H A&S 222d Introduction to Energy and Environment (Life Under the Pale Sun)
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I. INTRODUCTION TO HUMAN ENERGETICS

We will encounter several very different views of the environment: McNeill's history (which has considerable sociology and philosophy built in) which though inspired still leads to gloomy feelings; the up-beat can-do environmentalism of Amory Lovins (the book *Natural Captitalism,* www.rmi.org); the skeptical conservatism (hey, no problem) of Bjorn Lomborg (the book *The Skeptical Environmentalist,* www.lomborg.com) and the opposing views of scientists (www.anti-lomborg.com).

The early part of McNeill's book (up to p20) briefly reviews the historical trends that lead up to today. The combination of great increases in **population**, economic activity (related to 'wealth' or '**affluence'**) and level of **technology** all multiply together to define the impact…the 'footprint'… of mankind on the environment. This trio of effects has often been described, for example by Paul Ehrlich in his early books, *The Population Bomb* and *The Population Explosion* where it is called '**PAT**' as an aid to memory [McNeill only mentions the first two of these]. McNeill is one of a growing number of scholars trying to put both 'the planet's history' and 'the people's history' together, with the aim of improving our (and its) future. We will talk this term about some deep problems relating to life on Earth, and in the grandest notion of all, the life 'of' the Earth, described as a problem of evolution.

McNeill talks about 'rats' and 'sharks': versatile adaptability (rats) vs. supreme adaptation to exploit one particular environment (sharks). 20th C. humanity is more shark-like: stable climate, cheap energy, but this is dangerous strategy. "In the 20th Century, societies often pursued a shark strategy amid a global ecology ever more unstable—and hence more suitable for rats….The same characteristics that underwrote our long-term biological success—adaptability, cleverness—have lately permitted us to erect a highly specialized fossil-fuel based civilization so ecologically disruptive that it guarantees surprises and shocks…we have created a regime of perpetual ecological disturbance.." (McNeill p xxiii).

" The human race, without intending anything of the sort, has undertaken a gigantic, uncontrolled experiment on the Earth. In time, I think, this will appear as the most important aspect of twentieth-century history, more so than world war II." (McNeill p 4). This 'experiment' has many aspects. One is global climate: the temperature, rainfall, winds, soil moisture, Arctic ice and so on. We will consider the greenhouse 'experiment' in the Air and Water units. Another is the development of diseases and epidemics: the combination of individual health and transmission and evolution of disease in crowded, fast-moving global populations. While we cannot study health issues in detail, they are much in our minds. However, it is the health of the planet and all its creatures that should concern us. Human beings are just one, dominant species.

"…in natural systems, as in human affairs, there are thresholds and so-called nonlinear effects." (p 4).

Numbers tell the story. Very roughly 80 billion humans have been born since we evolved a few million years ago, and more than 6 billion of these (7.5%) are now alive. The human body, viewed as an engine that converts chemical energy from food into glucose, then into mechanical work is about 18% efficient (This number would increase if we included our heat production as well…how would you measure this?).

We can put out no more than about 1 horsepower (=746 watts) and that only for very short periods (here I disagree with McNeill, p12, who argues for only 100 watts). You can try this idea out by connecting an electrical generator to a bicycle, and sending the electricity to a light bulb. Over an entire work day we cannot put out much more than an average power of a puny 20 watts (take a 2500 kilocalories per day food diet, convert it to watts and multiply by the 0.18 efficiency factor above, using 4.185 Joules = 1 calorie). Yet by mining the photosynthetic energy of the deep past (fossil fuel) we have multiplied our strength. McNeill introduces the idea of 'energy slaves'…the work done for us by fossil fuel, expressed in units of human power output. The 'average' citizen of Earth has about 20 such energy slaves (McNeill p.14). How many energy slaves does the average American employ? This rate of mining of energy has increased by a factor of 5 in the 19th Century and another factor of 16 during the 20th Century (McNeill p15).

The global use of energy from fossil fuels and renewable energies amounted to 3.8 x 10^{20} Joules per year in 1999 (Physics Today, April 2002). If words are easy to remember this is 3.8 exaJoules. With about 6.3 billion (6.3 x 10^9) people now alive you can calculate what each of McNeill's "20 energy slaves per person on Earth" is worth in watts of power. The rich nations (roughly 1.2 billion people) used energy at a rate about 7 times that of the poorer 4.1 billion people (1990 figures). That is, 2/3 of global energy supplies are used by the richest ¼ of the population. We will see quite a few energy numbers, but one I find particularly sobering is: driving along in your car a moderate steady speed, you are using 100,000 watts of power from burning gasoline. Your efficiency is about 1%. This is calculated by taking the roughly 20% efficiency (that is, 0.20) in turning the gasoline into mechanical work, multiplied by the ratio of your weight to the car's weight, roughly 0.05 (we are talking about people-moving here). The 99% lost could be recaptured and sold for a profit. Actually, the efficiency is far worse than 1%, if you attempt to figure in the costs of mining the energy and bringing it to you gas tank. Economists might argue about this, but the *transmission, conversion and extraction* of energy is a long, complex chain. The efficiencies of each link in the chain multiply together to make a very small net efficiency. The 'true cost' of a gallon of gasoline is much greater than the $1.20 we pay (far cheaper than fizzy drinking water). It leads directly to social-political costs involving wars, dictatorships and great inequality of health and happiness across the face of the Earth.

Another key idea is the **energy profit ratio** (EPR, *The Age of Oil is Over*, web): we read that a few decades ago, about 1 unit of energy are required to mine, refine and distribute 100 units of energy in the form of fuel oil or gasoline. Now this EPR is down to 1:10. This is very important (if it is accurate). It describes why we are so hooked on oil. It was that 1:100 that McNeill emphasizes, in describing the 20th Century as being so biased in our experience that it will get us into deep trouble.

Of the competing energy sources, biofuel, ethanol (0.7-1.7) [note, a number less than one means it takes more energy to produce the fuel than you will get out of it!], methanol (2.6), coal (1:8, used to be 1:100), solar photovoltaic (might reach 1:10 someday), wind is the most promising; a Danish study argues that an EPR of 1:50 might be soon reached.

We begin to see conservation as a supremely valuable 'hidden energy source': a much more efficient and less polluting vehicle could be on the roads today (www.hypercar.com). Conservation throughout our lives could increase the likelihood of a happy future for everyone: people, insects, plants. *The foremost problem is really not, as many people think, that we are running out of oil but that we are running out of environment.*

II. THE SCIENCE CORE: PHYSICS OF ENERGY

In this course, Energy and Environment (as in its predecessor, Earth, Air, Water and we should add, Fire, since Energy is our first unit), we have a 'science core' of ideas and lab demonstrations, and we surround this with lectures and readings and essays on background and applications: environmental history of the past century and studies of environmental practice globally and in the Arctic.

SOME ENERGY NUMBERS

Questions of Scale. Our lab experiments and computer models are small, yet the Earth is so big. In many cases we build 'scale models' of natural systems, just as you build a model airplane. With careful design these can tell us a lot and can be poked and prodded and changed until we understand them. Understanding the natural world involves lots of exercise with powers of ten (there is a small picture book and film called *Powers of Ten* (www.powersoften.com) which is highly recommended). It is not easy to have a feeling for huge numbers or tiny ones. But living with the ideas and experimenting with them helps. That is why we have a bicycle connected to an electric generator: so you can feel what it means to light a light bulb with your own muscle. Some of our most important phenomena, like the ocean circulation, exist at many different scales, as if Nature were making her own models.

In our normal lives, *thermal* energy—the vibrations of atoms that make us feel warm—and *chemical* energy—the energy stored in bonds between atoms—are 'rich' or 'concentrated'. *Kinetic* energy—energy of motion or potential for motion—is comparatively poor or dilute. *Radiant energy* is electromagnetic waves of many forms, including light to infrared 'heat radiation'. *Electric energy* in all those computers and motors and hybrid cars and lights is a subset of electromagnetic energy. *Nuclear energy*—the energy stored in nucleus of atoms, is the original energy source which powers the sun. Our peaceful and warlike use of the nuclear fusion reaction is truly a case of 'playing with fire'.

The energy output of the sun is about 10^{27} watts, radiating to space from its bright surface, which has a temperature of about 5900K. By the time it reaches Earth, 93 million miles 0r 150 million kilometers away, it amounts to about 1366 -1372 watts per square meter (watts m^{-2}), just above the atmosphere. On a bright sunny day at noon you may have about 1000 watts per square meter (1 kilowatt) arriving at the ground: the rest is blocked or absorbed by the atmosphere. But averaging over night and day, summer and winter, tropics and poles, the Earth's surface absorbs only about 120 watts m^{-2}. We saw that the Earth's atmosphere acts as a greenhouse 'blanket', almost transparent to incoming visible sunshine but the outgoing heat radiation at much lower temperature than the sun's photosphere is heavily trapped. It reverberates making the net downward radiation roughly 3 times the downward visible-light radiation at the ground.

The solar energy absorbed by growing plants on land and in the sea is enough to grow roughly 6×10^{14} kg of glucose per year (glucose being a simple sugar, here used to represent the more complex biology of green plants), and the biomass energy produced contains about 10^{22} Joules of energy. This is 30 times bigger than the use of fuel energy by human beings (see below). However only a very small part of growing plants turn into future oil and coal and gas deposits, and we are now using them up far faster than they are being regenerated.

ENERGY: CONCEPTS

Forms of energy *(related to various kinds of physical* forces*):*

- *mechanical* – kinetic and potential
- *thermal* – internal thermal energy, radiation (hidden form of mechanical, electromagnetic energy)
- *electrostatic and electromagnetic* (including light waves, radio waves, infrared 'heat' waves, the energy in electric currents)
- *chemical* -- based on the bonds between atoms (often light atoms…the lightest, hydrogen is the 'best') and within atoms (electrostatic, electromagnetic)
- *nuclear* – based on changing the nucleus of a heavy atom, splitting (fission) or combining (fusion) them. This is the ulimate source of almost all of Earth's energy…fusion deep in the sun where the nucleii of two hydrogen atoms (each of which is a proton) combines to make the nucleus of a helium atom, and in doing so give off tremendous energy.

In the sections below we will develop the following set of ideas.

▪1 *Energy is conserved: yet it can change form*
  ▪2a *Mechanical energy*
  ▪2b *Thermal energy*
  ▪2c *Chemical energy*
  ▪2d *Radiant and electric electromagnetic energy*
  •*2e Nuclear energy*
▪*3 Forces can change energy*
▪4 *The sun is the 'mother' of most of our energy*
▪5 *Energy is converted from one form to another: some forms of energy are 'rich' (concentrated) and some are 'poor' (dilute, with low concentration).*
▪6 *Energy moves, or is transported from one place to another: this is an essential part of human energy use.*
▪7 *Power is the rate of change of, or rate of transmission of, energy: they have different units.*
▪8 *An engine is a device that produces mechanical energy from thermal or chemical or electrical energy*
▪9 *Energy efficiency involves conversion of energy into a useful form (such as mechanical energy) plus a discarded 'waste' energy*
▪10 *Chains of energy conversion can be long and inefficient.*
▪11 *Energy storage, natural and artificial is important to physical and biological systems.*

1. Energy is conserved: yet it can change form. Conservation of energy is a keystone idea in physics. Energy is neither created nor destroyed, it just changes from one form to another, or is transferred from bit of matter to another. This is a principle that has been found to work with high accuracy on Earth.

{Yet we should add that physicists looking at forces driving the expanding Universe have found that huge majorities of its mass and energy have gone missing! What they have romantically called 'dark energy' and 'dark matter' have been invented to make things right, and are being sought by astronomers and astrophysicists

> Dark Energy appears to be, based on the brightness of the most distant type-Ia supernovae, a mysterious force that is accelerating the expansion of the universe. These recent discoveries have provided good evidence that there is such an outward force on the universe (variously called the cosmological constant, "quintessence," or "dark energy"). Data about the rotation of galaxies shows us that the outer parts rotate as fast as the inner parts. This only makes sense if there is a spherical distribution of matter in each galaxy, which is not what we see. Therefore we infer that there is a certain amount of Dark Matter in each galaxy. This could be some exotic particles, or just lots of stars too small to have ignited.
> http://imagine.gsfc.nasa.gov/docs/ask_astro/answers/010104a.html
> http://sciencenews.org/20000429/fob1.asp}

Even the experts at NASA have trouble getting the 'units' right sometimes: 'energy' and 'force' have different units as we see in mechanical energy relationships based on Newton's laws.

***2a. Energy conservation and 'mechanical' energy*.** Newton's three laws of motion set the stage for the Industrial Revolution, the physical sciences, astronomy, machines of all kinds. They deal with the quantities mass, momentum, forces and acceleration, all of which need to be carefully defined to make progress. Newton did not operate alone: laws of orbital motion of moon and planets had been worked out by astronomers long before, and electricity has reshaped our world equally but that had to await James Clerk Maxwell in the Victorian era, for a complete physical theory; thermal energy also needed to be understood separately, for instance with the concept (or 'model') of a gas made up of molecules flying round like billiard balls and occasionally colliding by Maxwell and Boltzmann (such a model can be viewed in motion at http://comp.uark.edu/~jgeabana/mol_dyn/KinThI.html).

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Newton's 2d law states that if you do place a force on an object, it will accelerate, i.e., change its velocity, and it will change its velocity in the direction of the force.

It accelerates in the direction...

That you push it.

Secondly, this acceleration is directly proportional to the force. For example, if you are pushing on an object, causing it to accelerate, and then you push, say, three times harder, the acceleration will be three times greater.

If you push twice as hard...

It accelerates twice as much.

Thirdly, this acceleration is inversely proportional to the mass of the object. For example, if you are pushing equally on two objects, and one of the objects has five times more mass than the other, it will accelerate at one fifth the acceleration of the other.

If it gets twice the mass...

It accelerates half as much.

http://id.mind.net/~zona/mstm/physics/mechanics/forces/newton/newton.html

or,

$$F_x = MA_y$$
$$F_y = MA_y$$
$$F_z = MA_z$$

where the subscripts indicate the three directions: (x,y,z) = (east, north, up). There is a problem though; we do not know precisely what is meant by ‘force’ and ‘mass’. These have come down to us through experience and observation of the simplest kind. Force is something you exert on a body, and it causes the body to move. Push harder: that’s more force. In Newton’s day there was a realization that these vague ideas had to be *measureable.* In particular it was noticed that a wire spring, coiled up, will be extended when a mass is hung from it, and it is stretched roughly in proportion to the amount of the mass: say adding sand to a bucket in carefully measured spoonfuls. Thus a *standard of measurement* of mass began to develop. In this case it had the extra complication of being related the force of gravity. *Weight* and *mass* are thought by physicists to be proportional to one another, if the positions of all the objects in question are otherwise the same. But we know that a pendulum-clock will advance at a different rate on the top of Mt. Rainier than in Seattle, because it is farther above the Earth’s surface.

Let’s take Newton’s law of motion and use it to define mechanical energy. Suppose the motion is just in one direction, x, so we can forget the subscripts and say F = MA in that one direction. Suppose X is the position of the mass, which will vary with time, t. We write

$$X = X(t)$$

The *slope* of the curve of X against t is the velocity, which we call V. We define slope to be the tangent of the angle of the curve with respect to the horizontal (time-) axis. On a sketch this would be simply

$$V = \Delta X/\Delta t$$

for small increments of time, Δt and distance moved, ΔX. In what follows, the symbol Δ is not a constant or a number, but an *operator,* or *action.* It means “small change in...” Similarly, on the graph V(t), the slope of V is what we define to be the acceleration,

$$A(t) = \Delta V/\Delta t. \qquad (1)$$

If we feel comfortable with defining the mass based on our experience of the ‘amount of matter’ or more clearly by saying that twice as much of the same stuff will have twice as much mass, M, and A is clearly defined above, then we might think of Newton’s 2d law as defining what force, F, is. But we have argued that an independent idea of force had emerged from coiled springs and gravity and human interactions, so that Newton was indeed relating three things that people could agree on individually.

Newton’s 1st law is sort of a special case of his 2d:

If an object is not pushed or pulled upon, its velocity will naturally remain constant. This means that if an object is moving along, untouched by a force of any kind, it will continue to move along in a perfectly straight line at a constant speed.

Once moving at a steady speed...

In a straight line...

It will continue moving...

At a steady speed...

In a straight line.

This also means that if an object is standing still and is not contacted by any forces, it will continue to remain motionless. Actually, a motionless object is just a special case of an object that is maintaining constant velocity. Its velocity is constantly 0 m/s.

Once standing still...

It will stay still.

It is important to realize what a huge leap of understanding these laws are. If you push a block of wood on a table top it quickly stops: it does not 'move at steady speed'. Realizing all the interactions involved in moving bodies around us, Newton could visualize an ideal experiment free of these complications. And, he was right.

We now derive the equation for ***mechanical energy conservation***. First we look at the energy of a moving mass, or ***kinetic energy.*** Multiply the 2d law by velocity, V.

$$F\,V = M\,V\,A$$

using equation (1) above

$$FV = M\,V\,\Delta V/\Delta t$$

now we write an expression for V^2 at time $t + \Delta t$:

$$\begin{aligned}(V + \Delta V)^2 &= V^2 + 2\,V\Delta V + (\Delta V)^2 \\ &\approx V^2 + 2\,V\,\Delta V\end{aligned}$$

In the last step we dropped $(\Delta V)^2$ as being small; its ratio to the term we kept, $2V\Delta V$, is

$$\tfrac{1}{2}\,\Delta V/V$$

which is small (written as << 1) if we make the time interval small enough.

So the change in V^2 over a small time interval relates to the change in V according to:

$$(V + \Delta V)^2 - V^2 = 2V\,\Delta V$$

which we can write as

$$\begin{aligned}\Delta V^2/\Delta t &= 2V\,\Delta V/\Delta t \\ &= 2V A \qquad (2)\end{aligned}$$

In words, the slope of the curve V^2 as a function of time, t, is just twice the velocity, V, times the acceleration, A.

This is a key result of calculus (one of the few calculus statements we will use this term). It is important to check relationships like this by seeing that the *units* are the same on both sides. The units of velocity are distance/time, units of acceleration are distance/time^2 and so both left- and righthand side of equation (2) have units distance^2/time^3 and we are fine.

Going back to equation (1) we have

$$FV = M\ \Delta(\tfrac{1}{2} V^2)/\Delta t.$$

We suppose the mass M of the object does not change, so this is the same as

$$\boxed{FV = \Delta(\tfrac{1}{2} MV^2)/\Delta t.} \qquad (3)$$

The force muliplied by velocity is the rate of change of $\frac{1}{2} MV^2$ with respect to time. The left-hand side is called the 'rate of doing work' and the right-hand side is the 'rate of change of kinetic energy, call it KE, defined as $\frac{1}{2} M V^2$. You push on something and it accelerates, changing its kinetic energy.

This simple calculation now gives us a clearer 'metric' for energy: our fundamental energy unit, the Joule, must have the same physical dimensions as does KE. The units of energy therefore are the units of $\frac{1}{2} MV^2$, that is mass x velocity^2 or mass x length^2/time^2. Write this as ML^2/T^2 or $M^2L^2T^{-2}$. Thus F=MA becomes a far-reaching basis for understanding energy of all kinds, and 1 Joule = 1 kg meter/sec^2

The ***potential energy*** comes next. Equation (3) shows that kinetic energy can change. If the force F is constant in time, then we can write the left-hand side, the rate-of-doing-work, as

$$F\,V = \Delta(F\,X)/\Delta t$$

and this leads to a great simplification. Equation (3) becomes

$$\Delta(1/2\ M\,V^2 - F\,X)/\Delta t = 0$$

The sum of the two terms in brackets is constant in time. -FX is called the ***potential energy.*** This can be written

mechanical energy = kinetic energy + potential energy,
= constant in time

for a mass moving in the presence of a constant force, F. Or, introducing new symbols PE for potential energy and E_M for mechanical energy,

$$\begin{aligned}E_M &= KE + PE \\ &= \tfrac{1}{2} M\,V^2 - F\,X.\end{aligned}$$

More generally, F can vary in particular ways and this mathematical trick still will work. If we are talking about vertical motion (in the z-direction) in the presence of gravity, F will be the local gravity force -Mg where g is the constant 9.8 meters/seconds^2 near the Earth's surface. Then replace X by Z, giving

$$E_M = \frac{1}{2} M V^2 + M g Z \qquad (4)$$

A ball falling due to gravity is the simplest example. Pendulums and swings are somewhat more complex examples of conservation of mechanical energy, in which there is a rhythmic trading of kinetic and potential energy, happening precisely so as to keep their sum constant (if friction is neglected). If we use Newton's 2d law for the acceleration in the direction perpendicular to the rope, then the same result (4) is found.

That moment at the top of a 'swing' when your velocity V vanishes, is the moment of greatest potential energy. If your swing takes you two meters up, your velocity should reach

$$V_{bottom} - V_{top} = \sqrt{(2g(Z_{top} - Z_{bottom}))}$$
$$= \sqrt{(2 \times 9.8 \times 2)} = 6.26 \text{ meters/second}$$

at the bottom of the swing. (To do this, we have solved equation (4) for the velocity change between top and bottom of swing. Notice that the mass, M does not affect the answer.) This is for an ideal world with no friction. Well, how much friction is there; how good a 'model' is this of reality? What experiment would you do on the swing to find out very quickly?

2b.Thermal energy

We introduce a new conservation law which was originally based on careful experiments of the temperature of gases, changing in response to heating or changes in pressure ('squeezing'). Symbolically, the **1st law of thermodynamics** says

change in internal thermal energy, say E_T, of a substance = net heating (or cooling), Δ'Q, plus the mechanical work done on the substance, Δ'W:

$$\boxed{\Delta E_T = \Delta' Q + \Delta' W}$$

There may be energy 'sources' in which energy is stored, possibly in exotic forms like radioactive decay or radiation of light, but once these are accounted for, the thermal energy equation is accurate.

In this formula the internal energy, E_T , is, for a simple gas, proportional to its temperature. In fact this warmth is mechanical energy in disguise (the vibration and translation of atoms or molecules). A more visible form of internal energy is the kinetic energy, KE, in the overall movement of the 'substance'… as when you hit a baseball. The *kinetic-molecular theory of gases* developed this idea, and showed that what we call temperature is simply proportional to the average kinetic energy, KE, of the gas molecules! Thermal energy of liquids and solids is more complex, involving chemical bonds, internal modes of vibration and rotation and hence effects of quantum physics. It is thus less 'knowable' in detail yet in practice we use experiments to define thermal properties of these materials. Phase change, when a liquid boils to become a gas, or freezes solid, involves breaking or forming of bonds between molecules. Large amounts of energy are released or absorbed. If you heat a pan of water from room temperature to the boiling point you use only 1/8th the energy that it takes to boil all the water into vapor (as you might guess by comparing the times it takes to do either).

2c. Chemical energy. A very rich (concentrated, intense) form of energy lurks in the bonds between atoms that make up a molecule, and within the internal structure of each atom. Chemical substances are most often made of identical molecules...which are assemblages of individual atoms. The atoms bind together in a stable fashion. A second, independent idea: these molecules either are far apart and interact only through abrupt collisions (in a gas) or are closer together, interacting constantly (a fluid) or are so close together that they lock into a rigid pattern (crystalline solid). It is quite intuitive that if you increase the temperature, the kinetic energy of the individual atoms increases, and these bonds can be broken: yet great energy is required to break apart molecules. Similarly, great energy can be *released* when atoms come together to form molecules.

Thus the attractive forces between atoms to form molecules, and between molecules, and within individual atoms all relate to energy states…analogous somewhat to the simpler energy of an orbiting satellite or a thrown ball.

2d. Radiant electromagnetic (e.m.) energy William Clerk Maxwell worked with the results of many observations of charged bodies, stationary or moving, and of intensely moving electrical charge that one has in a wire with current passing along it. His fundamental equations (which appear on T-shirts of MIT students) describe many things, including the electromagnetic waves that appear when charges are rapidly oscillating. An alternating current in a wire can radiate…that's radio and tv. What is so remarkable is that the entire spectrum of e.m. waves of many different wavelengths and frequencies, corresponds to so many important phenomena: visible light, infrared light ('heat waves'), ultraviolet radiation, x-rays, radio waves. Here we are interested in the observation that a heated body radiates waves and their wavelength depends in a remarkably simple way on their temperature. The 'black-body radiation' of German physicist Max Planck is a curve telling us how the temperature of different parts of a candle flame relate to the wavelength of the em waves…violet, blue are hot, shorter wavelengths, red is less hot, longer waves and deep red even less hot, still longer wavelenths, and when a fire dies away it still radiates heat as much longer, infrared radiation which we cannot see yet we feel.

Radiant heat interacts with whatever it hits; the sun warms us. Once we are warmed we re-radiate some of that heat, at a different wavelength (a different color). This property is essential to the way the Earth traps and stores and eventually re-radiates the incoming sunshine.

Electric energy, for example in the electrical current passing along a copper wire, is central to modern life. It is a special case of electromagnetic energy, and can be thought of as a stream of electrons (although that is not really correct in detail). The energy and power units for electricity involve voltage (volts) and current (amperes), which like joules and watts can expressed in simpler units. The power (P, watts) moving along a wire with resistance (R, ohms) is equal to the product of current (I, amperes) and voltage (E, volts):

$$\begin{aligned} P &= I\,E \\ &= E^2/R \end{aligned}$$

Here we have used Ohm's law relating electrical current, voltage and resistance of the conductor:

$$E = I\,R.$$

3. Forces are important to energy. The ‘work done’, in the 1st law of thermodynamics above, is defined as a force multiplied by the change in volume of the air sample . If we compress a bag of air by squeezing it, the work we have to do is equal to the force multiplied by the distance our fingers move. Another way of expressing this is pressure times change in volume of the air [pressure is force per unit area, and change in volume is just distance compressed times the area of the surface of the bag]. We see that squeezing a bag of air should increase its temperature even though no heat has flowed into it. So, there are two ways to find the work done here: *pressure multiplied by volume change*, or *force multiplied by distance*. The mechanical work and heat flow do not violate the conservation of energy: they just move energy from one body (perhaps you) to another (the bag of air). These ideas will come clearer when we ‘build’ a heat engine.

4. The sun is the ‘mother’ of most of our energy. It puts out roughly 10^{27} watts of radiating energy in all directions, based on nuclear fusion, where light hydrogen atoms fuse to make heavier helium atoms; energy of fusion has been created on Earth but not yet tamed. The power of arriving solar energy averages (over the year) 1376 watts/meter^2 at the top of the atmosphere, about 1000 watts/meter^2 at high noon, at the Earth’s surface and averages about 240 watts/meter^2 over day and night, summer and winter, at the surface (this is an average over both oceans and land). Note that this varies very greatly with latitude.

5. Energy conversion from one form to another is an organizing idea for the environment. At all scales from microbial life to plants, animals and their machines, on to the Earth’s oceans and atmosphere, and the workings of the Universe, energy is being converted, and the direction is often: nuclear=>chemical=>thermal=>mechanical although there is also much conversion in the opposite direction. We will encounter this conversion in many examples to follow.

6. *Energy flow from one place to another.* Energy transmission is essential to its use: movement in pipes, wires, radiation (light, heat (infrared radiation), uv (ultraviolet radiation), radio…all these are electromagnetic waves). When electrical energy is sold from Washington to California and then sold back, at least ½ of it is lost on the way. Electrical transmission is done by stepping up a very high voltage, which reduces losses. It is in alternating-current form (AC) usually though there are arguments in favor of high-voltage direct-current (DC) transmission. During the electrical power shortage in California two years ago, electricity was ‘borrowed’ from the northwest, but transmitting it there and then back involves considerable loss.

7. Power and energy. Power is the rate of gain or loss of energy, or the rate of transmission of energy. **1 watt of power = 1 Joule (of energy) per second (J sec^{-1})** . Think of the analogy of filling a reservoir with water: the flow of water (in cubic meters per second, $m^3\ sec^{-1}$) is the rate of filling it, analogous to power, and its volume (in m^3) is analogous to energy. Notice that dividing the volume by the flow rate gives a time (check the units: $m^3/m^3\ sec^{-1} = sec$) which is the time it takes to fill the reservoir. This simple idea is surprisingly useful throughout this course. It helps in thinking about the flow and concentration of pollutants too. It is important to keep power and energy clearly in mind, and confusing when someone talks about kilowatt hours of energy and kilowatt hours per year of power. We will look at energy flow in a variety of systems, mechanical, thermal and electrical. This gives us an understanding of 'power'.

8. An engine is a device that converts energy from one form to another for example, heat input can be converted to mechanical energy, as seen in the 1st law of thermodynamics. *A heat engine* converts heat to mechanical energy (in a 4 stage process of heating, then expanding, then cooling, then compressing a gas... to do work). The Stirling engine in the lab is such an engine, and works at quite high efficiency, converting candlewax into mechanical work (which then disappears back into heat as it is 'dissipated'). We will develop the details of this idea shortly.

***9. Energy efficiency refers to the conversion of energy into a useful form plus an un-used for*m:** a heat engine takes thermal energy and produces mechanical energy + 'waste' thermal energy, with

efficiency = mechanical energy generated /input thermal energy.

As we have said above, human beings are about 18% efficient in converting food Joules to mechanical energy (the rest goes into heat and unused chemical energy); a 2500 kilocalorie per day diet is about 115 watts of intake, giving about 20 watts output (multiplying the efficiency times the input; (yet in short bursts we can do at least one horsepower of power output (=746 watts)…run upstairs, 5 meters in 5 seconds…calculate mgh/time). Other common engines also run at about 20% efficiency in converting energy: a car for example. But, that is not the end of the story of efficiency for cars or humans, because you need to define what really is 'useful work done'.

We will later describe the efficiency of the ideal 'heat engine' of physics, which puts a firm upper limit on the amount of work you can get out of a heat- (or fuel-) driven engine.

High quality, concentrated energy is often degraded by several conversions, each at low efficiency…with much of being wasted. Efficiency of an ideal heat engine at producing mechanical energy rises with very hot intake of heat and very cold exhaust…but these are absolute temperatures. Of course the 'waste heat' can be put to use separately. By *concentrating energy (as with lenses and mirrors) this efficiency can be increased.* Vaclav Smil's discussion of *entropy* enters here: it describes the availability of energy, and how that relates to contrasts: hot and cold, top of mountain, bottom of valley, top of swing (when swinging on a swing), bottom of swing.

There is a big contrast between 20 Joules of energy in a ton of water moving 20 cm/sec (in our water channel) and a million Joules in a candy bar: the chemical energy in the candy bar is a very 'rich' concentration of energy; mechanical energy of the flowing water is relatively 'low-grade' energy. Yet we do have hydropower because of the *scale*: the immense flow rates involved. A hydroelectric dam may be 90% efficient at converting the local potential energy of the reservoir water above to electricity; yet that water has descended thousands of meters from its source, losing almost all of its initial potential energy. In a river energy is constantly dissipated into heat, and to do this the river must be turbulently whirling rather than smoothly flowing. You could estimate the power of a flowing river: it is the rate at which kinetic energy flows past a fixed point: essentially kinetic energy per cubic meter times rate of flow past a point, which is velocity times area. This is

$$\tfrac{1}{2}\rho V^2 \times AV \text{ or } \tfrac{1}{2}\rho AV^3$$

where A is the cross-sectional area of the river (depth h of the water x width w), V is its mean velocity, ρ is the mass density of water (= 1000 kg/m^3).

{Note that the *units* of this formula are

$$\text{kg x meters}^2/\text{seconds}^3$$

which are the units of kinetic energy per unit time, or power. Whenever you write a formula think about its physical units, combinations of mass, length and time and also some energy related units like temperature. It is the easiest way to find a mistake.}

A river flowing at V=2 m/sec, h=5 m deep and w=100 m wide represents a power (energy-flow) equal to

$\tfrac{1}{2}\rho AV^3 = \tfrac{1}{2} \times 1000 \times 2^3 \times 5 \times 100 = 2 \times 10^6$ watts…**2 megawatts**.

Note the cubic dependence on river velocity: at 6 m/sec the river will have 3^3 or 27 times the power, 54 megawatts. While this sounds like a lot, a velocity v could come via 'free fall' of the river from a height $h = \tfrac{1}{2} v^2/g$. This comes from equating the potential energy ρgh (energy per kg of water) to the kinetic energy $\tfrac{1}{2}\rho V^2$ (per kg) that results from the fall.

So, for 6 m/sec velocity we would need a waterfall of height only 2 meters….except for the 'splash':

$$\rho gh = \tfrac{1}{2}\rho V^2$$

ignoring any loss of mechanical energy to heat. Hydropower dams are surprisingly efficient in a local sense (converting the mgh kind of potential energy of the reservoir above into kinetic energy, thence to electrical energy).

The Irish Energy Centre uses the formula:

hydropower available in watts = 8000 x AV [volume flow (m^3 /sec)] x h [head (m)].

The 'head' is the vertical height through which the water falls. This is equivalent to an 82% efficiency since the formula with no energy loss would be (combining the above results): power = ρghAV and g is equal to 9.8.

Grand Coulee Dam, which since 1941 helped to reshape the Northwest with cheap electricity, generates 6.5 x 10^9 watts..=6500 megawatts..=6.5 million kilowatts. It is also the largest concrete structure ever built. US households use on average about 2 kilowatts of electricity, so the Grand Coulee Dam can power 3.25 million such homes. Washington State's utilities have the used the following fuels in 2003: hydropower 66.6%, coal: 17.7%, nat gas 9.8%, nuke: 4.6%, other: wind 0.4%, waste 0.17%, biomass 0.54%, oil 0.04%, landfill gases 0.09% (Source: *Seattle PI,* October 2004).

In the USA annual electric hydropower generation is about 2.8 x 10^{18} Joules, which is a small but important part of the national energy use profile: in total the USA uses about 10^{20} Joules per year, which is ¼ of the entire Earth's energy use! Solar energy amounts to 7 x 10^{16} Joules per year, very small in proportion, but growing rapidly each year.

10. Chains of energy conversion can be very long and inefficient, if the useful energy is for example 20% transmitted on at each stage (think of sun => plants => oil => gasoline =>car) because 20% of 20% is 0.2 x 0.2 = 0.04…4% and …and so on: $(0.2)^4$ = 1.6 x 10^{-3} = 0.16% (actually the efficiency of photosynthesis is far less than 20%). And now we move to water, air (and earth): they should really seem simple by comparison. Our bodies and our cars are converting chemical energy into mechanical energy with about 20% efficiency. Since energy is not destroyed, we speak of the 'waste heat' that represents part of the remaining 80% (together with some unburned energy that is rejected as waste or 'exhaust'). Electricity moves through the power grid from generation plants to users. We need to work on these numbers, but an estimate of the efficiency of the power grid is 33% (J. Rifkin, E/The Environmental Magazine, Jan/Feb 2003). We will introduce the idea of the hydrogen economy: the hydrogen fuel cell is 40 to 65% efficient, in a local sense (just as with oil, producing an distributing the hydrogen involves additional losses).

***11. Energy storage is essential to its use*;** and likely involves conversion from one form of energy to another. Gasoline, natural gas (mostly methane, CH_4), oil, candlewax all store energy at about 30 to 50 kiloJoules/gram (=megaJoules/kg, or $30x10^6$ to $50x10^6$ J/kg), while hydrogen is the winner at about 145 kiloJoules/gram (yet by volume, it has less energy than methane, because it is so light). Quite literally, oil is liquid ancient sunshine! Foods range from 2 to 17 kJ/g (same as megaJoules per kg) in stored chemical energy, hence recently stored sunshine. Hydropower can be stored by pumping water back uphill until it is needed. An electrical battery stores energy in chemical form, to be released by a chemical reaction (often involving an acid dissolving a metal electrode; sulfuric acid and zinc, say). The strong appeal of hydrogen fuel cells is that stored hydrogen is cleaner and simpler and less wasteful of other materials than is a chemical battery.

In succeeding lectures we will look in more detail at chemical energy, its relation with biological life, and particularly the role of carbon. This introduces the natural carbon cycle, growth of plant life through photosynthesis, storage as fossil fuels and human mining of these fuels, burning them and putting carbon back into the atmosphere, oceans and biosphere in large quantities.

The most dramatic storage of energy in the context of this course is the reservoir of fossil fuel energy that accumulated over millions of years and is being mined and combusted in a tiny fraction of that time.