Chapter 6

Mathematics and Energy

With the exception of humans and some chemosynthetic ecosystems powered by geothermal energy, all other known ecosystems on earth are powered either directly or indirectly by the sun, mostly via photosynthesis, which usually converts about 1% to 2% of incident solar energy into "plant energy." If we include geothermal with solar energy, then humans stand alone in trying to use sources of energy other than these.

In this chapter I will, among other things, outline an argument for the following claim: *The most economical (as in "cheapest"), fastest, and most reliable way to provide non-carbon based energy for human societies is to make use of solar energy in its various forms.* About half the solar energy that reaches the ground drives the hydrologic, i.e., water, cycle. This is truly an immense amount of energy. Wind, solar thermal, solar photovoltaic, ocean thermal, ocean wave, ocean (moon caused) tides, and "cool" geothermal (available at shallow depths nearly everywhere) are all sources of energy. "Hot" geothermal, that issues from the earth due to radioactive processes ("nuclear energy") within the earth, is plentiful in select locations. The good news is that it is technologically possible to power our societies using these energy sources. It is also possible to make the transition to these sources in measured steps over the next twenty years. This incremental process would give us and the rest of the earth and its ecosystems time to adjust to whatever unintended or unforeseen consequences this process might entail. It is also possible that "subunits" of society can start this process without waiting for national leadership, although the most efficient transition could be effected by enlightened leaders. Biofuels may have a role to play, but there are some major difficulties we will discuss. Nuclear power, which is the favorite of some, is not competitive with or as reliable as a well designed, sustainable, solar-driven system; and we will examine this assertion as well.

6.1 How Much Solar Energy is There?

We need to be able to measure energy in order to discuss it. I go into more detail in VII about various forms of energy: electric, mechanical, chemical, heat, and how the units of measurements for each interrelate. In this chapter I will measure energy in terms of the metric unit of *joules*, i.e., J. I explain in some detail what a joule of energy is in VII. For now the important thing to know is that *energy* is different from *power*. The unit of power that I will use in this section is the *watt*, i.e., 1 W. By definition 1 *watt* is 1 J per *second*, i.e., $1\ W = \frac{1\ J}{sec}$. Thus "energy per unit time is power." Note that "power multiplied by time is energy." A unit of energy you are no doubt familiar with is the kWh, i.e., the kilowatt-hour. For electric energy you pay about 10 cents for 1 kWh. You can burn a 100 W light bulb for 10 $hours$ with 1 kWh. (Do you see this?)

A kWh is a unit of energy, so it should be equal to some number of joules. For practice let's calculate that number as follows: $1\ kWh = 1\ 10^3\ W * 1hr = \frac{10^3\ J}{sec} * 3600\ sec = 3600(10^3)\ J = 3.6(10^6)\ J.$

I am going to need to use the units of $joules$ and $watts$ to discuss solar energy flows. Recall that $1\ TW = 10^{12}\ watts$ (a terrawatt). From [411], a book from 1981, I get the following information:

"The sun radiates energy at a rate of about $3.9 * 10^{26}$ *watts (W). Of this, some half a billionth, or 172,500 TW* $= 172,500 * 10^{12}$ *W, falls on the top of the earth's atmosphere, and about 81,100 TW reaches the ground. The world's hydrologic cycle is driven by an energy of about 41,400 TW, and the total energy of wind (1200 TW), waves, and ocean currents is several thousand TW. Solar energy is fixed in plants by photosynthesis at the net rate of about 133 TW. The total flux of geothermal heat to the earth's surface is about 32 TW. In contrast, the world's population 4.3 billion people directly used energy – not counting the indirect use of solar energy embodied in food and fiber – at a total rate of about 9 TW (with a probable error less than 10%). This is a great deal of energy in human terms, equivalent to the energy that would be consumed as food by an average of 15 full-time slaves (each eating 3000 Cal/day) for each person on earth; yet it is only a ten-thousandth of the rate at which solar energy reaches the earth's surface. Because of the way in which humankind converts energy, however, that 9 TW is rapidly becoming a significant force in the workings of global climate – the greenhouse effect and global warming are the result.*

"In particular, approximately 8 TW of the roughly 9 TW is derived from burning fossil fuels – solar energy stored millions of years ago when a tiny fraction of the total plant matter was trapped by freak conditions in an anaerobic swamp where it was protected from oxidation. Through unique conditions extending over geologic time, pockets of fossil fuels totaling over 70,000 $TW - y$ *were trapped beneath the earth's surface."* (Note for a more detailed account of how sunlight became stored as fossil fuels see [130].)

So what has changed since 1981? I will leave it to you to determine at the time you read this if the sun is coming up each day with approximately the same intensity it had in the 1980s. Two things have definitely changed: world population, and global energy consumption. As 2009 turned into 2010 the world population was about $6.8(10^9)$, up from $4.3(10^9)$ in about 1978. Above it states that the rate of consumption of (non-food/fiber) energy of these 4.3 billion people was about 9 TW, give or take 10%. In about 2009 that number has increased to 12.5 TW, according to [326, p. 60], where this number is a maximum not an average. Wikipedia estimates 15 TW, and that as an average. For 2005 the World Resources Institute, www.wri.org, gave global energy consumption as $11,433,918$ $ktoe$, where $ktoe$ means $kilotonnes\ of\ oil\ equivalent$. I will leave it to you in Exercise 6.1 to figure out what this means, since this is a common unit of measurement. In other words, is the wri.org estimate closer to 12.5 TW or 15 TW?

Exercise 6.1 Energy Numbers Where applicable in the following do a little research and determine your answers as carefully and quantitatively as you can, for the year you are reading this.

(i) Express the amount of solar power that reaches the top of earth's atmosphere in *petawatts*, i.e., PW, and *exawatts*, i.e., EW. See Table Greek Prefixes, page 60.

(ii) From 1981 to 2010, or until the year you read this, has the energy output of the sun changed? Increased, decreased, stayed the same, oscillated? By how much measured in *watts*?

(iii) Vaclav Smil, [640, p. xv], states that the solar radiation reaching the earth per year is 5500000 EJ. Is this in approximate agreement with the $172,500$ TW figure given above? Hints: $EJ = 10^{18}$ J, and how many seconds are there in a year?

(iv) From 1981 to 2010, or until the year you read this, is the earth absorbing more solar energy or less, or the same? By how much measured in *watts*?

(v) If $4.3(10^9)$ people have 15 slaves each, each eating 3000 Cal/day, how many $joules$ per *second*, i.e., W, of power is that? Note: 1 $Cal = 10^3$ cal, and 1 $cal \approx 4.18$ J. Is your answer consistent with the text above?

(vi) Is it true that fossil fuel energy represents solar energy that was stored over a period of about 10^8 $years$?

(vii) One (metric) *tonne* of oil has 41.868 $gigajoules = 11,628$ kWh of energy, according to www.wri.org. First of all, check to see if this last equation is (approximately) correct. Next, compute how many joules of energy $11,433,918$ $ktoe$ represents. Then if this was the amount of energy consumed globally in 2005, what was the average power consumption in *terrawatts*, i.e., TW?

Putting aside for the moment the possibility that there is enough geothermal energy by itself to more than satisfy global human needs for energy, [247, Chapter 5], let's see how far we can get with just direct solar and wind energy resources. The starting point is roughly $80,000$ TW of solar power reaching the ground, about half of which drives the hydrologic cycle – from which every hydroelectric power plant draws its energy, by the way. So let's start with $40,000$ TW of solar power. If we take the 15 TW figure and more than double it to 40 TW, we are looking at a little less than $\frac{1}{1000}$ of the solar power not already driving the hydrologic cycle. This represents roughly 8 or 9 hours of sunlight to capture one year's worth of energy for all global human uses. I am being very conservative, because you can find correct quotes in the literature, from 2007 for example, which say that the sunlight falling on the earth about every 70 minutes equals the total annual energy use of human's worldwide. Now although there is plenty of direct solar power/energy, it is prudent to get by on as little as possible; thus minimizing the chances of unintended consequences. Sunlight is actually doing many things, and we probably do not understand all of the details. We do know that about 133 TW is driving photosynthesis, so keeping global human use to a small fraction of that number is likely wise.

Now [326, p. 60] estimates that 580 TW of direct solar is still available after subtracting areas of the earth that should be protected, areas that are inaccessible and/or otherwise less than desirable to develop. Included in this excluded area are the open oceans. Consistent with these restrictions is the following calculation of the National Renewable Energy Laboratory (NREL). NREL determined that in the United States urban areas and residences cover $140(10^6)$ *acres*, and that putting solar photovoltaic collectors on just 7% of this area would provide all of the U.S.A.'s current electricity requirements, cf., [413, p. 16]. This is a rather remarkable fact that a small portion of areas already heavily impacted by human activities such as roofs, parking lots, highway walls and so on collect enough sunshine to power America's electric grid.

What about wind? In [326, p. 60] global wind power is estimated to be $1,700\ TW$, somewhat more than the $1,200\ TW$ given in the article above. Applying the same restrictions we applied to solar, [326] estimates that 40 to 85 TW of wind power remains available for human exploitation. Again, wind is a vital part of the global ecology, just as is sunshine; so it would be prudent to take as little as possible to avoid unintended consequences. But that said, I think it is reasonable to assume, especially if we proceed incrementally, assessing impacts at each stage, that there exists an immense amount of available wind power that can be exploited with minimal upset to global ecology.

Thus it appears that there are many times more solar and wind resources than would be required to power a global human civilization with more than twice the 2009 population of $6(10^9)$, viz., 14 or 15 billion people. And there are geothermal, and ocean (thermal, wave action, and tidal) power as well, each potentially huge energy sources. As I have indicated earlier in this book, however, it is unlikely that human population will exceed $10(10^9)$, since limits of land, water and other resources will constrain the growth of human numbers before the limits imposed by the availability of energy are reached.

6.2 Solar Energy is There, Do We Know How to Get It?

In a word, the answer is YES! The proof, of course, is in the actual doing. I discovered this the hard way while building a house, operating a farm, or doing experiments in physics and chem labs. Often the biggest obstacle that must be worked around in order to implement a "clear vision" turns out to be the behavior of fellow humans with whom you must work in order to accomplish a goal.

The complete paper proof of my claim that we can "do it" with solar requires more details than I can put in one chapter. I will, however, outline some of the major points in a moment. For those who really want to get deeply into this subject, I claim that sufficiently many of the rest of the details can be found in the literature. A short summary is "A Path to Sustainable Energy by 2030," by Mark Z. Jacobson and Mark A. Delucchi, *Scientific American*, Nov. 2009, [326]. A 235 page book that "proves" my claim is by Arjun Makhijani, *Carbon-Free and Nuclear Free: A Roadmap for U.S. Energy Policy*, available at www.ieer.org, the web site of the Institute for Energy and Environmental Research, cf., [438], (to read this you need to know that 3414 $Btu = 1\ kWh$, where *Btu* stands for *British Thermal Unit*, a unit of energy). Finally, and perhaps by geographic accident, I am most familiar with the work of the Rocky Mountain Institute, in Snowmass and Boulder Colorado, www.rmi.org. The co-founder, Chairman, and Chief Scientist, Amory B. Lovins has as deep a grasp of the math, physics, economics, and practical problems of generating useful energy as I have ever encountered. He also has the hands on experience of having consulted with over 100 utilities, including coal, gas and nuclear facilities. There is a wealth of information about energy on the rmi web site. In any event, these three different sources demonstrate, each with a slightly different perspective, that we have the technical knowledge to make the transition to a solar/wind driven economy rather quickly. Do sufficiently many of us have the imagination and political will to do it? That remains to be seen. Not to overstate the case, but Nature is testing humanity. We must pass the test, for if we fail – well I recommend Cormac McCarthy's book, *The Road*, for a taste of a possible post-apocalypse, pre-extinction future!

Increased Efficiency Lowers Consumption of Energy Without Reducing Useful Work Done. The amount of energy we derive from sustainable sources is growing, and the lower our total energy demands the sooner these renewable sources will meet our needs. We can decrease our demands for energy now by being more efficient. Amazingly, just within the United States, if each state used electricity as efficiently as the top ten most efficient states (in 2005) we could shut down 62% of U.S. coal-fired electric generation with no lowering of productivity. Since one of these states is California, you might say, well, they have a mild climate. The foregoing statement has already been adjusted to take into account the economic mix and climate of each state, cf., [426, p. 3].

According to [412, p. ix],

> *"The U.S. today wrings twice as much work from each barrel of oil as it did in 1975; with the latest proven efficiency technologies, it can double oil efficiency all over again."*

From www.rmi.org:

> "Denmark just grew its economy 56% without using more energy." (statements made in 2009) "Japan wrings 2 - 3 times more work from its energy than the U.S. does, ..."

As long ago as 1991 I was in a math office in Tokyo, Japan, during the summer. The university was connected to a "smart grid" which allocated electricity according to an "optimality algorithm." My energy use was much less than were I at home (in the U.S.), but I did not notice much difference in the office – while outside it was quite hot and humid. Things have come a long way since then, but the point is that whole-system design integration can often make very large (sometimes even tenfold) energy savings! (www.rmi.org)

One could fill many pages with examples of increased efficiency. The main lesson, however, is simple. We can use our brains to design systems of cities with houses, businesses, industries, that use much, much less energy than we are used to at present in the U.S. with the same level of comfort and productivity – and save money at the same time. The lower our total energy consumption the easier it will be to satisfy those demands with sustainable energy sources – and the sooner it can happen.

One observation from [326, p. 60] is that if we ran on wind and solar electricity, we could achieve additional efficiencies over fossil fuel or biomass combustion. For example, only 17% to 20% of the energy in gasoline is used to move a gasoline-powered vehicle, the rest of the energy is waste heat. An electric motor can convert 75% to 86% of electric energy into motion. The technical reason for this is part of the Second Law of Thermodynamics, which I explain in VII. There are theoretical and practical limits on the efficiency of any "heat engine" like a gasoline-powered car or a coal-fired power plant. Electric motors are not subject to the same limitations. While we are still using coal generated electricity, however, Lovins observes that saving one unit of electric energy saves three units coal energy, again, in part, because of the Second Law. Thus the *first step* in our program is to increase efficiency!

Decentralized, Modular Systems versus Centralized Systems. Now I want to present a mathematical principle with a large range of applicability. For example, in the next exercise the modular system could be a combination of solar and wind generators versus a large coal-burning plant, nuclear plant, or even a large concentrating solar collector plant! Electric generating systems built in stages consisting of several smaller units (or modules) have an *intrinsic mathematical advantage* over a single, large plant with the same total size. The large plant would need to have some built-in "economies of scale" if it were to have a chance of besting the system of smaller units; and it turns out that these economies of scale are rarely realized and do not compensate for additional advantages of the "modular system." The following exercise was inspired by [662, Chapter 4].

Exercise 6.2 Building Power Sources One Module at a Time vs. Big Central Power Plants: The Modular Method vs. the Centralized Method In this exercise we create 100 MW of new electrical generating capacity, and we are going to do this in two ways. Let us suppose that it takes 10 units of time to build one big central plant that generates 100 MW of power after 10 units of time (from beginning to end of construction), but it generates nothing during construction. I will call this the *"centralized method."* On the other hand, suppose it takes 1 unit of time to build a smaller power source which delivers 10 MW after 1 unit of time has passed from start (to finish) of construction. If we repeat this process, then after 2 units of time we will have our original first 10 MW power plant, which will have been in operation for 1 unit of time, plus an additional 10 MW just coming on-line. We can then repeat, adding a third 10 MW plant during a third unit of time, and so on. I will call this the *"modular method."*

(i) Suppose that building 1MW of generating capacity costs the same, whether in the 10 MW units or the big centralized 100 MW unit. What is the total cost of building 100 MW of generating capacity by either method?

(ii) To make the math easy, suppose that all power plants are generating electricity at full capacity (once construction is completed) all the time. After 2 units of time how much electricity has the modular method produced (and hence sold)? Same question for the centralized method. (If "unit of time" is too abstract, assume the unit of time is some fixed number of hours. So your answer will then be in MWh, megawatt-hours.)

(iii) Answer the same question as part (ii) after 3 units of time, 4 units of time, . . . , 10 units of time, 11 units of time.

(iv) What is the total amount of electricity produced by the modular method after 11 units of time? Same question for the centralized method?

(v) Same questions as part (iv) after 20 units of time. Will the centralized method ever "catch up" to the modular method?

(vi) Which system is more reliable? In other words, what are the chances of all 10 modular units failing all at once versus the chances of the big centralized unit failing ("all at once")?

(vii) All systems need maintainance. Discuss how the modular units can be maintained according to a routine maintenance schedule while never falling below 90% generating capacity. Can you say that for the big centralized system? Does this mean that during planned maintenance the centralized system economically falls even further behind the modular system?

(viii) Which system is easier to finance? Which offers the quickest return on investment?

(ix) If you represent a poor developing country, which method do you think will be most attractive?

(x) Can the modules be geographicaly distributed so as to minimize transmission costs and electrical transmissions losses? Does this option increase the reliability of the modular system? Is the modular method more efficient?

It turns out that in the U.S. about 98% to 99% of power failures originate in the grid! So the modular method, with many electric generating units geographically dispersed, will be more reliable from the customer's point of view just because on average there is less grid between a given customer and some source of power, cf., [413, p. 7].

For billions of people in the world their energy crisis is not being able to readiliy gather enough fuel-wood to cook or heat. I can clearly recall the image of a woman carrying a bundle of (cooking/heating) wood on her head: an image repeated in China, India, Nepal, rural Africa, Mexico, Peru, Honduras and doubtlessly in many places I have never been. One of the books that deals with the fuelwood crisis from the point of view of those suffering it is [474]. For people in a remote village a modest bit of assistance will enable them to build a small scale, independent solar or wind generating facility, and in a short time. Such folks will likely never be "on the grid," and would have to wait forever before a large scale energy facility of any kind were made available to them. Trading deforestation for renewable sun and wind energy that they can control benefits these populations in immeasurably important ways.

6.3 Four Falsehoods

Among folks who accept the fact that we must phase out fossil fuels, there are those who propose solutions that include the "nuclear option" and those that do not. Fortunately for the purposes of this book there are two bonafide "environmentalists" who are on opposite sides of the question as to the efficacy of relying on nuclear power, at least in the near future. These contrasting views are pedagogically useful because we must confront a reality. Labels such as "green" and "environmentalist" will likely become increasingly meaningless without at least a cursory examination of what exactly it is that is being proposed as being "green." As with all popular labels, they become adopted by folks with intentions quite independent – often exactly opposite, consider *greenwashing* – of the original meaning of the label. It is also not unheard of for people to argue sincerely for positions which later on have consequences quite opposite of what was intended. This is called a "mistake." Thus for any presentation of an important topic it is important to get beneath the superficialities and symbols as soon as possible and do one's best to understand the meaning of what is being proposed and the likely consequences. Looking for mathematical structures is often (though perhaps not always) of help.

Thus in October of 2009 Stewart Brand's book, *Whole Earth Discipline*, appeared which argues for nuclear power as essentially the only viable option to burning coal, if we are to honestly confront global warming. Stewart Brand was a co-author of the orignal *Whole Earth Catalog*, a classic of the early environmental movement. Amory Lovins, mentioned above, has published many articles on all aspects of energy which are available at www.rmi.org. In particular, his article, "Four Nuclear Myths: A Commentary on Stewart Brand's *Whole Earth Discipline*" and on similar writings, [413], does just what the title says. I have taken the liberty of calling the four nuclear myths just "Four Falsehoods," since the misconceptions therein are held not only by proponents of nuclear power but by many others as well; and myths, as I have used the term, often contain enough truth to make them useful – but these four are not helpful. For a more detailed and extensive discussion than I can provide here, please read as much as you can of the "pros" and "cons" of nuclear, solar, and wind power. The four falsehoods that we will discuss now, however, are at the heart of the disagreement.

Variability is not the same as Reliability: Solar/Wind Can be the MOST Reliable. The *First Falsehood* goes like this. *Since the sun does not shine all the time, solar photovoltaic panels are not reliable. Since the wind does not blow all the time, wind generated power is not reliable. Thus solar and wind cannot be relied upon to power our grid, since they are not "on all the time."* (Being "on all the time" is often equated to the term "baseload electric power," but this is technically incorrect, so we will not use this terminology, cf., [413, p. 5].) Brand's book asserts that fossil fuels, hydro, and nuclear are the only sources that can be "on all the time." Thus a grid cannot rely on solar or wind, unless massive energy storage facilities are built.

The picture in the wind/solar sceptics mind is ONE set of wind generators at rest because the wind is not blowing, or ONE set of solar panels at night. This picture applies to one individual or small community whose system is off the grid, isolated from society. Such a simplistic system can be made to work, I know of examples; but that is NOT what we are dealing with, with respect to, say, the electic grid of the United States, or any industrialized country.

I need to define two crucial terms: *variability* and *reliability*. The term reliability can be applied to individual electric generation plants, and it can be applied to the *entire grid.* Reliability (or more precisely unreliability) is measured by the amount of downtime a facility experiences due to *technical failure.* Variability, as it applies to wind and solar generators, refers to variation in output determined by variations in wind and sunshine. (There could be variation as experienced by the customer in the long (or near) term for coal, nuclear or hydro plants due to shortages or price spikes in fuel or water, but we will ignore this.) Let's look first at reliability in the U.S. of various types of generators and the grid from 2003–2007. Coal plants were down for scheduled or unscheduled maintenance 12.3% of the time, 4.2% of the time without warning, cf., [413, p. 5], [326, p. 63]. Nuclear plants were down 10.6% of the time, 2.5% without warning. Gas-fired plants were down 11.8%, 2.8% without warning. The technical failure rates for solar photovoltaics and wind (on land) is less than 2%, and less than 5% for wind turbines at sea, cf., [413, p. 6], [326, p. 63]. Since existing plants go down from time to time already, back-up contingency plans exist already as well, to keep the grid functioning in case of plant failure. But as noted above, 98% to 99% of power failures experienced by customers result from failures in the grid! Thus solar and wind generators very reliably convert sunshine and wind into electricity whenever available!

So is it possible to design a solar/wind system that compensates for the variability at any fixed location? The answer is yes, with very modest storage, not "massive" storage. According to [326] 3.8 million large wind turbines, each rated at 5 MW, distributed strategically worldwide would generate 51% of global energy. Another 40% of global energy would come from photovoltaics and concentrated solar plants, with $\frac{3}{4}$, i.e., 30%, from solar panels on rooftops of homes and commercial buildings. Solar energy is more evenly distributed than is wind. The model in [326] includes 900 hydroelectric plants worldwide, 70% of which are already in place. The analysis at www.rmi.org and the one in reference [438], though not identical with [326] reach the same conclusion, i.e., an economy based on solar and wind is technologically possible. The interesting thing to note is that by having "smart grids" the parts of the grid that are "up" at any given time can perform backup for those parts that are "down" to such an extent that storage of energy can be quite modest. A smart grid can also manage demand, creating new efficiencies and lowering costs. New transmission lines would have to be built, but the solar/wind system would displace the need for 13,000 new central coal or nuclear plants that would have to be built over the next 20 years, requiring their own transmission line upgrades of greater extent than that required by a solar/wind system. As pointed out in [326], the world manufactures 73 million cars and light trucks every year, so producing the wind turbines and solar panels needed is well within current manufacturing capabilities. Since reliability is a *statistical function* of the entire grid and its embedded generators, by being "smart" we can design a solar/wind electric system that is just as reliable as the one now, likely more so, cf., www.rmi.org.

By the way, storage technologies exist right now; and improvements can surely be expected. Right now, pumped storage (pumping water uphill when excess power is available, letting it run downhill to generate electricity when needed) exists, some not far from where I live. Compressed air storage, molten salts are other alternatives. Electrolysis, using excess capacity to break down water into H_2 and O_2, stores electric energy as chemical energy. (Not that there would be many, but current gasoline engines can be converted rather cheaply to run on natural gas or H_2.) There is a known chemical process for making various alcohols with the following inputs: water, carbon dioxide, wind electric energy. This is an additional method of energy storage, cf., Exercise 6.4. Alcohols can also be used as transportation fuels, cf., ethanol. A predominantly electric motor, battery powered, vehicle fleet could provide an immense storage capacity, charging while parked or giving energy back to the grid as needed. A national electric rail system could utilize immense amounts of energy in real time without the need for storage.

Of the four falsehoods, the first is the one too many people see as "obviously true," and it has a subtle mathematical content. The other three I will mention briefly and leave a more complete analysis as an exercise, cf., [426]. Thus the *Second Falsehood* is that *wind and solar systems require enormous amounts of land, more than central power plants like nuclear generators, hence are environmentally unacceptable.* I have already mentioned that sufficient solar energy can be captured on roofs of buildings, parking lots, and so on, without more ecological impact than already exists. Concentrating solar facilities could be more impactful. For example, they should not use water, which is often scarce in places with the most intense sunshine, rather molten salts or oil or some substitute for water. The necessity of the simple process of cleaning dust from solar collectors should not be overlooked. But solar clearly need not take up "a lot of space." Regarding wind, giant wind turbines are quite compatible with agriculture. Animals happily graze and tractors operate right up to the base of supports and between turbines. Income from wind turbines can have the beneficial side effect of helping farmers stay on their land. There is sufficient wind resource so that sensitive areas such as wilderness or major bird migration routes can be avoided. Improvements in design and siting have reduced bird kills such as occurred at Altamont Pass, Calif. More improvements can and should be made; but for those concerned about birds (such as myself): regulation of house cats, pesticides and cars; reducing light pollution at night (turning off skyscraper lights at night for the benefit of the many species of night migrating birds, for example), putting decals on all commercial and residential plate glass windows; would have more effect, cf., [247, p. 84], www.audubon.org.

The *Third Falsehood* is that *all options, including nuclear, are needed to combat climate change.* Nuclear power is not necessary, since solar and wind (or more generally a diverse portfolio of sustainable energy sources) can do the job more cheaply and safely and be installed more quickly. We will say a bit more about this later. The *Fourth Falsehood* is that *nuclear power's economics matter little since governments must nevertheless use it to protect the climate.* See [426]. If this same logic were applied to solar and wind we would do it first and be done with it. Wind power in the 1980s was prohibitively expensive at 30 cents per kWh. Today wind joins geothermal and hydro in the "less than 7 cents/kWh" category, and can be as low as 3 cents/kWh wholesale. Solar is relatively expensive at the moment with costs trending downward. Solar would be competitive if all subsidies were dropped for all forms of power. For example, private insurance for a nuclear power plant is not available at any price; more on this momentarily. And let's not forget that wind and sunshine are free energy, nobody owns the sun (yet).

Exercise 6.3 A Solar Powered Future is Possible: Inevitable?

(i) Go as deeply as you have time for into the details of a "smart grid" and how it can compensate for the variablity of sunshine and wind at fixed points. What does a "smart grid" have to do with mathematics? What is the role of the management of demand? How does our knowledge of wind and weather patterns, satellite monitoring of the earth and weather prediction capabilities relate to a smart grid?

(ii) Investigate the costs of wind and solar electric generation at the time you read this. Innovations are frequent. What innovations in efficiency have not yet been deployed as you read this?

(iii) What methods of storage of energy are available or commercial when you read this?

(iv) Investigate the second, third and fourth falsehoods as deeply as you have time for.

(v) What sustainable sources of power have been commercially exploited and where, when you read this. For example, cool and hot geothermal, algae biodiesel, ocean (thermal, wave and tide) energy.

(vi) I happen to believe that for the most part we humans only do what Nature forces us to do. If we build a fleet of nuclear plants, how long do you think it will be before Nature forces us to build a renewable/sustainable energy infrastructure? Will it be easier or more difficult to build such a sustainable system after a "nuclear age?"

6.4 Nuclear Power: Is it Too Cheap to Meter?

My inital response is that it is too expensive to matter, especially when sustainable alternatives do exist.

Costs are High: Both in Dollars and to Democracy. No private investors can (will?) put up the capital to build a nuclear power plant, cf., [426, p.

18]. From [426, p. 19]: "... nuclear power *requires* governments to mandate that *it* be built at public expense and without effective public participation – excluding by fiat, or crowding out by political allocation of huge capital sums, the competitors that otherwise flourish in a free market and a free society." If this quote seems a bit harsh, come up with a list of counterexamples. France is not one of them. In the U. S. I would venture to guess that nuclear power is as divisive politically as, say, the abortion issue. Consider the fact that the American public is forced to provide "insurance" for nuclear power plants, since none exists otherwise. This is done via the Price Anderson Act, which transfers the bulk of responsibility of any nuclear plant accident to the general taxpayer. Even so, if you do lose your property, health, or life to a nuclear plant accident, you (or your estate) are likely to get no more than pennies on the dollar. Anyone who complains about the possibility of a catastrophic nuclear plant accident runs the risk of being called "irrational." It is not irrational to ask the nuclear industry and participating utilities, including shareholders, to put their money (and their financial exisitence) on the line and lobby the U.S. Congress for repeal of the Price Anderson Act – and take full responsibility for any nuclear plant they own or operate. It is very telling that *if most liability for nuclear power plants were not transferred away from industry, by say the Price Anderson Act, there would be no chance of another nuclear power plant being built in the U.S., period.* In fact, the ones that presently exist would likely be decommissioned if their owners/operators were liable for an accident.

Thus in the U.S., taxpayers must subsidize any nuclear plant construction and then insure it, with about as much effective public participation as was had in the "bailout of Wall Street" in 2008–9, cf., page 41. Since the people will end up paying for whatever is done, one way or another, given a choice, folks would most likely want to buy the cheapest, fastest, safest, and most reliable option. Associated with each of these four "variables" or qualities is empirical data that leads to a clear choice.

Nuclear Power is Not Carbon Free. It is asserted that nuclear power is "carbon free." This is not actually true if you consider the entire life-cycle of a nuclear plant. Nuclear power results in up to 25 times more carbon emissions than wind energy, cf., [326, p. 59] and [247, p. 165]. The construction of a nuclear plant, which uses steel and concrete, results in carbon emissions. (There is a new, experimental, low-heat cement making process, *green cement* using *biomineralization* that might be used to reduce carbon emissions from concrete, a significant achievement if it works commercially.) The mining and enrichment of nuclear fuel uses fossil fuels, at least currently, to a considerable degree. Transport and storage of nuclear waste and decomissioning of the plant also result in carbon emissions. Consider the following, [426, p. 1]: "Expanding nuclear power ... *will reduce and retard climate protection.* That's because – the empirical cost and installation data show – new nuclear power is so costly and slow that, based on empirical U.S. market data, it will save about 2 - 20 times less carbon per dollar, and about 20 – 40 times less carbon per year, than investing instead in the market winners – ...." Briefly the "market winners" are: efficiency and "micropower" such as we have discussed, and cogeneration.

Nuclear Power and Proliferation of Nuclear Weapons. Nuclear power is inextricably linked with nuclear weapons. In about 2009 and beyond there was (is) an international "problem" with Iran and their nuclear power program. Why? Because the process of enriching nuclear fuel, if taken further with the same technology, creates nuclear weapons grade material. The Iranians do not want "foreigners" violating their national sovereignty and inspecting what they are up to. They probably would like to have nuclear weapons to counter the nuclear arsenal of Israel. Tensions mount. This situation is not unique: consider India and Pakistan, North Korea and South Korea (backed by the U.S.), Russia and the United States, China and Russia or India, and so on.

There is the sentiment that the U.S. government promoted "Atoms for Peace" after WWII, at least in part, to morally make up for the fact that we vaporized ("nuked") some of our opponents in that war, cf., [82]. There has been an enormous subsidy for nuclear power originating in this connection with the military, without which it is doubtful any nuclear plants would ever have been built.

Building thousands more nuclear power plants increases the probability that nuclear weapons will be found in more and more hands. This is called nuclear proliferation, and it increases the chances of a nuclear attack or exchange at some level. Having witnessed the reaction of the U.S. and the curtailment of civil rights via the Patriot Act after being attacked with box-cutters and civilian airplanes, what sort of reaction would you expect after detonation of a "suitcase" nuclear bomb in a major city? One has every right to at least suspect that a nuclear fueled world will eventually be not only much more dangerous, but much more politically repressive.

Nuclear Waste. Nuclear waste, from mining, military activities, and nuclear power plants needs to be isolated from the biosphere, else serious consequences can result. The world has been waiting for over 50 years and no such isolation or disposal mechanism has been found and/or implemented. There are many claims and promises, but no implemented solution. There are many technical problems and social ones as well. How does one design a containment strategy that will function longer than, say, the length of time human civilization has existed – let alone the length of time any nation state has managed to "keep it together?"

Exercise 6.4 Nuclear Power, Renewable Power, Embodied Energy, Subsidies, and Democracy

(i) Estimate the *embodied fossil fuel energy* in a nuclear power plant. In other words, fossil fuel energy is used to mine and process all of the material that is used to build and fuel a nuclear plant: uranium mining and enrichment, iron/steel, concrete and so on. Fossil fuels are used to transport all of these materials to the construction site, and fossil fuels are used to do the actual construction – which takes years (and decommissioning). How much fossil fuel energy is embodied in the full life-cycle of a nuclear plant? What is the shortest length of time it takes to build a nuclear plant? What is the longest time it has taken so far (at the time you read this)?

(ii) How much time does it take for a typical nuclear power plant to have generated an amount of electrical energy equal to the embodied fossil fuel energy of the plant?

(iii) Is a nuclear power plant CO_2 emissions free? Eventually a nuclear power plant will start displacing CO_2, but at what cost? How much more CO_2 is displaced per dollar invested if that money is invested in cogeneration, renewable energy and efficiency instead of in a nuclear plant?

(iv) Repeat the analysis done in parts (i), (ii) and (iii) for wind power generators and solar collectors. How quickly can a 5 MW wind turbine be installed on land? At sea? How quickly can an array of solar collectors, say 1 MW, be installed?

(v) Is France, which gets the bulk of its electricity from nuclear power, a counter-example to any or all of the arguments given against nuclear power in this section?

(vi) Is the fuel supply for nuclear (fission) power virtually unlimited? What is the status of "Fourth Generation" nuclear power plants which are claimed to consume over 99% of the energy in their fuel and to produce waste with a half-life of hundreds of years (as opposed to millennia)?

(vii) What is the status of nuclear fusion power (on earth) at the time you read this?

(viii) At the time you read this and for a couple decades before, look up and compare the status of U.S. and foreign government subsidies, in their entirety, for fossil fuels, nuclear, and renewable energy.

(ix) Vandana Shiva gave up a promising career as a nuclear physicist in 1972 saying that: *"...nuclear power as much as nuclear war are systems where you cannot have democracy, they're inconsistent with democracy, and I love democracy too much."* (See the video/audio archive www.democracynow.org December 13, 2006.) What does she mean? Do you agree or disagree? Comment.

(x) What is cogeneration?

(xi) Given a free choice, in what form of energy generation would you like to invest your own money?

(xii) What is the status of research on nuclear fission reactors when you read this? What is the status of research on nuclear fusion reactors when you read this? Are nuclear reactors subject to Hubbert's Peak mathematics? (Note: Claims that nuclear reactors can make more fuel than they use are based on breeder reactor technology and fuel reprocessing. Are there any additional problems with breeder reactors or fuel reprocessing?)

(xiii) Robert Zubrin, in [743], points out that $H_2O + CO_2 +$ wind electricity can produce various alcohols, which reduces carbon dioxide in the atmosphere and produces fuel. How old is this technology? Any improvements by the time you read this? Is this a way of storing wind energy? (Note: Zubrin emphasizes biofuels, which is not what I am talking about in this exercise, for reasons that will soon be apparent.)

(xiv) Has a solution of the problem of what to do with nuclear waste been solved to your satisfaction at the time you read this?

(xv) Compare the gallons of water consumed per megawatt-hour of energy produced for nuclear, coal, gas, solar, and wind generation, cf., [247, p. 167].

(xvi) A commonly held/promoted view is that the March 28, 1979 accident at the Three-Mile Island nuclear plant did not result in significant health effects on people. There are contrary views, for example, see Harvey Wasserman's interview on March 27, 2009 (www.democracynow.org), and his interview with www.fair.org. Research at least two opposing views of the accident and decide which, if any, have rigourous documentation backing up assertions. Where there is lack of documentation, what does that tell you? There are 2400 families who have filed a class-action lawsuit against responsible parties involved in the 1979 accident; as of 2009 they have not had access to a federal court.

(xvii) Has the Nuclear Regulatory Commission (NRC) ever taken illegal gratuities from a nuclear plant operator while at the same time failing to find license violations by said operator which were later determined to exist? See the interview with Arnie Gundersen, February 24, 2010, www.democracynow.org. How was the legal system used in an attempt to silence him?

6.5 Net Primary Productivity and Ecological Footprints

I would like to focus on sentences from the long quote in Section 6.1, that may lead to some concern, viz., "Solar energy is fixed in plants by photosynthesis at the net rate of about 133 TW. . . . people directly used energy – not counting the indirect use of solar energy embodied in food and fiber – at a total rate of about 9 TW." At this time I do *want to count* how much of that solar energy being fixed in plants by photosynthesis is being used either directly or indirectly by humans. The answer is important, educational, and alarming.

There is a concept that attempts to describe the job photosynthetic plants are doing on the planet, viz., *net primary productivity*, *NPP*.

There are at least two ways to measure net primary productivity of plants: (1) the rate at which solar energy is fixed by plants, recalling that solar energy per unit time is solar power; and (2) the rate at which *kilograms* of carbon are fixed by plants. (Carbon is used because of its key role in photosynthesis, cf., page 103; and the fact therefore that "life on earth as most of us know it" is carbon based.) An estimate of (2) can be found in several places, one of which is [283, p. 257]. The estimate of (1) given above is 133 TW. The estimate of (1) given by [283, p. 240] is 75 to 125 TW. Elsewhere in [411] they talk of net photosynthesis being around 100 TW. I could argue that deforestation since the 1980s has decreased NPP, others may argue that global warming has increased it. Let's just agree to look at the order of magnitude, 10^2 TW as our working estimate of NPP. I now ask the question: What fraction of global NPP do humans appropriate (use directly or indirectly) to support their activities?

In [694] it is stated that "Nearly 40% of potential terrestrial net primary productivity is used directly, co-opted, or foregone because of human activities." A closer look at the paper reveals the following estimates: 3% NPP directly "eaten" by humans or their animals, 19% NPP eaten or directly used, and up to 40% eaten, directly used or indirectly used. For example, clearing a forest, building a city or road displaces plants, and so on. Such were the estimates of appropriation of NPP in 1986 when the global human population was $4.94(10^9)$.

Many articles have followed the classic paper [694], too many for me to discuss here. For example, more detailed studies have compared "NPP for specific geographical areas" with "human appropriation of NPP in that area." In some areas people consume far more than the NPP in that area, in other areas people consume far less than the NPP of the area in which they live. If some people are consuming far more of the planet's plants' productivity than exists in the "neighborhood" where they live, they must be consuming NPP in areas where other organisms live. Since almost all living things depend ultimately on the NPP of the planet's vegetation, some organisms will have to stop eating, that is *die*, for this to happen. This is because, as we have noted before, Nature "abhors a vacuum." Thus if it is possible for organisms to live in some area they will. There are no “blank” places on the globe where NPP can be taken without taking the food from something already living on that NPP.

Thus we are led to the concept of *ecological footprint*, cf., [695].

Exercise 6.5 Ecological Footprint and NPP

(i) Can you describe some geographical area that is clearly consuming more of the earth’s NPP than exists in that area?

(ii) If about 5 billion people appropriated 40% of global NPP, i.e., 40% of NPP was not available for use by any organisms other than those 5 billion people, what might be the implications for a world population of 10 billion people? 15 billion people?

(iii) If NPP is about 100 TW, and about 5 billion humans appropriated 40% of this NPP, how much is this appropriation measured in TW? How does this compare with the 9 TW of direct energy use of the 4 to 5 billion people in about 1980? Discuss.

(iv) Compare Exercise 7.16 and see if you can calculate the global ecological footprint of the human race. Feel free to research the papers/books/Web sites that have been written on this subject, cf., for example, [248, 687]. What role do fossil fuels play in facilitating the implementation of this footprint?

6.6 NPP, Soil, Biofuels, and The Super Grid

Whenever I hear about any program to produce *biofuels*, my first thought is: What will it do to the soil? If it comes down to a choice between eating (which requires soil to a large extent) and manufacturing biofuels which negatively impact soil – I choose eating. Fortunately there are, at least theoretically, attractive alternatives which do not harm soil.

Biofuels, Soil, and Food. If a biofuel is made from a food stock like corn or wheat, the price of that food will increase due to the economic “law of supply and demand.” There are already large populations of people who are hungry at any given moment in time, even in the United States; any increase in food prices can thus result in extreme hardship for some, and possibly social instabilities. Indeed there are billions of people living on \$1 or \$2 a day who have no room to maneuver when it comes to buying anything, especially a necessity like food.

There is another “bottleneck” for biofuels. While solar energy is plentiful, it is inefficient to get it via photosynthesis if all you want is energy, not the biomass associated with photosynthesis. All solar panels and wind turbines have higher efficiency than the typical 1% to 2% energy-efficiency of green plants. Biomass energy is, however, in chemical form; thus it is a form of energy storage.

From [640, Chapter 2] the theoretical peak efficiency of the process of photosynthesis is 11%, but no plant comes close to this. On ecosystemic scales tropical and temperate marshes and temperate forests are about 1.5% efficient. Arid grasslands are around 1.0% efficient. The best rates for highly productive natural formations, e.g., wetlands, and crop fields are 2 to 3%. The highest recorded field values of efficiency under optimum conditions for short periods of times are 4 to 5%. What this means is that if 1 kWh of solar energy is utilized by a plant with 1% efficiency, the result is .01 kWh of energy stored as biomass.

Thus solar energy tapped via biofuels first faces the low efficiency of photosynthesis. Then any process that converts biomass to ethanol, biodiesel or other biofuel further reduces net efficiency. As mentioned above, much higher efficiencies are already available with photovoltaic and solar thermal collectors and wind turbines, for example. Biofuels, such as biodiesel, however, have the advantage that they are portable liquid fuels that store energy in stable form and can be used in already existing engines with minor modifications; whereas electricity is, at the moment, more difficult to store and use in some applications – such as tractors, trucks, airplanes, individual automobiles. (One airline has already successfully flown a jet internationally, partially powered by liquid biofuel.) A relevant concept here is *energy density*. Biodiesel stores more joules per kilogram than say an electric battery. (Energy density is also measured in units of joules per unit volume.) I note in passing that restaurant grease is a potential source of raw material for biodiesel that is actually so used at the University of Colorado. It turns out, however, that more money can be made turning such grease into soap and cosmetics, for example.

Exercise 6.6 How Much Biofuel Can the World Possibly Produce? This exercise is a really rough estimate of the actual situation, but it is worth doing.

(i) If you make biofuel out of a plant whose photosynthesis is 5% efficient and you have a process that creates biofuels from this plant's biomass that is 20% efficient, what is the net efficiency of this two-step process?

(ii) If 81,100 TW reaches the earth's surface, and the area of the earth is $5.1(10^{14})\ m^2$, on average how much solar power reaches 1 ha? (Note: Clearly, the answer for a particular area on the earth depends on its position, i.e., equator or pole, time of year, time of day, and so on. Feel free to ignore these details if you wish. Also recall that 1 ha = 1 *hectare* = $10^4\ m^2$ = 2.47 acres.)

(iii) To get 20 TW how many hectares would be required if we used the plants from part (i)? How does your answer compare to the area of the earth? What fraction of the earth's surface is required? What fraction of the earth's land area, not counting Antarctica or Greenland? (Note: Ice-free land area on earth is about $1.33(10^{14})\ m^2$.)

(iv) How senstive are your answers above to the initial efficiencies assumed in part (i)?

(v) What difficulties might be encountered in actually implementing a biofuel program on this scale? What might be the consequences?

(vi) Look up the energy densities of diesel, gasoline, wood, electric batteries of various types and compare them.

Let's now take a detailed look at a biofuel like ethanol from wheat. I have already mentioned that this is a process fraught with problems: tendency to increase the cost of food, tendency to deplete soils. Is the energy return so great that it is worth it? The following discussion and exercise will answer that question.

Lester Brown, cf., [59, p. 29], makes the following observation. From 1950 to 1973 a *bushel* of wheat could be traded for a *barrel* of oil. In 1975 the ratio became $\frac{3\ bushels}{barrel}$, in 1990, $\frac{6\ bushels}{barrel}$, in 2000, $\frac{9\ bushels}{barrel}$ and in 2005, $\frac{13\ bushels}{barrel}$. From the Earth Policy Institute web site we see: in 2006, $\frac{12\ bushels}{barrel}$, in 2007, $\frac{10\ bushels}{barrel}$, in 2008, $\frac{11\ bushels}{barrel}$.

Exercise 6.7 Wheat to Oil, Oil to Wheat
A *barrel* of oil contains 42 U.S. *gallons* and will yield 19.5 *gallons* of gasoline. According to [59, p. 34], under ideal conditions (in France) wheat yielded 277 *gallons* of ethanol per *acre*. (Ethanol has 67% the energy content of gasoline.) Suppose under ideal conditions you can get 60 to 70 *bushels* of wheat per *acre*. Suppose a typical farm operation uses 12 *gallons* of fuel per *acre* (assume it is gasoline, whereas it most probably is 8.75 *gallons* of diesel).

(i) How many *gallons* of gasoline is used to get 60 to 70 *bushels* of wheat? What is this in *gallons* per *bushel*?

(ii) Assuming these 60 to 70 *bushels* of wheat are converted to ethanol, what is the gasoline equivalent?

(iii) How many *gallons* of gasoline equivalent are we getting per *bushel* of wheat?

(iv) If you trade 13 *bushels* of wheat for a *barrel* of oil, then convert the *barrel* of oil to gasoline, how many *gallons* of gasoline are you getting per *bushel* of wheat?

(v) If the farmer wants a *gallon* of gasoline equivalent in fuel which is cheaper: trading wheat for oil or making wheat into ethanol?[1]

(vi) What implications might this exercise have for the world's food supply? How might things change, economically and otherwise?

(vii) Look up corresponding facts about corn, say grown in the midwest of the U.S. and do this exercise over to see the energy yield in terms of ethanol made from corn.

(viii) Investigate how much water it takes to make a gallon of ethanol from wheat, from corn. It takes water to grow the grain, and it takes water in the plant that converts the grain to ethanol.

(ix) What are the net carbon emissions of producing ethanol from wheat, or corn?

(x) One of the reasons I did the above calculations involving wheat, and indirectly petroleum, was due to the "intrinsic" value of a food commodity such as wheat. However, in this modern age of financial "innovation" the monetary value of an essential commoditity such as wheat can be manipulated as a pawn in a much larger financial game. The same is true of oil, or any other commoditity. See Exercise 2.7, page 38. Estimate the manipulation of the price of wheat for some ten year interval of your choosing. .

Exercise 6.8 The United States and Biofuels[2] Of the $2.3(10^9)$ *acres* in the United States, in 2004 about $450(10^6)$ *acres* were cropland, $580(10^6)$ *acres* were pasture/range land. These figures can change as water supplies and other environmental factors change. In 2004 for transportation the U.S. consumed about $60(10^9)$ *gallons* of diesel fuel, and $120(10^9)$ *gallons* of gasoline, both from petroleum. Taking into account that biodiesel energy density is slightly less than that of petroleum diesel and that gasoline engine systems are significantly less efficient that diesel engines, the equivalent in biodiesel consumption is about $140(10^9)$ *gallons*. Rapeseed, a potential source of biodiesel fuel, can yield 100 to 145 *gallons* of rapeseed biodiesel oil per *acre*.

[1]I was in Brazil in 2006 and biofuel from sugar cane (650 gallons/acre) was sold at fueling stations at about half the cost of gasoline. It is more likely that corn, with 354 to 400 gallons of ethanol per *acre*, would be made into ethanol in the U.S.; that is yet another exercise which you can do, see part (vii) above.

[2]Information for this exercise and the next can be found in publications/Web sites for the United States Department of Agriculture, USDA, the Department of Energy, DOE, the National Renewable Energy Laboratory (Golden, Colorado), NREL, and university biodiesel programs such as the University of New Hampshire Biodiesel Group.

(i) How many *acres* of U.S. farmland are required to produce $140(10^9)$ *gallons* of biodiesel?

(ii) What fraction of U.S. cropland is your answer to (i)? Is this possible?

(iii) NREL, the National Renewable Energy Laboratory, did a study which indicated the possibility of producing $7.5(10^9)$ *gallons* of biodiesel from 500,000 *acres* of land under ideal conditions. These ideal conditions referred to farming algae ponds with high flows of nutrients and sunlight: the solar power found in the deserts of the American southwest, with nutrient levels such as are found in agricultural runoff, for example. How much land is required for $140(10^9)$ gallons of algae-biodiesel?

(iv) What promise and problems do you envision with algae-biodiesel?

(v) Switchgrass and miscanthus (elephant grass) are perennial grasses that grow on soils considered too poor for food crops. They also are credited with being able to improve soils, building carbon content, for example. Such plants can be used as sources of *cellulosic biofuels* (from 1000 to 1250 gallons/acre). What is the status of such a potential source of fuel at the time you read this?

(vi) I have not discussed the role biomass might play in the generation of electricity. Could biomass be used to provide quick on-off electricity as local backup for variable wind and solar? In the U.S. is methane gas from landfills a viable source of energy? Can cogeneration (of heat and electricity) increase the efficiency of a biomass energy plant? See [247, Chapter 6]. What might be the role of biochar, cf., [389], and page 112?

Exercise 6.9 The Geometry of Algae: The Power of Being Small

(i) Assume for simplicity that an alga is a sphere of radius r. What is the ratio of the area of the sphere to the volume of the sphere? Recall that the area of a sphere of radius r is $4\pi r^2$ and the corresponding volume is $\frac{4}{3}\pi r^3$.

(ii) The type of algae used to grow oil/biodiesel is microalgae, less than .4 *mm* in diameter. What is the ratio of surface area to volume for a sphere this small? Why does being small give a large surface to volume ratio?

(iii) Such algae cells can grow 20 to 30 times faster than typical food crops, can produce 15 to 300 times more oil per acre (depending on the species), and have a harvest cycle of 1 to 10 days (again, depending on species). It is the volume of algae that grows (and divides), nourished by absorbing nutrients through its surface. Using parts (i) and (ii) explain why being small allows algae to reproduce so fast, i.e., absorb more nutrients through its surface per unit volume in a given period of time and thus grow? (Note that some types of algae are nearly *half* oil!)

(iv) Algae will grow in polluted (recycled) water. For example, plastic tubes of sea water polluted by agricultural runoff or human waste sitting in the sun on pavement next to a sewage treatment plant. Algae does not compete with food, can provide oil and useful organic byproducts. Estimate (or look up) the amount of oil that could be produced from algae, in the U.S., in the world. See Exercise 6.8 (iii).

(v) What is the status of algae biodiesel at the time you read this? Is it commercial or still experimental (or forgotten)?

(vi) At the time you read this what is the status of the research project to find or create bacteria that create oil from raw ingredients like CO_2?

As Human Population and Its Impacts Go Up, We Will Likely Go Down the Food Chain. The previous exercise indicates that by going down the food chain to a lower trophic level, higher yields of biomass can be obtained.

A question I have asked/discussed before: How many people can the earth support? See [102], for example. There likely is no precise answer to this question. Such an answer depends on the technological capabilities of humans at the time, the availability of resources in relation to that technology and the variety of cultures present on the planet – and how much other species are valued/needed. According to Section 5.2, the answer also depends on what trophic level humans feed at. For example, eating whales, fish, cows and so forth have humans feeding on at least a trophic level of 3, higher if carnivores are part of the human diet. A diet consisting entirely of algae would at least lower our trophic level to 2 or less.[3]

Exercise 6.10 The NPP Tradeoff: Eating vs. Everything Else

(i) Assume the "rule of 10" going from one trophic level to another, cf., Section 5.2, assume there are "X" people on earth all of whom eat nothing but meat. How many more people could the earth support if all "X" people switch to an algae-only diet? Assume that all humans do not move around and do not impact global NPP except via direct ingestion/eating.

(ii) Assuming the figures from Section 6.5, viz., humans (and their animals) directly eat 3% of NPP, 40% of NPP is either eaten, directly or indirectly used, does this change your estimate in part (i)? By how much, roughly?

(iii) Do you think a significant number of humans will ever be subsisting at trophic level 1 or less?[4]

(iv) Pick a year, say, 2004, where world oil consumption is "Y" barrels in that year. Assume the world's human population is constant. What fraction of these "Y" barrels of oil will eventually be replaced with biofuels like biodiesel and ethanol? What fraction of these "Y" barrels of oil will eventually not be needed due to conservation measures and increased efficiency? Which of these two percentages is the largest? What impact do you think biofuel production will have on the world food supply? Now, in fact, the human population is not constant. It is growing with increasing energy demands and increasing food demands. Do you see a possible problem?

Regarding part (iii) of the last exercise, humans certainly have driven some animal species to extinction at least in part because said animals were tasty. One other reason for extinction is habitat destruction, which is part of the appropriation of NPP discused before. For example, the passenger pigeon of America is extinct, cf., [546, pp. 168-170]. Whales are not abundant, due in part to predation by humans for meat and whale oil. As I previously mentioned the cod off Cape Cod and the sardines once canned on Cannery Row, California, are economically, perhaps biologically, extinct. Major fish populations around the world could collapse if present trends continue. American bison nearly went extinct, partly because of being eaten, partly due to war. On October 22, 2006, the BBC[5] and print media carried the story that hippopotamuses in eastern Congo could be wiped out of Viriunga National Park.

[3]I am definitely not giving dietary advice here, I am not recommending a diet of algae – even if delightfully, artificially flavored. This discussion is for critical thinking purposes only.

[4]A press release from the *National Environmental Trust*, October 19, 2006, cf., http://www.net.org/marine/antarctica_briefing.vtml tells of illegal industrial fishing in the waters off Antarctica wherein krill, tiny shrimp-like creatures, are being vacuumed up in vast numbers. Krill are near the bottom of the food chain in these rarely patrolled southern waters, providing food for seals, whales, penguins. The krill are largely fed to farmed salmon, which somewhat complicates the trophic number assigned to humans in this case. These fishers are also taking fish higher on the food chain, like Chilean sea bass (an PR invented name, by the way – what is this endangered fish's real name?). Parts of these ecosystems are under much stress.

[5]British Broadcasting Corporation

This national park was home to one of Central Africa's greatest hippopotamus populations, 22,000, in 1988, according to the Web site of the Zoological Society of London. The population has been reduced to about 400 in 2006 because of a combination of war and predation by humans for food. Because the list of such stories is quite long, some scientists have seriously tried to compute the year when most humans will be feeding on a trophic level of 1 or less.

I want to end this chapter with a new view of humanity and its ecological niche. In the future each nation-state can be viewed as an organism of a special new type. These new organisms will tread as lightly on photosynthetic processes as possible (appropriating a minimum of NPP), and will mainly be powered by sustainable energy sources other than plants! Direct solar energy is, of course, a leading candidate for a source. Wind; ocean thermal, wave, and tide; and geothermal energy are all additional candidates. These new organisms will have built a new "brain" and "neural network" that more optimally provides energy to the "cells" that make up these new organisms. We will have to upgrade the existing electrical grid to what some folks call *The Super Grid*.

Exercise 6.11 Cost and Benefits of the SUPER GRID

(i) Investigate the costs and benefits of upgrading the electrical grid in your country to Super Grid status, i.e., a "smart" grid, capable of backing up wind and solar generators that are "off line" with others that are "on line" and producing power – to such an extent that minimal storage facilities need to be built. You can get started by looking at [247, Chapter 13], or www.rmi.org.

(ii) Does the technology exist already to create the Super Grid?

(iii)Estimate the costs and benefits of NOT creating a Super Grid.

(iv) A smart grid holds the potential for gathering enormous amounts of detailed data on the electrical use of individuals. This information, in real time, can be used to greatly increase the efficient use of energy. It can also be used to invade privacy. What regulations should there be on the use of such data? Who owns this data? Are there any technological developments that might be used to protect privacy while still allowing for efficiencies? See VI.

(v) For the last century municipally owned utilities (MUNIS) which are owned "by the people" of a given municipality have on average provided power more reliably and more cheaply than investor owned utilities. Not only are not many folks aware that MUNIS exist, they are unaware of this last mentioned fact, cf., [705]. Given that a Super Grid would be connecting a multitude of small, decentralized generators, would it make sense to have a nationally owned utility company, owned by everyone? Or possibly a federation of local MUNIS, much like the United States is a federation of states? What political obstacles exist to creating any Super Grid? To creating a National Energy Company, or a federation of MUNIS? How might these obstacles be overcome?

(vi) There is an interesting possible synergy between geothermal and lithium-based batteries. It is projected (in 2009) that one ton of lithium per month can be extracted from the wastewater produced by a geothermal plant built on the San Andreas Fault southeast of Palm Springs, California. What is the status of this technological development at the time you read this? Has a new battery technology replaced lithium-based batteries, eg., nano or ceramic technology? Or, has lithium production from geothermal plants become commercial, and has it become a key component of an emerging Super Grid?

(vii) In 2010 the Marin EnergyAuthority, MEA, (www.marinenergyauthority.org), began providing participating citizens of Marin County, California, with energy purchased directly by the citizens and not through PG&E, Pacific Gas and Electric, the former monopoly utility. According to Marin County Supervisor, Charles McGlasham, the effort took eight years due in large part to opposition from the monopoly energy utility. The arrangement of the MEA is midway between having a monopoly utility on one hand or a municipally owned utility, MUNI, on the other. The MEA went on the market and purchased energy, which in 2010 was 78% renewable, thanks to a 2002 California law referred to as "community choice aggregation." The MEA still delivers power via PG&E's grid and maintains the infrastructure with PG&E workers employed still by PG&E. According to McGlasham, PG&E wants to make it more difficult (practically impossible?) for other communities to follow in MEA's footsteps by promoting to the tune of 10s of millions of dollars, Prop. 16, of June 2010. (This would be a constitutional amendment requiring a two-thirds majority of a political unit to vote for adoption of a similar energy authority.) Did Prop. 16 pass? How is the MEA doing?

(viii) Two versions of the Super Grid can be summarized briefly in the words "centralized" and "distributed (or decentralized)." Discuss the political forces for and against each of these versions. Discuss the economic and engineering pros and cons of each of these versions. Discuss and compare the impacts to land and health of each of these versions.

(ix) Can "the" electrical grid be built to withstand impact from extreme solar storms (on the sun)? How often do such solar events take place, and what are their potential impacts? Is the current electrical grid that serves you built to withstand such a solar event?