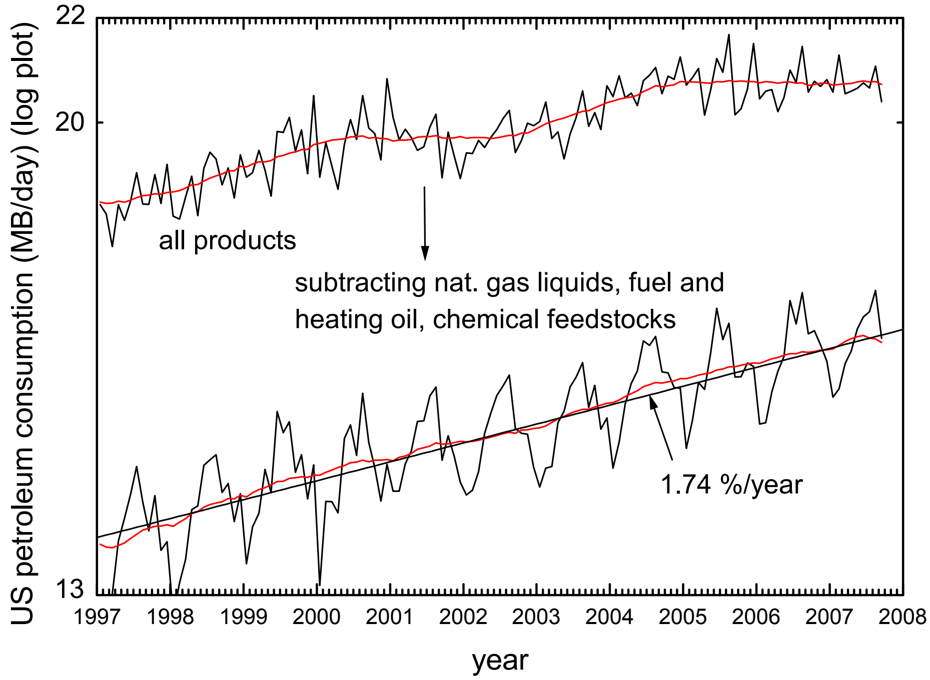


While sometimes it is explained that we are becoming more efficient at making more money with less energy, according to the DOE, it is more due to a

shift of economic activity out of the industrial sector and manufacturing, that use large amounts of energy per unit of output, into service industries that use only very small amounts of energy

So we make more money per unit energy because we work in an office instead of a factory.

On a side note, the slight dip in energy use recently can be attributed to warmer winters. This factor, and the reduction in industrial use of petroleum, can be seen in the following chart of total US petroleum use, and that minus heating and fuel oil, natural gas liquids which are primarily for heating, and industrial feedstock:



The seasonal variation is due to gasoline consumption per our yearly vacation ritual.

Getting back to the shift from our shift from an industrial economy to an office-worker based one, well, someone has to make the stuff, and

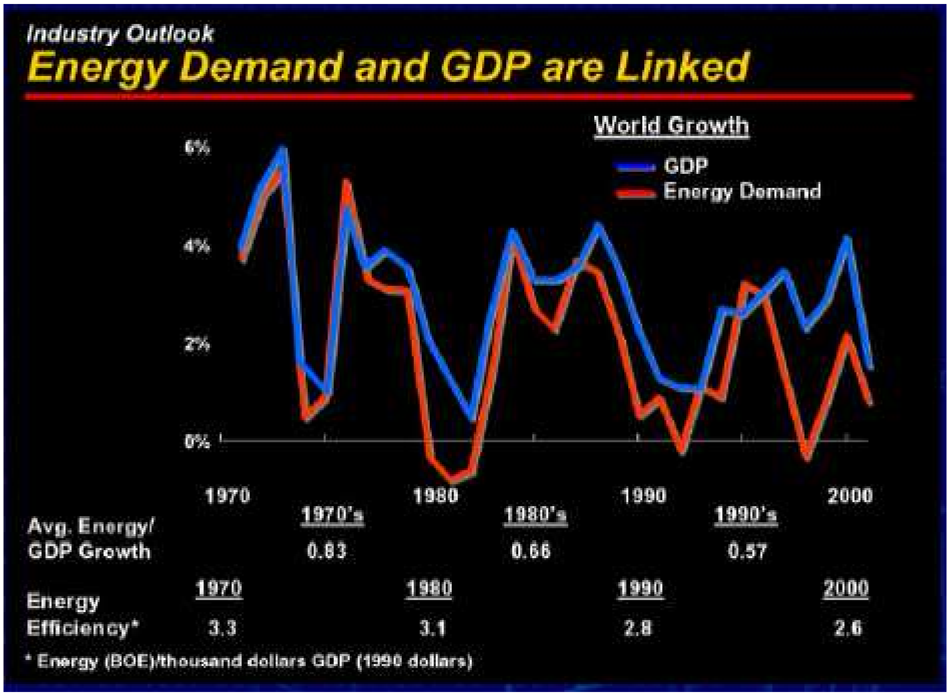
China's energy consumption for unit domestic gross product (GDP) rose slightly by 0.8 percent in the first half year (2006), the National Bureau of Statistics (NBS) said Tuesday.

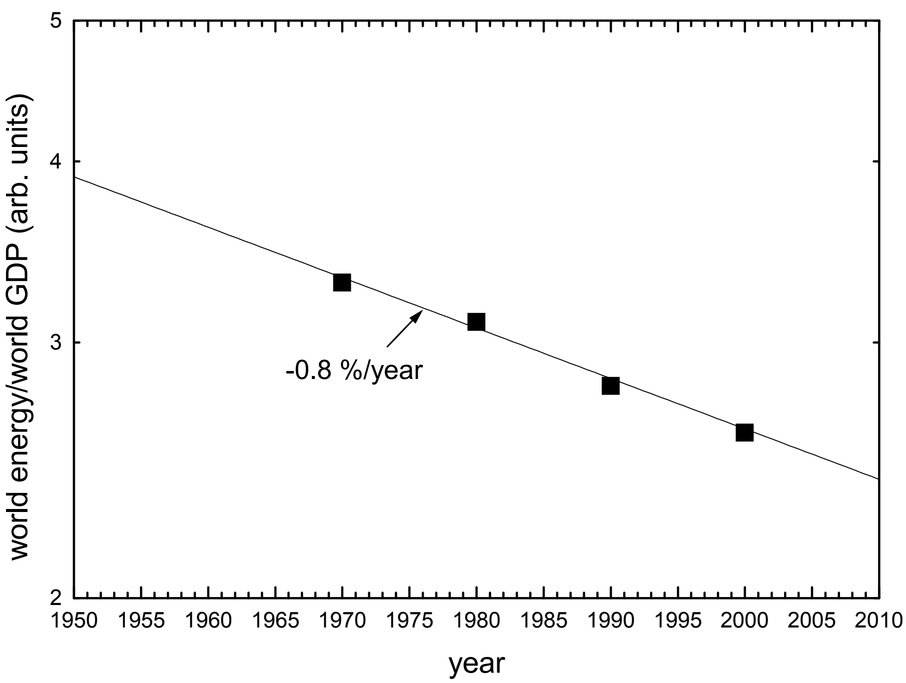
"The situation is not promising for regions and major industries to cut their energy consumption. It will be a very challenging task for them to attain this year's goal", a NBS official said.

Ukraine's energy intensity in terms of GDP has actually risen by a factor of 1.56 (1989-1997)

So basically we're just transferring the requirement of greater energy use while transferring where goods are actually made.

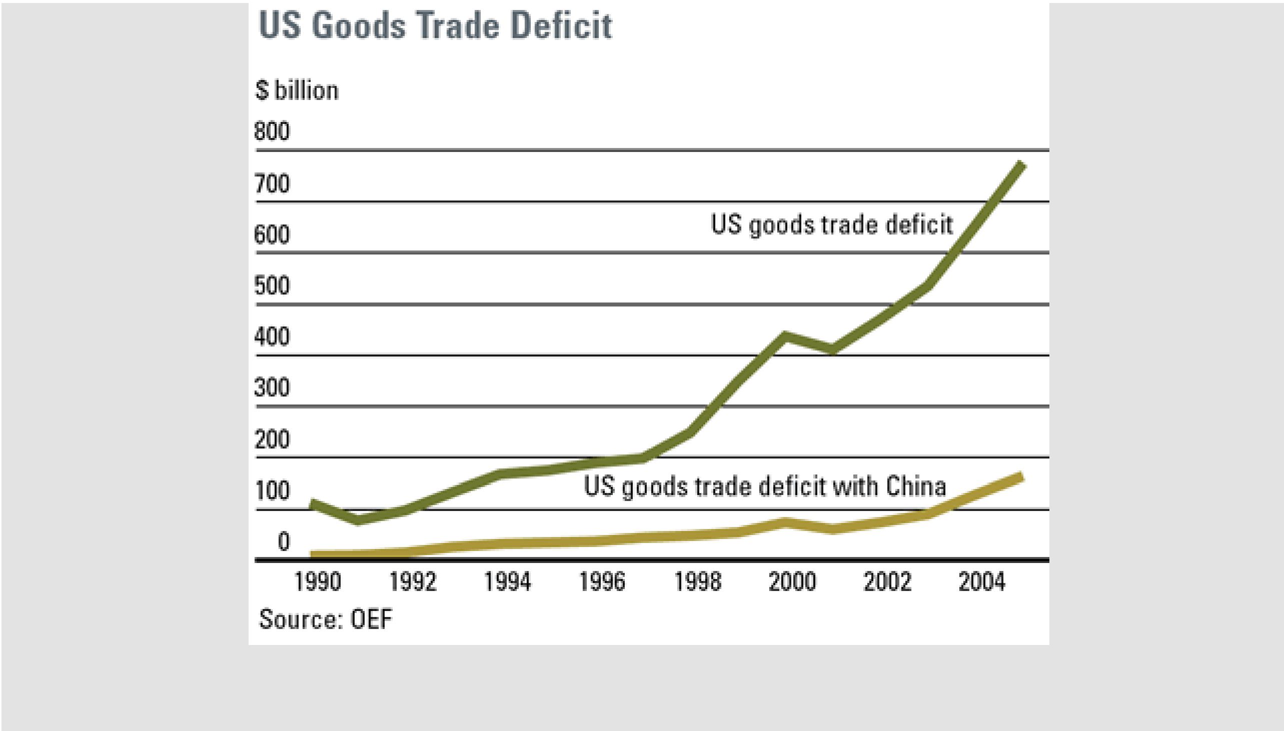
There is actually an overall increase in energy efficiency worldwide as can be seen in this chart:





But it is not falling at 2 % per year as for the US, rather at 0.8 %/year. This can probably be attributed to actual energy efficiency, such as the use of computers and telecommunications that allow us to get more done per energy use.

The US's 2 % reduction of energy/GDP has come at a price:



So, what's the answer? If our GDP continues to grow at 3.1 %/year, it will be 23.6 trillion dollars in 2030. If we can continue dropping energy per GDP at 2 %/year, it will be 5,400 BTU/dollar, or we will require 130 quads/year in 2030, which does not sound so bad.

Now, keep in mind that for your chart I have said we will start at the right side. This will eliminate increases in efficiency from the analysis. In 2001 we used 36.8 quads of "useful energy". One approach is to assume that 2-0.8 = 1.2 % energy/dollar will continue to be shifted out of the country. Then if GDP continues to go up at 3.1 %/year, "useful" energy will only go up at 3.1-1.2 = 1.9 %/year. This means that in 2030 we will require 63.6 quads of "useful" energy. There would be a shift in the ratios of industrial use to commercial/residential and transportation.

We'll talk about this and come up with a number in class. I'll bring my calculator.