Chapter 11. The Human Footprint

We begin exploring the human relationship with the environment by investigating our consumption of land, food, water, and energy. The biomass fixed by plants every year (*net primary productivity, NPP*) determines the carrying capacity of the earth. We already appropriate a large fraction of NPP for our use. Greenhouse warming and declining fossil fuel reserves motivate investigation of the hidden costs of fossil fuel usage and to explore alternative energy sources. Finally, human-caused global changes at the chemical level are considered, particularly environmental toxins and genetic manipulation.

11.1. Water, Land, Food, and Energy

From just looking at a typical person in the United States you would never guess that they consume about 2,500 m^3 of water every year! That is roughly 7000 liters (or quarts) per day. No wonder sometimes there are long lines at public restrooms. Actually, U.S. citizens drink less than 0.1% of this total each day. All water used in houses and buildings add up to less than 9% of the total. Mining and manufacturing account for another 10% of the total water used. The dominant two categories are power plant cooling (38%) and irrigation, both for crops to eat and for crops to feed livestock (43%). Lake Columbia, WI is reliably ice free throughout the winter due to discharge of hot water from power plants. Our use of water is tied closely to our food and energy choices.

Considering that the area of the earth is $4\ \pi\ (6367\ \text{km})^2 \sim 5\text{x}10^{14}\ \text{m}^2$, and the earth is ~30% land, the area for growing crops is $\sim 1.5\text{x}10^{14}\ \text{m}^2$. But only about 10% of the land surface is planted in crops. With 6 billion people on the planet, your fair share of agricultural land is $\sim 3000\ \text{m}^2$, or 50 m x 50 m, or about the size of half of a football field to grow all of the food that you eat in one year.

Let's compare our fare share crop area to the area required to sustain us from a food calorie perspective. The average adult consumes 2000 kcal per day, which is 100 J/s or 100 W. Due to conservation of energy, this heat must be lost to the environment. Food makes you glow like a 100 W light bulb, but in the infrared. (No wonder it is hot in a crowded arena in the middle of winter!) Since plants contain $16\text{x}10^6$ J/kg and average edible crop production is 0.06 kg/m^2 per year, we need about 3,000 m^2 to grow crops to sustain each of us every year.

This is remarkably similar to what is obtained from dividing existing cropland evenly among all people. But this is not really surprising, since the fact that 6 billion people are alive implies that the existing cropland is about right for the existing population. Yet clearly there are inequities in food distribution that create starvation for many people today. This also suggests that we will have to encroach on natural habitats in order to create more cropland as our population grows.

When one considers our choice of food this situation is even more serious. The energy transfer efficiency from one trophic level to the next trophic level is typically 20-50%. If you eat 1 kg of corn you would need to feed 7 kg of corn to a cow to get 1 kg of meat. Pig consumption implies 5 times as much land, energy, and water for 1 kg of food relative to eating corn directly.

Chickens are more efficient in this trophic conversion. If you eat chickens instead of corn you need to have about twice as much land. Thus, if all vegetarians switched over to eating meat we would not have enough land to produce the crops to feed the animals that we would eat. This also suggests a powerful lever for those of us wishing to reduce our land, water, and energy footprint: we can reduce our meat consumption.

Here is a summary for a typical person in the U.S.A. You use 2500 m^3 of water per year, mostly for cooling power plants for your electricity and for crops to eat or to feed the animals that you eat. Your fair share of existing agricultural land is about one half of a football field, which provides enough food to keep you alive, as you glow in the infrared with the power of a 100 W light bulb. Even partial vegetarianism is a globally conscientious choice regarding the use of land, water, and energy. You use 10,000 W of energy all of the time, which is 100 times the energy content of your food. You are part of the U.S.A., which has only 5% of the world's population, but uses 25% of the world's energy.

If you are interested in how your personal use projects onto your carbon footprint in kg CO_2 emitted per year by your, you may wish to calculate your carbon footprint (e.g., http://www.madisonenvironmental.com). Most of us spew out about 10,000 kg CO_2 per year.

11.2 Limits to Human Habitation

Annual *net primary productivity (NPP)* is defined as the solar energy fixed by plants minus what they use for their own respiration. NPP is measured in Gt per year and represents the energy left over for all consumers and decomposers, including humans. One may gauge the impact that humans have on the biosphere by evaluating the fraction of NPP that is appropriated by humans for their use. Many people regard human impact as being too modest to come close to reaching planetary limitations on our growth. Yet ecologists estimate that we are already appropriating nearly 40% of NPP on land (Vitousek et al. 1986, Diamond 1987). These estimates are based on an international database of global productivity, carbon storage, agriculture, forestry, land use, and land conversion. The earth's surface is divided into biomes and productivity measurements are taken in the field. The area and productivity are multiplied and summed over the biomes.

The total NPP on the land is 132 Gt/yr, and 92 Gt/yr in the oceans, for a total of 224 Gt/yr for the earth. Humans and domestic animals directly consume plants and fish and use wood for lumber, paper, or fire, using 7 Gt/yr, about 3% of the total NPP. However, less than 10% of organic crop matter is edible and less than 50% of harvested forest is marketable. Land that was once natural but has become converted to cropland, pasture, cities, and roads represents chronic or permanent diversions. Our total appropriation of NPP is 60 Gt/yr (58 Gt/yr from the land and 2 Gt/yr from the sea). Thus, humans consume about 40% of NPP on the land already. Diamond (1987) concludes that "even if we appropriate the entire global NPP and exterminate all species except ourselves and our servant species, we will soon reach biological limits to our population growth, given our present doubling time of 40 years and our current mix of extraction techniques." Regardless of our innovations, it will be extremely challenging for this planet to support twice as many people.

11.3 Energy Use

The use of energy is intimately linked with the global climate and our sense of selves. We hope that by hard work and innovation we can develop new technologies that will "get us ahead of the curve" and garner us greater and cleaner sources of energy. This chapter will explore fossil fuel usage and its implications for climate change, human health, war, and the economy. Renewable energy sources are explored, with a focus on fossil fuel. Finally, interesting insight can be gained by considering the flow of energy in the earth system. It turns out that global annual human energy usage is less than 1 zetajoule (1 ZJ, or 1 billion trillion joules of energy), while some 400 ZJ flows around in the atmosphere and ocean. But from a "Zetajoule perspective" one can appreciate that anthropogenic greenhouse gases shunt large amounts of this flow in directions that would not otherwise occur, a powerful amplification of human energy consumption.

11.3.1. The Zetajoule perspective

A unifying perspective on the scale and impact of human energy consumption can be had by examining energy usage and energy flow. The following notes were taken while listening to a lecture by Harvard chemistry professor James G. Anderson at the University of Wisconsin – Madison in on April 6, 2009, "Strategic Choices for Global Energy: Constraints from Feedbacks in the Climate System". Near the end of his talk he posed the simple question of whether we would rather spend $1.7 trillion to buy oil and pay for the military to support our interests, or $1 trillion to go to total renewable energy, based on wind and solar, with a two-way smart grid for redistributing energy.

One zetajoule (ZJ) is defined to be 10^{21} J, or 1 billion trillion joules of energy. Since there are about 3×10^{7} s in one year, 1 ZJ/year ~ 3×10^{13} W = 30 TW, where 1 TW (terawatt) = 10^{12} W.

One may estimate global power demand as (population) x (income per person) x (energy use per dollar output) in terawatts (1 TW = 10^{12} W). In 2005, we consumed 2 TW per billion people, times 6 billion people, for 12 TW total. A conservative doubling of individual energy use by 2050 suggests 4 TW per billion people, times 10 billion people, for 40 TW total, thereby approaching 1 ZJ/yr. This anticipated increase in power would require building 1000 large coal plants per year, or about 2.5 per day. Alternatively, we could build 250 nuclear power plants every year for 40 years. China is currently building 2 large coal plants per week. A proposed coal power plant in Cassville, WI would generate 3.3 million tons of CO_2 annually, which is more than the emissions of the 90 least-polluting countries combined, and is about the same as the emissions from Nepal. The Cassville plant would address the energy needs of 300,000 Wisconsinites, compared to the 3.2 million that live in Nepal. This emission rate for the one coal plant would be the same as introducing 650,000 new cars on the road. This pathway would greatly accelerate global warming. (The Defender 2008)

We can put human influences into perspective by starting with the observed solar output of the sun, 10^{34} J/yr ~ 10^{13} ZJ/yr. The earth, with a radius of 6367 km at a distance of 150,000,000 km from the sun, intercepts about 1 billionth of the solar output. But this amounts to 10^4 ZJ/yr, about 1000 times more than the anticipated total global human energy use in 2050. Right now, about 6000 ZJ of energy circulate in the atmosphere and ocean system. But anthropogenic greenhouse gases are acting to redirect energy flows. Since anthropogenic CO_2 emissions reached 8.5 Gt/yr in 2006, even above IPCC scenario business-as-usual scenarios, concentrations are exceeding 390 ppmv. Yet only 350 ppmv is required to exceed the threshold of arctic sea ice preservation. About 18 ZJ have gone into melting ¼ of the Arctic sea ice. It is estimated that anthropogenic greenhouse warming over the next 50 years will cause trapping of 200 ZJ in the ocean, 7 ZJ in the atmosphere, and 9 ZJ in the continents. Thus, humans exert a much larger influence on energy flow than energy associated with the fossil fuels themselves.

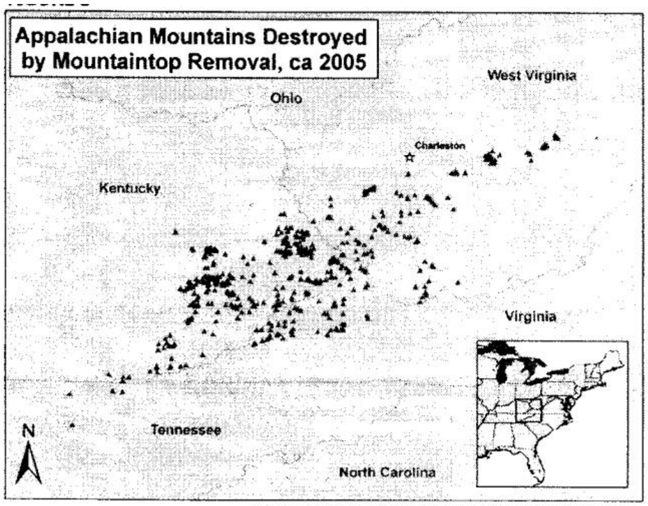
11.3.2. Electricity

Electricity usage is usually measured in terms of the average power over an hour, or kilowatt-hours (kWh). 1 kWh = 1000 J/s x 3600 s = 3.6 x 10^6 J of energy.

Much of our energy consumption is in the form of electricity, with a wide variety of energy sources being first converted to electricity before we use the energy. The invisibility and cheapness of electricity makes it quite attractive to use. It only takes 1 kW-hr (7 cents) to wash a load of laundry, which is quite appealing. Yet in the eastern United States the vast majority of electricity is generated by burning coal, oil, and natural gas. Even California's electricity generation is 32% from natural gas, with 39% hydropower, 25% nuclear, and 4% renewable. In Wisconsin electricity generation composes 35% of greenhouse emissions (The Defender 2008).

The amount of carbon dioxide emitted per kWh varies greatly among types of electricity generation. Fossil fuel usage used in creating wind turbines and their infrastructure translates to emitting 9 grams of CO_2 emitted per kW-hr (Shrader-Frechette, 2008). Extraction and processing of raw materials for solar power implies emission of 32 g CO_2 per kW-hr of solar energy. Mining and processing radioactive materials for nuclear power leads to emitting 66 g CO_2 per kW-hr of solar energy generated. This is minuscule in comparison to coal power plants which generate 1010 g CO_2 per kW-hr. Combined-cycle natural gas coal plants are significantly more efficient, but still emit 443 g CO_2 per kW-hr.

It is perhaps amazing that a gallon of gas costs about the same as a gallon of milk or a gallon of mineral water. But we need to consider that \$1 on your electric bill implies 10 kg of CO_2 discharged into the atmosphere. (This can be obtained from the cost of coal-generated electricity being 1 kg CO_2 per kW-hr and 1 kw-hr costing \$0.07.) Each year a typical U.S. family of four consumes 10,000 kg of coal through electricity usage, an 8 m^3 pile of coal that would easily bury a picnic table every year, much of which comes from removing mountain tops in Appalachia (Fig. 11.1). If you put \$10 per month into purchasing wind power, you would keep 4000 kg of CO_2 out of the air each year. This would help us avoid the coming fossil fuel extraction crunch.



Adapted image; original courtesy of It's Getting Hot in Here

Figure 11.1. Appalachian mountaintops destroyed by removal of coal as of 2005 (courtesy of It's Getting Hot in Here).

11.3.3. Fossil fuel use

For many decades, large industrial nations have depended heavily on strategic supplies of fossil fuel in certain parts of the world. In the United States, we have a particularly robust relationship with fossil fuels, including artificially low gas prices, high military costs to maintain strategic control of oil reserves, and high per-person emission of CO_2. Annual world energy consumption has grown from 3 billion metric tons of oil equivalent in 1960 to over 10 billion metric tons of oil equivalent. However, due to population increase, the global per capita energy consumption peaked in 1970 at around $3x10^8$ J/yr. Most of the energy used has been in the form of oil, coal, and gas. Over 50% of the world's gas and oil reserves are in the Middle East or Russia, while over 70% of the world's coal reserves are in Russia and North America. Worldwide we have about 1000 billion barrels of oil in the well, take one down, pass it around, 1000 billion barrels of oil in the well. We have used 800 billion barrels already, and we are probably at our peak extraction rate about now (Fig. 11.2, Campbell and Laherrere 1998).

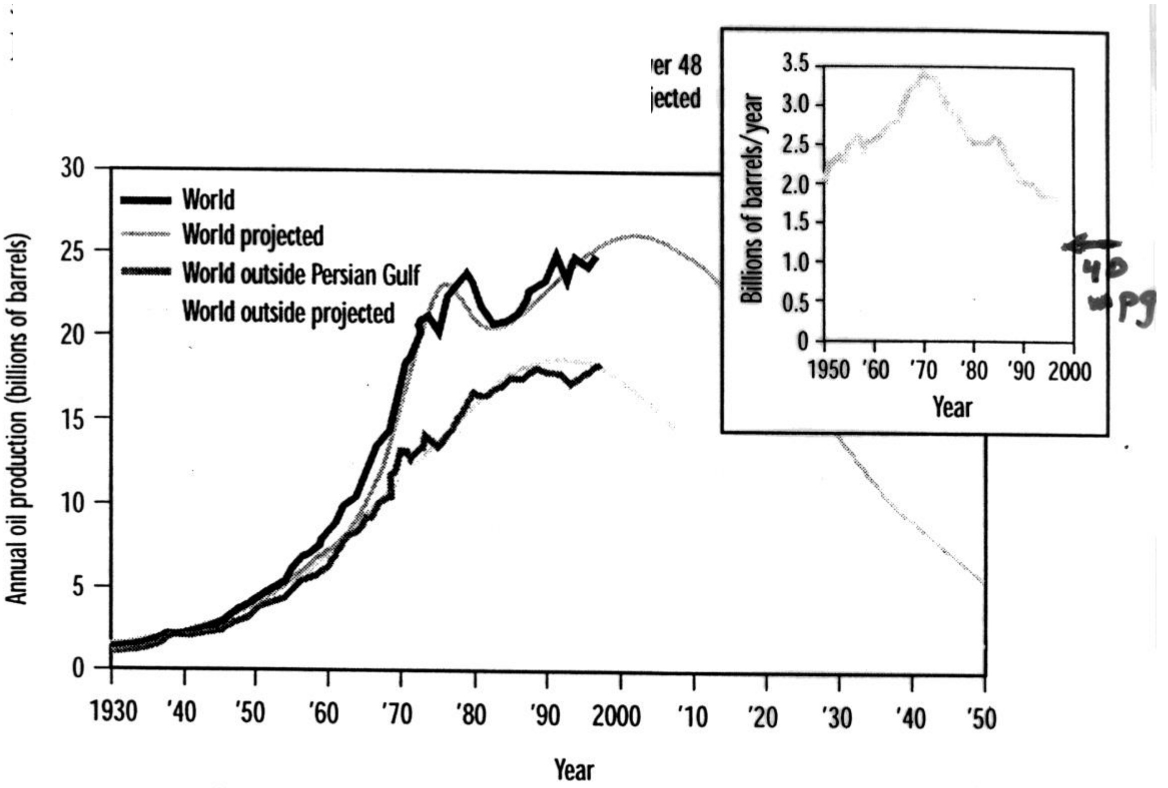
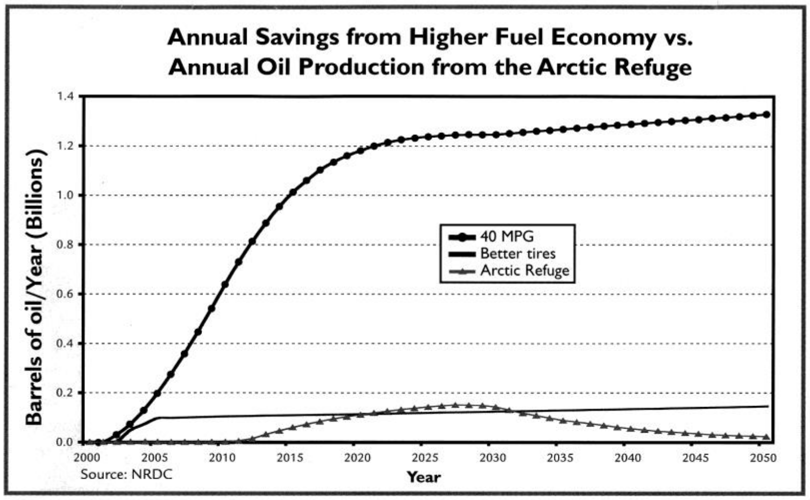


Figure 11.2. World annual oil production per year in billion of barrels, subdivided into total, world outside of the Persian Gulf, and projections (fine lines). U.S. oil production in the lower 48 states (inset) peaked in 1970 and world oil production is expected to follow suit.

The production of oil in the lower 48 United States peaked in 1970 at about 3.5 billion barrels of oil per year and is down to about 1.0 billion barrels per year (Fig. 11.2, inset, Campbell and Laherrere 1998). It is interesting to note that going to a 40 mpg standard for the current U.S. mix of cars would save about 1.2 billion barrels of oil per year, roughly equal to domestic production! Over the past 10 years there have been extraordinary increases in the number of leases for oil drilling in Utah, Colorado, and other western states. While it is better to depend on our own oil, it is likely that the amounts that are there are a drop in the barrel compared to our current consumption of some 5 billion barrels of oil per year.

Oil companies have recently submitted bids of $2.6 billion to the U.S. government for the right to drill for oil on the north slope of Alaska (WWF 2008). Court cases have marginally prevailed so far in favor of protecting the pristine environment relative to the modest oil reserves that are present. The annual savings rate from higher fuel economy is shown in comparison to the annual oil production from the Arctic Wildlife Refuge in Fig. 11.3 (NRDC). Geologists estimate that the Arctic Refuge would yield about 0.1 billion barrels of oil per year. Efficient replacement tires for the U.S. fleet would yield more oil than the entire Arctic Refuge. If the fuel efficiency of the U.S. sport utility vehicle fleet were improved by 3 mpg it would save 49 million gallons of gas per day, in comparison to White House projections of 42 million gallons of gas per day production from Alaska's Arctic National Wildlife Refuge. A 40 mpg standard for cars and light trucks by 2012 would save 50 billion barrels of oil over 50 years, which is 15 times more than the Arctic Refuge would yield over the same period. (The Capital Times, 2001) Higher mpg standards would mean that we could keep that oil in the ground for another year into the future.



Over 50 years, a fuel economy standard of 40mpg would save 15 times more oil than the Arctic Refuge is likely to produce. Efficient replacement tires would yield 70% more oil than the Refuge.

Figure 11.3. A comparison of billions of barrels of oil per year from extraction in the Arctic Wildlife Refuge (red), with savings more efficient tires (blue), and savings from a 40-mpg mileage standard for cars and light trucks in the U.S. (green). Over 50 years, better tires would save 70% more than the Refuge would produce, while a 40-mpg standard would save more than 15 times the amount of oil that the Refuge is anticipated to produce (NRDC).

11.3.4. Fossil Fuel Accidents

Famous oil spills have left smothered marine life strewn along hundreds of miles of coastal waters, including the Exxon Valdez spill in the pristine Prince Williams Sound in the Gulf of Alaska in 1979. My first academic undergraduate hourly job at the Pacific Marine Environmental Laboratory in Seattle in 1975 was to run an oil spill trajectory model for anticipated spills in the Gulf of Alaska after construction of the oil pipeline and terminus atValdez.

A more recent example is the huge steady leak from the exploded oil rig at depth in the Gulf of Mexico. On April 20, 2010, the rig Deepwater Horizon exploded and sank two days later off the coast of the Mississippi River delta, killing 11 of 126 workers. Oil began spewing out of the sea floor and two days later the surface slick covered an area 50 x 50 miles. Figure 11.4 shows an image of the Gulf oil slick on June 19, 2010, taken by the MODIS instrument aboard the Aqua satellite (Moderate Resolution Imaging Spectroradiometer; http://www.ssec.wisc.edu/research/modis/). At present we don't know how long it will take to fix or what the ultimate damage will be to marine ecosystems.

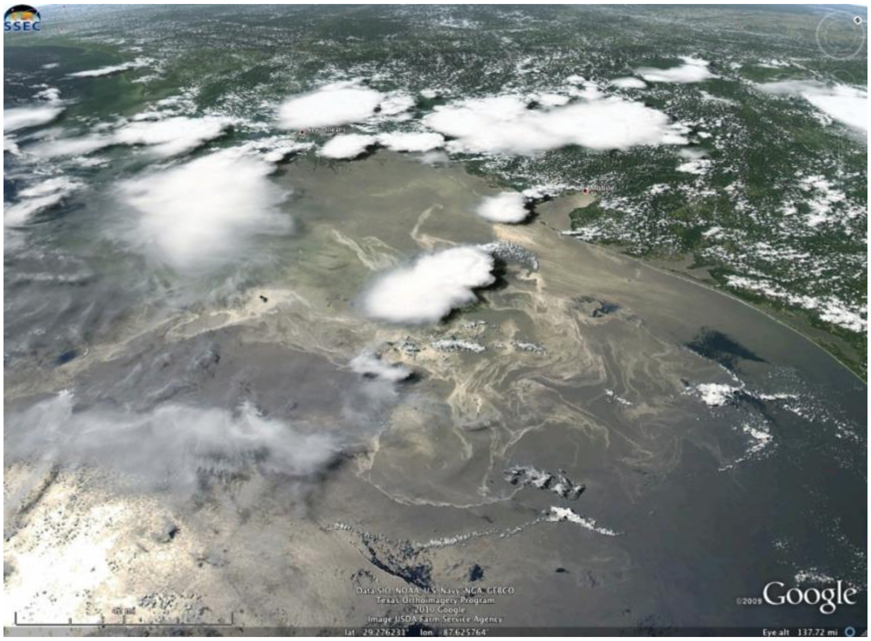
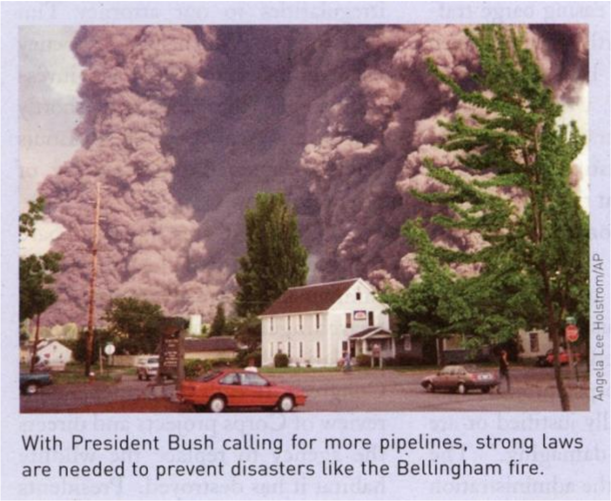


Figure 11.4. Image of the Gulf oil slick on June 19, 2010, taken by the MODIS instrument aboard the Aqua satellite (Moderate Resolution Imaging Spectroradiometer; http://www.ssec.wisc.edu/research/modis/).

11.3.5. Taking it personally: The Bellingham fireball

Death and mayhem associated with using fossil fuels while driving is so commonplace that we, in modern society, tend to turn a hardened mind to it. Explosions and injuries associated with the storage and transportation of gas, although less common, may catch our attention more easily. In the last decade, pipelines leaked an average of 6 million gallons per year, about half as much as was spilled from the Exxon Valdez (EDF 2001). In 2000 a natural gas pipeline in New Mexico exploded, killing 12 people at a nearby campground. Growing up in Bellingham Washington we used to go to Whatcom Falls Park pretty often, to jump off of different cliffs into wonderfully carved deep rock pools, from which Whatcom Creek would wend its way down to Bellingham Bay. A natural gas pipeline from Canada to the West Coast of the U.S. was constructed over the creek without much fuss. One morning in June 1999 neighbors called 911 repeatedly to report the smell of natural gas outside. The pipeline operator claims to have shut off the valve but it was not shut off for hours afterward. Several people were in the creek bed fishing when one of them lit a cigarette, causing a fireball that was seen for miles, which incinerated trees and killed everything within 200 feet of the creek as it made its way 1.5 miles toward Bellingham (Fig. 11.5). The only reason it didn't go into the downtown area was that it was stifled trying to go under the I-5 freeway. There is currently an effort to build the Viking Voyageur 800-mile gas transmission pipeline from the trans-Canada pipeline to Illinois through Wisconsin.



With President Bush calling for more pipelines, strong laws are needed to prevent disasters like the Bellingham fire.

Figure 11.5. Smoke from fireball entering Bellingham, WA in June 1999 resulting from a leaking natural gas pipeline, which killed 3 people (The Bellingham Herald, 1999).

11.3.6. Hidden Costs of Low Gas Prices

World oil production has been near 25 billion barrels of oil per year since about 1980 (Fig. 11.1). Due to depleting reserves, it is anticipated that the peak in oil production is right about now, with notable declines over subsequent decades. Yet demand for oil is forecast to increase by 60% by 2020. The diminishing supply creates a powerful need for energy intensive nations to maintain their source of oil at rather high cost. The half-life of existing petroleum reserves at current rates of extraction is estimated to be about 35 years, while that of coal is about 200 years. It clearly motivates us to invest in alternative energy sources.

North America uses more energy per person than other parts of the world. The energy consumption rate divided by the gross national product is significantly higher in the United States than in Japan or Europe. This reflects somewhat less energy-efficient manufacturing, transportation, and greater personal energy use among North Americans for their food and lifestyle choices. Figure 11.6 shows an estimate of CO_2 emissions per person per year, with North Americans holding the lead at 20 metric tons of CO_2 per person per year. This mass is about five times more than your car! In fact, every gallon burned in a vehicle emits 25 pounds of CO_2.The United States can do better in energy efficiency. From improved energy conservation measures during 1973-1990 in response to the OPEC oil embargo of 1973, U.S. energy usage was approximately constant but the GNP rose by 40%. It's time for a new resurgence of energy efficiency and alternative energy initiatives!

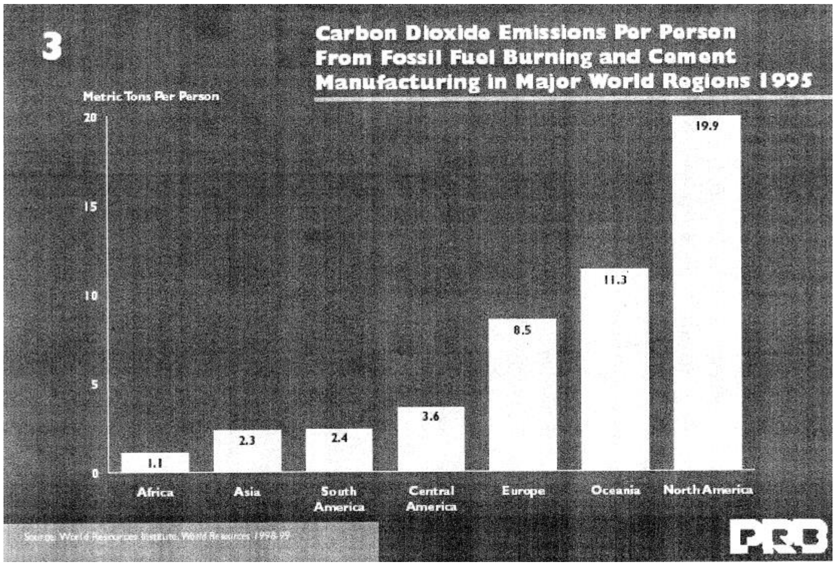


Figure 11.6. Carbon dioxide emissions per person per year from burning fossil fuel and making cement in 1995, broken down by major world regions. The average North American emits 20 metric tons per year, which is 10 and 20 times the average Asian and African, respectively (World Resources Institute).

Gas prices may be considered to be artificially low in the United States, with even current prices well below market prices in Europe and Asia. In effect, U.S. tax policy subsidizes low gas prices, since income taxes are used to pay for road building and other transportation infrastructure. This encourages people to drive more than they would have if prices more accurately reflected the costs of driving with gas. Income taxes pay for the military to maintain strategic fossil fuel reserve interests, rather than gas taxes. In other countries gasoline taxes are more often used explicitly for infrastructure beneficial to driving.

To highlight the relationship between military involvement and our energy supply, it is interesting to consider the cost of the first Gulf War. In 1987, the U.S. spent $40 billion on foreign oil, while in the Gulf War of 1990 the U.S. spent $15 billion per day to protect oil interests in Iraq. Tens of thousands of Iraqi soldiers were buried alive by sand bulldozers. Hundreds of thousands of people were exposed to debris from depleted uranium-tipped U.S. weapons. Each day of the Gulf War cost more than the entire decade of U.S. spending on the development of renewable energy.

The true cost of fossil fuel consumption includes the "big four": increased defense spending, increased air pollution, increased greenhouse warming, and an increased federal deficit. These profound negative aspects motivate us to seek alternative energy sources and greater energy efficiency. The more successful we are at this the more we will reduce military conflict, protect the economy, and reduce pollution and greenhouse warming.

11.3.7. Nuclear power

Nuclear power generates significant portions of electricity used in most parts of the United States. For example, the city of Madison, WI uses about 33% nuclear-generated electricity. In France 70% of electricity is generated by nuclear power. But the last nuclear generator built in the United States was in 1978, with the general public feeling reserved about them due to safety and security concerns. Recently President Obama has indicated support for construction of two new plants in Georgia. The total carbon footprint for generating a kW-hr, including fossil fuel used for removal and processing of nuclear fuel, is more than wind power, but two orders of magnitude less than coal power plants, thus having the appealing promise of reduced anthropogenic greenhouse forcing with increased electric power.

The key problem, however, is what to do with the radioactive waste, with a half-live on the order of ten thousand years. Since this is the time scale of civilization itself, with historical lifetimes for nations of, at most, several hundred years, it is highly unlikely that the distribution of waste material will be known continuously for 10,000 years. There is still no agreement to bury waste at Yucca Flat Nevada. Most of the uranium in mined in the United States actually comes from Native American tribal land, and virtually all nuclear waste is currently being buried on native lands (Caldicott, 2008; LaDuke, 1999). This disproportionate imposition on these people should be more broadly acknowledged in our society.

To render Yucca Flats and other potential permanent repositories of nuclear waste undesirable to future people, the U.S. government has suggested building a 100-m slab of asphalt to absorb sunlight, which would keep vegetation from growing, and alert future wandering nomads to stay away. Another suggested design to alert the wayfarer is a pile of cement “jacks”, which are sometimes used as breakwaters and coastal stabilizers, piled right on top of the waste site so no one will be interested. On the other hand, future people might think it was a spiritual sign to stay and try to grow crops and honor the mystical ancient ancestral wonder.

Even more alarmingly, nuclear fuel in varying degrees of military usefulness, is shunted around our nation’s railroads every day. Some of the typical routes through Wisconsin are shown in Fig. 11.7. This system is extraordinarily vulnerable to material “disappearing”, which has undoubtedly already occurred. The obvious problem is that groups of people who feel oppressed or are otherwise disaffected, can fashion true weapons of mass destruction. The Obama administration is making it a top priority to tighten up security for international and domestic nuclear waste transport. It would seem foolhardy to exacerbate this orange-alert situation by creating many new power plants, with the attendant problems of transportation and storage. If many small factions can acquire nuclear weapons fuel, is the world safer now? Are we safer by propagating this culture of nuclear weapons?

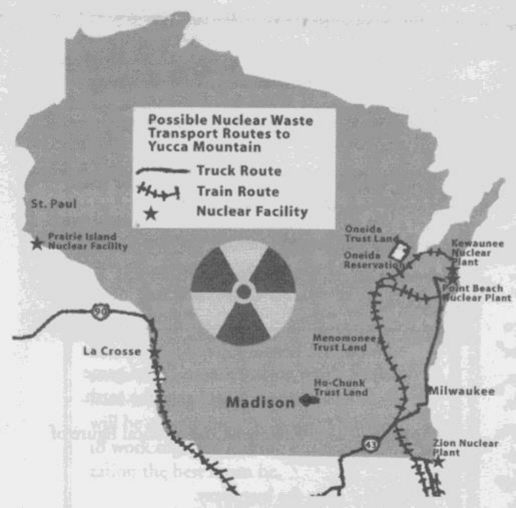


Figure 11.7. Possible nuclear waste transport routes through Wisconsin.

It is clear from newspaper reports that people in Utah and Nevada in the late 1950s were regularly warned to not breathe the air after nuclear tests. The Hanford, WA reactor complex has leaked radiation into the air and into the Columbia River many times, as is readily seen in sediment cores taken at the mouth of the Columbia River. There is considerable evidence that many people harmed by radioactive exposure, in the form of geographical clusters of certain types of cancer. Most people didn't get sick and die, but some did.

We must also be aware of the fact that the U.S. military has used radioactive depleted uranium-tipped weapons projectiles in the Gulf War and in the present situation in Iraq. They are used because their density greatly exceeds those of conventional tips and so penetrate target material much more effectively. But they are pulverized on impact, emitting a radioactive dust that falls on everything. The cause of the rapid rise of autism in the early 1990s has not yet been identified. Some authors have pointed out that the exposure of soldiers to depleted uranium in the early 1990s could have contributed to some of those cases.

It is also worthwhile to remember the terribleness of the weapons used at Hiroshima and Nagasaki. At present, there are many thousands of nuclear warheads owned by many countries which could destroy much of what we know today. All sane people in the world hope and pray that no one ever uses atomic weapons to kill people again. The genocidal nature of their magnitude is noxious to our soul. We recoil from it collectively and that is the right decision. To support domestic nuclear power is to foster and perpetuate military nuclear weapons usage.

It might be appealing to consider nuclear fusion, but the conversion of H to He leads to contamination of the containment vessels, which must be buried. It is a difficult engineering challenge to contain the blazing-hot plasma, which is similar to the sun. The containment devices that work the best so far look like doughnuts, or toroids, called tokamaks. Physicist Michio Kaku (2008) states that the current record of power generation is 16 MW of power for 1 s. The most advanced fusion project of this type is the International Thermonuclear Reactor (ITER), to be constructed in southern France. It is expected to generate its first plasma by 2016.

It is hoped that by 2022 it will be the first fusion reactor to generate more energy than it consumes.

Author: Joe Strummer
Album: Give 'Em Enough Rope
Song title: Guns on the Roof
Final refrain:

I'd like to be in Africa
Beating on the final drum
I'd like to be in the U.S.S.R.
Making sure these things will come
I'd like to be in the U.S.A.
Pretending that the war's all done
I'd like to be in Europa
Say goodbye to everyone

11.4 Renewable Energy

If we want to avoid the bad effects of burning fossil fuels and the risks associated with nuclear power, we must consider renewable energy sources, each of which has a non-zero carbon footprint due to burning fossil fuels during construction and implementation. We need to do this to stabilize the economy, and to reduce global warming and military conflicts. Viable options that are being explored include photovoltaics, biomass and solid waste ingestors, wind, tides, and geothermal energy sources.

It is important to keep carbon emissions to a minimum. A top strategy is to use photovoltaics to generate electricity directly and to use sunlight to separate hydrogen from water, which can then be used in hydrogen fuel cells. At present, hydrogen is made by steam processing methane and by burning coal to electrolyze water. However, one needs energy sources that are renewable underlying any fuel cell economy in order for it to be helpful to the environment. Solar power is desirable because, once panels are built, after about 3 years it is free electricity. The sun is the largest primary source of energy. However, construction requires use of elements such as copper (consumption half-life 40 years), Nickel (half-life 65 years), Lithium, and Cadmium. For more on fuel cells try www.fuelcells.org and Peter Hoffman's book *Tomorrow's Energy: Hydrogen, Fuel Cells, and the Prospects for a Cleaner Planet* (2001).

Alternative energy sources composed about 1.8% of world energy consumption in 1990, but some estimates anticipate that it will reach 12% by 2020. This would result from a simple extrapolation from the strong advances in biomass, solar, wind, geothermal, and oceanic over the past decade.

11.4.1. *Biomass fuels*

Another problem with using corn or grain-derived ethanol for fuel is its competition for the global food supply. Lester Brown (2009) writes that “A fourth of the U.S. grain harvest – enough to feed 125 million Americans or half a billion Indians at current consumption levels – goes to fuel cars. Yet even if the entire U.S. grain harvest were diverted into making ethanol, it would meet at most 18% of the U.S. automotive fuel needs. The grain required to fill a 25-gallon SUV tank with ethanol could feed one person for a year.”

11.4.2. Wind and waves

A variety of devices have been invented to take advantage of wave energy at the ocean/atmosphere interface, including the oscillating water column, serpentine Pelamis, McCabe wave pump, Archimedes wave swing, IPS buoy, and the Nodding Duck (Science News 2001). Wave energy is due to wind, which is a small fraction of the available energy created by differential radiative heating, about 4000 ZJ. Gorlov’s helical turbines, which look like beaters, allow energy extraction when currents or winds are going in either direction (Davis, 2005). They have been deployed off the coast of Norway, where intense currents over underwater sills can generate the Maelstrom, a dreaded sucking vortex, and considerable energy production. Other places in the world can be exploited in this fashion. The ultimate source of this type of energy is tidal interaction between the moon, earth, and sun, which implies a gradual diminution of the collective kinetic energy of the planets.

One interesting suggestion by Walt KcKeown, my first teaching assistant, that he thought up while sailing a Chinese junk off the coast of California, is a kite / sea drogue combination that blows endlessly around Antarctica. This device explicitly avoids the turbulent interface, with just a cable connecting the underwater drogue to the airborne kite. The friction of the kite pulling the drogue through the water separates H from the water, which passes up the conduit/tether to the kite, where it is stored until a mother dirigible from Capetown South Africa comes to collect the hydrogen gas for global distribution on the market.

Wind turbines represent a great promise for tapping into the kinetic energy of the atmosphere. Wind energy generation currently costs about 9 cents per kW-hr, in comparison to coal at 7 cents per kW-hr, so it is becoming more attractive economically as well as environmentally. An example of a small wind farm on the island of Kos, Greece in 2004 is shown in Fig. 11.8. Farmers and other landowners in areas with persistent winds are increasingly choosing to contribute to energy generation and their own income. Success stories abound, such as the 108-turbine wind project in Prowers County, CO, which increased the county’s tax base by 29%. In Texas, the taxable value of the wind power plants that deliver 1000 MW of power is $777 million, with $12 million supporting the local schools, $2.5 million going to local landowner royalty income, and 2500 jobs were generated. On average, wind turbines generate electricity 65-80% of the time (American Wind Energy Association).

Figure 11.8. Wind turbines on a ridge on the island of Kos, Greece, making use of winds off of the Mediterranean Sea.

However, several objections have been raised regarding wind power, with bird kill and blade noise gaining considerable attention in the public eye. Erickson et al. (2005) investigated bird mortality in the United States and estimated that, out of each 10,000 birds killed by human activities, less than one death is caused by a wind turbine. Out of every 10,000 killed, 5,500 are by hitting buildings and windows, 1,000 by cats, 800 by high tension lines, 700 by vehicles, 700 by pesticides, and 250 by communication towers. This would increase with more turbines built.

The wind noise issue may be a matter of who is doing the listening. Sound meters show that the sound of a wind farm at a distance of 300 m is about 50 dB, or no noisier than a kitchen refrigerator. This may sound progressive and comforting to those who own the land that they are on, but if it is imposed on you by a neighbor, the light but audible whooshing sound could be unwelcome, perhaps similar to a neighbor's wind chimes. It seems desirable to make use of a good renewable energy sources at competitive prices in a way that can generate jobs and foster energy independence. If we emphasize many small-scale local energy sources rather than large-scale production farms, we might create a more flexible and environmentally sound methodology more in tune with our human local nature.

11.4.3. Solar power

The largest source of renewable energy is solar radiation. Instead of burning fossil fuels, many people heat water with a solar water heater. In these devices water flows through a set of tubes embedded in a black plate covered with glass, connected to a storage tank through a circulating flow. The buoyant upward flow of heated, lighter water can be collected in an insulated storage tank for later use. An important facet of solar energy usage in building design is the "solar wall", or passive solar collector. Just inside exterior glass is a slot for a roller blind to keep heat in at night or to keep sunlight out if it is too hot. When the roller blind is up sunlight then passes through transparent insulation material and an air gap, and gradually heats up heavy building blocks, which slowly release their heat at night.

The photovoltaic (PV) solar cell consists of a thin slice of impurity-doped silicon which catalyzes conversion of the energy in a solar photon to the motion of an electron. The range of cost of conventional electricity is slowly rising and is ~7 cents per kW-hr, while the cost of PV electricity has declined from ~40 cents per kW-hr in the late 1980s to ~10 cents per kW-hr. A simple array of 36 solar cells, each 10 cm in diameter, provides about 40 W of power. It can be used to charge a car battery, which can then power up to three 10 W fluorescent lights, three hours of radio, and one hour of television each day (Fig. 11.9). You can buy one of these in Sri Lanka right now for about $100 U.S. With a larger solar array a small refrigerator could be added. This type of local power generation helps make local users less dependent on long-distance power transmission. It provides an entirely different model for the power grid, essentially the principles elucidated in *Small is Beautiful* by E. F. Schumacher.

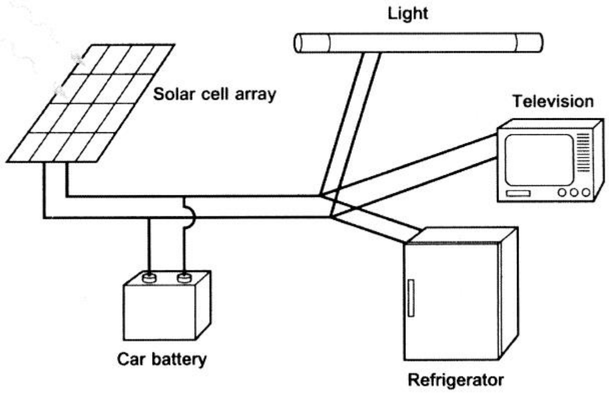


Fig. 11.12
A simple solar power installation for a small home is being marketed in Sri Lanka for less than $(US)100[52]. An array of 36 solar cells, each 10 cm in diameter, provides 40 watts of peak power. This is sufficient to charge a car battery which can power up to three 9 watt fluorescent lights and three hours of radio and one hour of television each day. With more restricted use of these devices or with a larger solar array, a small refrigerator can be added to the system.

Figure 11.9. A simple solar power installation for a small home (The World and I).

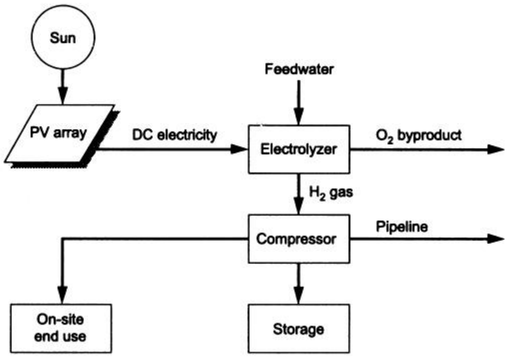
A solar PV array can be used to create local DC electricity, which can be used to electrolyze water, yielding the useful byproducts oxygen gas, O_2, and hydrogen gas, H_2. The hydrogen gas can be compressed and stored or transmitted in a gas pipeline to a central storage facility (Fig. 11.10). Some of the hydrogen gas could be used on-site, benefitting the local producer. Solar-generated compressed hydrogen can be stored in hydrogen fuel cells, which can be used to convert the stored energy of molecular hydrogen into electricity for a variety of applications, including transportation. This system would then constitute a nearly zero-carbon footprint power system.

11.4.4. Hydrogen fuel cells

Once solar energy is stored as hydrogen, a fuel cell can directly convert the chemical energy into electricity at efficiencies exceeding 80% without burning it to produce heat.

Somewhat similar to a battery, two electrodes are separated by an electrolyte. The electrolyte has the special property of being able to transmit hydrogen ions (protons) but not electrons. When hydrogen gas is supplied to the porous anode, the negative electrolyte (Fig. 11.10), it dissociates into hydrogen ions (H_+) and electrons (e_-). The H_+ ions migrate through the electrolyte to the cathode, the positive electrolyte, where they combine with the electrons with oxygen to make water vapor. The key energy flow is the external electrical circuit of the electron flow, which can be used to power cars.

Fig. 11.14
A solar photovoltaic (PV) electrolytic hydrogen system[57].



Fuel cell technology

A fuel cell converts the chemical energy of a fuel directly into electricity without first burning it to produce heat. It is similar to a battery in its construction. Two electrodes (Fig. 11.15) are separated by an electrolyte which transmits ions but not electrons. A fuel cell has a theoretical efficiency of 100 per cent. Fuel cells have been constructed with efficiencies in the range of 40–80 per cent.

Fig 11.15
Schematic of a hydrogen-oxygen fuel cell[58]. Hydrogen is suppled to the porous anode (negative electrode) where it dissociates into hydrogen ions (H^+) and electrons. The H^+ ions migrate through the electrolyte (typically an acid) to the cathode (positive electrode) where they combine with electrons (supplied through the external electrical circuit) and oxygen to from water.

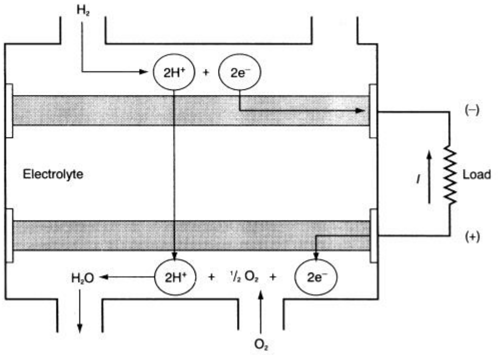


Figure 11.10. Fuel cell technology.

Over the past several hundred years there has been a gradual transition in energy use from fuels with high carbon content such as wood (~90% C, 10% H), to coal (60% C, 40% H) , to oil (30% C, 70% H), and natural gas (10% C, 90% H). Hydrogen fuel, H_2, represents the ultimate clean fuel with 0% C to burn and combine with atmospheric O_2 to make CO_2. Today 95% of hydrogen fuel is produced by steam reforming of methane, which produces carbon dioxide as well as hydrogen gas:

$$CH_4 + 2\,H_2O \rightarrow 4\,H_2 + CO_2. \qquad (11.1)$$

This method of producing hydrogen for fuel cell use clearly does not avoid production of CO_2. Electrolysis of water, however, generates hydrogen and oxygen:

$$H_2O \rightarrow H_2 + \frac{1}{2} O_2. \qquad (11.2)$$

If the electricity used to electrolyze the water is generated from renewable resources such as solar, hydro, or wind power, instead of fossil fuels, then this type of hydrogen fuel generation would be quite clean. It has been estimated that it would take about $2 trillion to renovate our infrastructure to use hydrogen fuel cells widely in automotive and utility applications. There is a growing movement to create a smart electrical grid to accommodate hybrid vehicles running on fuel cells and/or batteries charged at home. We always need to keep in mind, however, that the original energy sources need to be renewable for hydrogen technology to be truly cleaner than fossil fuel technology.

One possible limitation on the use of hydrogen fuel is public concern for fire or explosion. The legacy of the Hindenburg dirigible accident on May 6, 1937, at Lakehurst, NJ may still influence public perception. During an electrical storm the stern touched ground and burst into flames, perhaps ignited by the blue glow of electricity seen around the craft. The 35 passengers who were afraid that the ship would explode jumped to their deaths. The other 65 passengers who waited for the airship to land walked safely away from the accident. Recent NASA investigations revealed that this tragedy was not caused by the hydrogen gas, which burns invisibly, but by a combination of the highly flammable cotton fabric treated with doping compound stretched over the wooden skeleton, and the rocket fuel used for navigation, which explain the red-hot flames seen in historical photographs. Given that the public has relatively little experience with hydrogen fuel, it might be a good idea to have a public awareness campaign regarding how hydrogen burns and what the dangers are.

11.4.5. Development of Electrical Grids

The present model for electrical generation and distribution in the United States is large-scale generators, usually coal-powered, and long-distance transportation. It is hard to store electricity, and line loss with distance from a power station is a significant inefficiency in the system. The economics of the situation in the United States does not foster uploading local power sources to benefit the grid locally. Proponents of wind farms tend to think large-scale and seek the construction of large transmission lines. The Obama administration currently favors building more of them. Such power lines create a painful conflict between local land owners and insatiable demands for increased electrical consumption and transmission.

Taking it Personally: A 345 kV transmission line over my house

I have lived in rural Dane County for over 20 years, in a house on 3 acres on a dead-end road with a 30’ wide swath of mature woods through it. The American Transmission Company in 2005 proposed to build a new 345 kV transmission line from West Middleton to Rockdale and one of the three proposed routes would bisect my property and destroy the trees. At ATC’s public information session that I attended, the real estate specialist told me that they would have to cut all of the trees down to make way for the wires and 140’ towers, but that they would compensate me ~$25,000 for usage of 30’ right of way either side of the power line. When I asked him how much he thought its existence would deplete my property value he chortled and then estimated that we could probably sell it for about 60% of its present worth. I worked my entire life to buy this house where we raised our children. The undermining of what we commonly regard as an achievable goal in our country by the incredible power of large companies is astonishing. Are we really taking care of each other? Is there an alternative to this large-scale production and large-scale transmission approach, or must we all subscribe and some pointedly suffer?

In 2009, the Wisconsin Public Service Commission held public hearings. The following is a portion of my testimony:

“The proposed 345 kV transmission line is consistent with transporting power from future coal-fired power plants. Let us consider the effects of Dane County electricity usage on Appalachian mountain top removal. The typical person in Dane county uses 7,000 kWh of electricity each year, which requires the consumption of about 1 ton, or 1 cubic meter of coal, which results in the emission of 4 tons of CO_2 per person per year. If the amount of electricity used in Dane County were to double over the next 40 years, and if all of the extra electricity were to be generated by new coal removal and transmitted by the proposed ATC transmission line, Dane County would consume an additional 500,000 cubic meters of coal per year. In 40 years Dane County would consume an extra mountain top 100 feet high and 1000 feet wide. Building the ATC line represents a choice to go down the path toward further global warming, degradation of local property values, and accelerated consumption of mountains in Appalachia.

We can choose to build an expensive transmission line that will require increased coal consumption, or we can choose to enhance conservation measures and implement alternative energy sources. In this important and serious choice, there is a dichotomy of technologies: centralized power generation and large lines, versus local generation and small lines. The latter technology provides for the capability of each user to contribute to or draw from the grid according to their own needs and their own power generation, including wind turbines and solar panels. Construction of the 345-kV line is an investment in the opposite direction and would suppress the development and implementation of appropriate technology and economic methods. If we choose to develop renewable energy and a local, two-way grid, and not go farther down the road of coal consumption and enormous power lines, we will be making a clear-headed decision to reduce the climate and environmental impacts of our energy consumption. The old-school approach of big coal burning facilities and big transmission lines will ensure that Dane County residents contribute strongly to global warming, pollution, and degradation of the local environment. The choice is clear.”

The Public Service Commission decided to let the ATC build the 345-kW power line through Dane County. ATC sold the project to Dane County basically by appealing to their guilt in electricity consumption and fear about the future, even though the power line was explicitly for transmission *through* Dane County. In the end, a tiny parcel of land along our proposed power line route was found to be on the Federal Registry of historic significance so it was not chosen. It will be constructed along the freeway through Madison over the next few years.

If you stand back and look at the problem from a global perspective, it becomes clear that it would be a great mistake to go down the road of business as usual. We need to embrace proven renewable energy sources that are small, local, and distributed, which need small lines, not enormous ones. This will be enabled by exciting new economic models which allow individual users to invest in their own local energy sources, including solar and wind.

11.4.6. Energy use for computers

The use of personal computers, phones, games, and other small devices has markedly increased the demand for electricity. In addition to all of the electricity demand from having your personal devices plugged in, there is a significant power cost for simply maintaining electronic information in huge electricity-powered warehouses. There is a surprisingly wide range in estimates of total electricity usage for the internet, including energy to manufacture equipment, routers, PCs at home and in the office, phone switching equipment, web sites, and large dot-com companies. Estimates range from 40 billion kW-hr per year by scientists at the Lawrence Livermore National Laboratory to 300 billion kW-hr per year in an estimate in Forbes magazine (Koomey, 2002). This suggests an astonishing lack of knowledge about our own consumption, hence lack of knowledge about possible future demand. This seems disturbingly similar to our lack of knowledge about the number of species that we have on our planet.

A computer takes up as much space as a graduate student and generates as much waste heat as a graduate student. They are visceral extensions of ourselves and are becoming more highly regarded than pets. Would you more willingly buy a new computer or pay an equivalent veterinary bill for your pet? How do you feel when your computer is not working? Computers are scorned as ancient by others if they are a few years old. The United States throws away about 50 million computers per year with very little recycling of rare minerals and natural resources. Vast plumes of toxic chlorine used for cleaning computer parts in Phoenix' computer industry have polluted huge regions of their water supply. Germany requires that the cost of new computers include mandatory recycling. Apple is bringing out lines of computers with significant percentage of recyclable material. A new law in Wisconsin requires that manufacturers arrange for recycling and disposing consumer electronics, including video displays, computers, and printers. Yet the demand for new computers is far outstripping efforts such as these, energy issues related to computers include large uncertainty in actual demand, and the extraction and processing of rare materials can only become more challenging problems in the future. Solutions to the ecological down-side of computers and our information technology may be had by considering the psychological reasons underlying our behavior (Chapter 13).

11.5. Chemical Hazards

Another kind of anthropogenic global change is occurring everywhere at very small scales. Many serious chemical effects resulting from growing crops and livestock are being discovered. There is an emerging concern that plastics in the ocean environment get ground up by wave action into smaller and smaller particles, which eventually interfere with a range of biological processes at smaller and smaller scales. In an effort to keep our food supply ahead of the growing population and demand we are dosing cropland with ever-increasing amounts of nitrogen fertilizer (which requires burning fossil fuels and is the source of the greenhouse gas N_2O), fumigants (bromine compounds harm stratospheric ozone) and insecticides (contribute toward the demise of the domesticated European honey bee in North America).

11.5.1. Herbicides

In order to achieve effective crop yields herbicides are often applied to kill weeds prior to emergence of the crop. Atrazine is the most widely used herbicide and is commonly used on corn and soy bean fields. Wild male frogs exposed to 0.1 ppb atrazine grew extra testes and sometimes ovaries (Raloff, 2002a). Rainwater in the U.S. carries up to 0.4 ppb of atrazine. At sites in the Midwest and West, wild leopard frogs were found in streams with atrazine concentrations varying annually between 0.7 and 15.2 ppb, with 10-92% of males having underdeveloped testes. The malformations, where a testis is male at the top but increasingly female at the bottom, are a unique signature of atrazine exposure. A blend of atrazine and metolachlor increase tadpole metamorphosis time from egg to frog from 60 to 70 days.

There is also increasing evidence that exposure to farm chemicals can be harmful to human male reproduction. In one study, men from Columbia, MO, where ~60% of the land in the county is farmed, exhibited reduced sperm count and sperm motility by ~50-70% relative to men from Minneapolis, Los Angeles, and New York City (Raloff, 2002b).

11.5.2. Antibiotics and hormones

The problem of antibiotic use among farm animals was addressed in Chapter 10.3. Another facet of this problem is that antibiotics can have harmful effects on plants. After ingestion by humans and livestock, 90% of these drugs are excreted and enter open waters from sewage effluent and farm runoff. Farmers apply 7 million tons of sewage sludge and manure ("biosolids") to their fields. It turns out that antibiotics can stunt or kill soy beans and pinto beans (Raloff, 2002c). This highlights an emerging problem of cross-talk between trace constituents affecting animals and plants, about which there is a profound lack of knowledge.

Each year farmers also fatten 24 million beef cattle up by 20% by administering testosterone surrogates, which promote muscle-building, and progestins, which suppress the female estrus cycle so that more energy goes into muscle-building. These hormones run off unchecked into our rivers and streams. Male fathead minnows in Nebraska streams have reduced testes downstream of feedlots relative to upstream (Raloff, 2002d). Female fathead minnows exposed to androgenic pollutants from upstream feedlots exhibited forehead markings of reproductively active males. The European Union has banned the importation of North American beef treated with hormones.

11.5.3. Personal chemical products in our water system

Another surprising source of environmental contaminants is chemicals from human personal products that are washed down the drain or toilet and enter our creeks, rivers, lakes and well water supplies. The USGS studied 130 streams in 30 states during 1999 and 2000. They found that, in addition to 26 antibiotics, contaminants ranged from insect repellants and caffeine to fire retardants, birth-control pills, and antidepressants (Harder, 2002). The three most abundant types of contaminants were steroids, ingredients of plastics, and compounds from detergents. Estrogens can have strong long-term effects on aquatic organisms. Most of the compounds appeared in the ppb range of concentration, but there is increasing evidence that separate estrogens add additively to yield a stronger total effect. Chemical flame retardants in clothing and children's toys are found in very high concentration in North American human breast milk. In Europe these chemicals are banned, and the law requires proof of safety before a new agent can be used in the environment. In contrast, U.S. law requires proof of harm or risk before a chemical is banned (Crenson, 2002).

11.5.4. Mercury

Mercury is released into the atmosphere as a trace element in fossil fuels, primarily coal, where it rains out into lakes and streams, circulating throughout the planet (see Chapter 5). The EPA's safe level for mercury in lakes and streams is 1.8 parts per trillion, but rainwater in the upper Midwest typically contains more than 10 parts per trillion. Due to bioaccumulation in the food chain, fish have mercury levels millions of times higher than surrounding water. Mercury affects the brain, spinal cord, kidneys, liver, the ability to feel, see, taste, and move, and is especially damaging to a fetus. The mercury content of fish caught in the Gulf of Mexico varies from 0.3 to 1.5 ppm, including ling, amberjack, tuna, red drum, and mahi-mahi, according to the Environmental Protection Agency (EPA). The number of eight ounce servings per month that an average adult male weighing 160 lb. can safely consume ranges from about 3 per month to once every two months (EDF, 2003). This suggests that I was unwittingly endangering my daughter who loved to eat tuna sandwiches several times per week when she was growing up. For more information about mercury, please see http://www.epa.gov/waterscience/fish .

11.5.5. Autism and toxins

A great tragedy has befallen our children in the United States since about 1990, when the cases of autism increased dramatically to about 1 in 150. It is characterized by chronic inflammation across the brain, immune system, and digestive system. In some children exposed to mercury, mercury chelation can cure autism. Due to the coincidence of the rapid onset of autism cases in 1990 with the introduction of mercury-laden vaccinations, many suspected a causal connection (Kennedy, 2004). Yet the rate of newly diagnosed autism cases did not decline after the federal government stopped using mercury-matrix vaccinations in the early 2000s.

It has been recently discovered that autistic children do not make as much glutathione, which is crucial for removing toxins in the body (Neimark, 2007). There is a growing sense that our heavily industrialized, chemical-soaked environment may be the cause, that industrial chemicals may be impairing the brain development of children around the world, especially those with reduced glutathione production. Very little is known about the effects of chronic, low-dose, multiple exposures to chemicals and their effects on autism.

Figure 11.11 compares the rates of autism in Texas counties in the early 1990s (top) and in the late 1990s (middle). The bottom map shows pounds of toxins released in each county in 2001. The darkest patches in the bottom map show counties with the top 20% of increases in autism (Neimark, 2007). As with most epidemiological studies, the correlation is not definitive, but it is certainly disturbing.

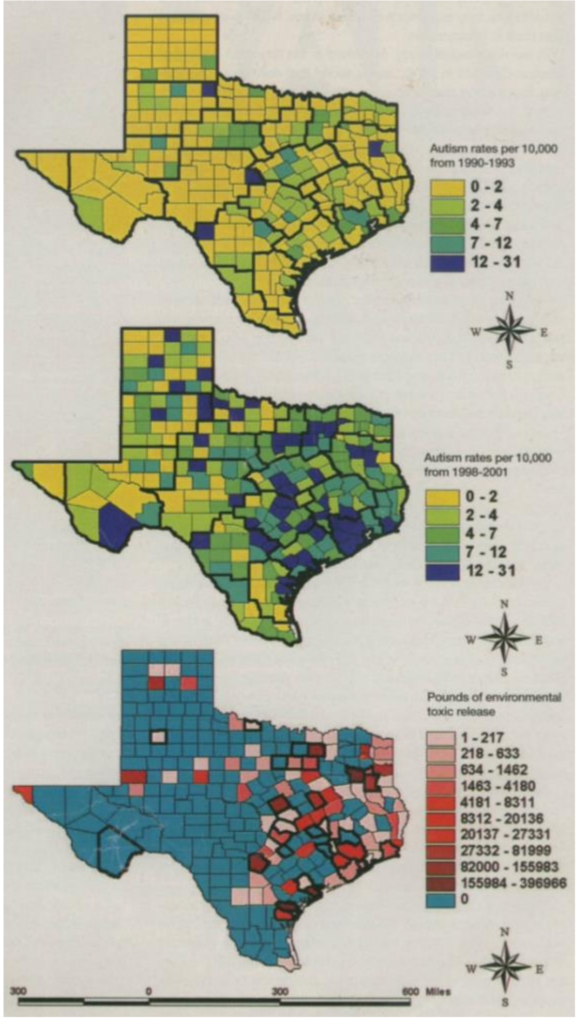


Figure 11.11. The toxic link to autism. The first two maps compare rates in Texas counties in the early 1990s (top) and in the late 1990s (center). The blue map (bottom) shows pounds of toxins released in each county in 2001. The darkest patches in the blue map represent counties where increases in autism rates over the past 10 years have been in the top 20 percent. The correlation between toxins and autism is suggestive, though not definitive.

Quantitative Investigations – Human Impact on the Earth

1. *What does your "footprint" in food look like?*
The average adult consumes about 2000 kcal (2000 food calories) per day.
a) How much heat energy does the average adult give off per second in Watts? (1 kcal = 4136 J, and 1 J/s = 1 W.)
b) If 16×10^6 J is released by consuming 1 kg of food, how many kg of food must an average adult consume in one year to sustain 2000 kcal of energy loss?
c) If one square meter of cropland produces 0.06 kg of edible plant food, how much crop land is needed to grow food for an average adult to eat for one year?
d) The total land area of the earth is about 1.5×10^{14} m^2. If we assume that about 10% of the land can be used for agriculture, about how much land would be allotted equally to each person alive today for growing food?
e) Since chickens, pigs, and cows are one trophic level above grain, it takes 2, 5, and 7 times as many kg of plant food to make 1 kg of chicken, pig, or cow. Most of the food consumed worldwide is plant food. Based on your answers to c) and d) do you think it is possible for everyone to eat mostly meat?
f) Humans currently appropriate about 40% of land net primary productivity (NPP). Estimate the holding capacity (human population) of planet earth if we appropriated all of land NPP. If the population doubling time is 40 years, how long will it take to reach this point?

2. *What does your footprint in water look like?*
In the United States people use about 5 m^3 of water per person per day. Madison, WI has about 200,000 people and it lies on the shores of Lake Mendota, which is about 8 km x 5 km x 15 m deep. If all of the water that people in Madison used came from Lake Mendota, what fraction of it would be used each year?

Key Terms

net primary productivity (NPP) -- solar energy fixed by plants minus what they use for their own respiration, often measured in Gt of fixed C

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