Renewable Energy Limits

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1**Renewable Energy Limits**

by Ross McCluney
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> "*The more we get out of the world the less we leave, and in the long run we shall have to pay our debts at a time that may be very inconvenient for our own survival.*" — Norbert Wiener

Introduction

The world's energy and environmental crises are inextricably linked. The processes of extracting, processing, and burning fossil fuels generates copious pollution of air, water, and land. Fossil-fuel-derived energy lies at the heart of other environmental problems. Fossil energy powers the bulldozers clearing rainforests. It runs the tractors and other farm equipment of industrial agriculture, compacting and mineralizing soils thus increasing their susceptibility to erosion. It provides the fertilizers and pesticides used by intensive food production systems, 'freeing' people for other pursuits. It enables the spread of cities dependent on motor transportation, and their attendant environmental impacts. The depletion of our fossil resources over the course of the twenty-first century is a serious concern requiring considerable attention by individuals, organizations, and governments.

Most leaders seem to think that science, technology, and some minor alterations in public policy will be sufficient to prevent these problems from adversely affecting humanity as a whole. Even solar enthusiasts seem to think that most of these problems will go away if everybody would just buy (or make their own) solar energy systems.

Other people believe that the threats facing mankind are much more serious and need more urgent attention and deeper action. These persons are concerned that leaders in all sectors of society are failing to see the long-term threats and refusing to do much about them, save for some recycling, a few pollution restrictions, a little energy conservation here, some solar energy there. Growing evidence is leading us to believe that the pessimistic view is the correct one, that current reforms will be insufficient for the long term.

Energy and Population

As illustrated in Fig. 1, world population expanded only gradually until the Industrial Revolution, reaching about one billion around 1850. Then came oil, and later gas, added to already established coal production, enabling the Industrial Revolution, the machinery of which was driven by abundant cheap energy from fossil fuels. In the three-or-so million year span of human life, the current spurt of fossil fuel use and depletion will have occupied only a tiny portion.

The recent exponentially rapid growth of world population (See Fig. 1) tracks growth in use of fossil fuels. Campbell described it thus:

> The abundance of energy has allowed the human population to expand greatly, multiplying three-fold during the lifetime of the present Queen of England. A new subspecies, called *Homo hydrocarbonum*, evolved... [and] will certainly be extinct by the end of this century.... We are not about to run out of oil, but production is close to peak. The transition will represent an unparalleled discontinuity as the growth of the past gives way to decline in the future.[1]

"*Homo hydrocarbonum*" will be replaced by "*homo somethingelseonum*". What that something else will be is the subject of this chapter.

Energy and Food

Ecologists tell us that food is an important controlling factor in population dynamics, including dieoffs of non-human animal populations, as well as our own. Because of the high fossil fuel subsidy to industrial food production and the need for fresh water for irrigation (much of it pumped using fossil fuels), and increasing purification of water polluted by intensive agriculture and urbanization (also dependent on fossil fuels), it seems clear that human populations will track the availability of fossil fuels on the downside, following Peak Oil.

In spite of this our leaders seem to take heart in signs of increasing agricultural productivity in many parts of the world. Other areas, however—with lands not as suited to high-yield agriculture, or suffering shortages of fossil fuels and deficient energy-based infrastructures—experience terrible famine and poverty. Further, much of the increased productivity has been accompanied by ever increasing dependence on fossil resources. As these resources become short in supply, agricultural productivity can be expected to decline. Even before we reach the down slope of fuel availability, food shortage for many hundreds of millions of persons is the daily reality.

On 15 October 2002, the United Nations announced that “Progress in reducing world hunger has virtually stopped, and mountain sources of fresh water essential to food production are melting away due to global warming.” Additional dire statistics were presented in ‘The State of Food Insecurity in the World 2002’, the annual report of the UN Food and Agriculture Organization (FAO). It stated: “As a result of hunger, millions of people, including 6 million children under the age of five, die each year.” The FAO estimates that there were around 840 million undernourished people in 1998-2000. Of these 799 million are in developing countries, 30 million in ‘transitional economy’ countries, and 11 million in the industrialized countries.[2]

Each year, chronic hunger and malnutrition kills millions of people, stunts development, saps strength and cripples victims’ immune systems. Where hunger is widespread, mortality rates for infants and children under five are high, and life expectancy is low. Even if agricultural productivity were increasing in all parts of the world, we would still have a serious problem. The reason is that high-yield species and energy-intensive methods of production are unsustainable without massive petroleum inputs. If the petroleum inputs go away, or even just stop growing and remain stable for a while, this will exert strong negative pressure on the world’s food production systems, as we shall likely be witnessing in the next few years.

Writing in 1999, Pimentel et. al. pointed to declining available cropland:

> In 1960, when the world population numbered about 3 billion, approximately 0.5 ha of cropland was available per capita worldwide. This half a hectare of cropland per capita is needed to provide a diverse, healthy, nutritious diet of plant and animal products -- similar to the typical diet in the United States and Europe. The average per capita world cropland now is only 0.27 ha, or about half the amount needed according to industrial nation standards. This shortage of productive cropland is one underlying cause of the current worldwide food shortages and poverty.[3]

The ratio of petroleum energy to solar-derived food energy was explored for the U.S. by Steinhart and Steinhart in 1975. They found that the total energy subsidy for all food types in the U.S. was 1000%. For every calorie of food energy consumed it took about ten calories of fossil fuel subsidy to grow, harvest, process, and deliver the food.[4] Though it is not nearly this high in world average terms, the fossil fuel subsidy required to simply maintain current high-yield food production is an integral part of world agriculture, and a warning of famine to come. Fossil energy subsidies to food produced by various methods are shown in Fig. 2. For the most energy intensive, developed countries, the solar energy content of the industrially produced food we eat is so low that, in reality, we are not “eating solar energy” but are “eating” oil.

As petroleum production starts declining, as water shortages grow—and if agricultural yields drop from environmental effects of fossil based agriculture, such as accelerated erosion and climate change—food output will decline and prices will rise. If world population continues its currently inexorable growth after Peak Oil then per capita food supplies can be expected to shrink. This will pose threats of serious economic and social upheaval—as the number of starving people increases and as others seek violent means to correct the massive global imbalance of wealth and food. Those with economic power probably won’t suffer much. Though food will be more costly, they’ll still be able to buy it. The less well off, however, may not be content to starve while others are well fed. Wars of terrorism can be expected to grow, and be augmented by new, non-ideological wars between the haves and have-nots. The resource wars have already begun.[5]

To the Renewables

Many people hope we can avoid the threatened difficulties by switching from petro-energy to solar energy, backed by increased energy conservation. The possibilities seem promising. New technologies include wind- and solar-powered electric generating stations, solar heating systems, ocean energy systems of several kinds, and possibly geothermal energy.

The threats of future upheaval add urgency to work in the fields of energy conservation and solar energy production. Partly because of this urgency, research, experimentation, and use of energy efficient and renewable energy technology is very exciting and moving forward, though slowly. Important demonstration projects around the world offer stimulating work, opportunities to create new low-energy-consuming systems, challenges to develop and install many solar technologies, and the potential for contributing to the betterment of humankind.

It was just this motivation that led me to leave a promising career at NASA to pursue research in solar energy 27 years ago. My solar work *has* been stimulating and rewarding, in spite of a diminution of US federal and world-wide governmental and intergovernmental funding for solar research over the years, relative to the inflation adjusted levels of the 1970s. The expected expansion of research funding failed to materialize, and the field is not growing as rapidly as it should.

Perhaps for the same reasons, current use of solar energy technology is limited, compared with total energy use. As energy price increases result, sooner or later, from declining oil production, the use of both renewables and energy conservation can be expected to increase, perhaps enough to make up for declining oil production. Coal reserves could be used to extend our fossil energy future somewhat following the decline of oil, but switching "backwards" to coal—a less desirable source—will be difficult and may be unwise. We might try to expand our use of nuclear fission, but this also means a further growth of our nuclear waste disposal problems. Along with this comes increased susceptibility to nuclear terrorism, and to large, even catastrophic, accidents due to the aging stock of nuclear reactors that must be decommissioned. Nuclear energy is a false hope, narrowing our best choices to conservation and solar energy.

To The Future

Though energy conservation and solar energy are to many our great hope for the future, these technologies do have some limitations. As we seek to make solar energy and conservation popular, the number of people demanding more energy use is also increasing worldwide, exacerbating the problem. Developing countries generally seek to emulate the wasteful and profligate energy consumption ways of the industrial world. As an example, the United States consumes more energy per capita than any other nation on Earth. 1If current solar and conservation development efforts succeed, and if world population is allowed to continue increasing at its current 1.4% rate (with a doubling time of a mere 47 years), whatever gains we see through energy efficiency and renewable energy expansion threaten to be offset by increased demand for more energy worldwide. Energy demand increase results from a combination of population growth and growth in per capita energy use. In the developed world, both are growing relentlessly.

I was in Beijing's Tiananmen Square a few months before the June 1989 uprising there. My feelings were divided as I watched news reports of the event back home. On the one hand I was excited for my new Chinese friends that a more open or even democratic society might finally come to China. This was countered by a realization that this democratization likely would be followed by rapid economic expansion and material prosperity—along the lines of the energy-wasteful and polluting industrialized world. "What would happen," I asked myself, "if even twenty percent of China's 1 billion people suddenly purchased automobiles?" (see 'The Chinese Car Bomb'). In the 13 years since that event China has modernized, through accelerating its industrialization. So my fears of environmental threats are becoming real, in spite of some good efforts by the Chinese government to develop along a less polluting, less wasteful path.

The population of China is now around 1.3 billion. That of India is about 1.1 billion. Together they constitute over a third of the 6.3 billion world total. The rapid industrialization of these two countries will place a heavy burden on the world's ecosystem.

Just as we are trying to improve energy use efficiency and switch (slowly) to renewables, the demand for energy worldwide is growing, illustrated in Fig. 3 from the UK Atomic Energy Authority (Note that one gigatonne oil equivalent, or Gtoe, is equal to 41.868 EJ and 39.68 quadrillion Btus) and in Fig. 4 from the U.S. Department of Energy's Energy Information Administration. The first of these projects energy use patterns considerably into the future, so can only indicate wishful expectations.

Energy Transitions

There have been several energy transitions in the past. Previous transitions from wood to coal and then to petroleum and natural gas were fairly rapid and singular, as illustrated in Fig. 5. This curve was prepared around 1972, so the curves to the right of that year were based on projections of future energy use in the U.S. No other, previous form of fuel competed very well against each newly discovered one. Here are some reasons.

- New fuels were in most respects better than former. They were more concentrated, easier to store and transport.
- All alternatives to the new fuel were more expensive, therefore less economically viable.
- There was essentially universal agreement that the new fuel was better, so there was little dissension over the transition to it.
- With the exception of coal, the new fuel was generally cleaner.

Hydropower and geothermal, although clean, obviously cannot be transported, except as the end-product electricity, and their availability for new energy generation is geographically limited.

We are finding that the next energy transition, away from the fossil fuels, will be toward not just one marvelous new source but to *a variety of different ones*, all possessing only the fourth one of the above cited advantages. The new transition will be more difficult than the previous ones.

Direct Use of Solar Energy

Solar radiation has been proposed as the great new replacement for fossil fuels. Though relatively clean (except for some pollution during manufacture and disposal of the hardware), solar (and sky) radiation is more diffuse, a less concentrated resource than petroleum, and is also not easily or cost-effectively stored. To store it requires conversion to some other energy form, such as heat, electricity, or chemical energy. This is difficult, costly, and has inhibited the spread of solar technology; in some cases it even has serious environmental drawbacks.

In a partially "solarized" society, one can envision using our remaining, but declining non-renewable energy sources for storage—to fill in the times when solar is not available. In a more fully solarized economy, electricity generated with solar-derived stored energy could provide the backup, but then the problems of battery disposal loom large. Biogas and methanol from (solar powered) crops come to mind for storing solar energy. But obtaining energy from these sources is very land intensive, even more so than direct solar or wind.

Hydrogen gas is a much touted means of energy storage. It can be solar-produced, through solar powered electrolysis of water. It is clean burning and nontoxic. However, it is the lightest of the chemical elements and difficult and costly to store and concentrate in its elemental form. Research is in process to find ways of storing and releasing hydrogen chemically, avoiding the need for expensive, heavy, and potentially dangerous high-pressure storage tanks. If the problems can be overcome, our hopes for hydrogen as a portable fuel may be realized, but it will be neither easy nor inexpensive.

It is true that a copious quantity of energy arrives from the Sun each day. It falls all over the Earth, but to harvest it directly, in sizeable quantities, means that it will be diverted from alternate uses in nature. Massive use of solar energy will require alteration of vast areas of the land and water surfaces of the planet, changing biosphere systems in the process.

Solar radiation is not the "be all and end all" energy solution for the world. In addition to being dilute, solar conversion systems currently require fossil fuels to manufacture them. As Baron described it in 1981, "A major solar energy cost component is the cost of nonrenewable resources of oil, natural gas, coal, and nuclear energy consumed in producing and constructing the systems for solar heating and solar electric plants." [6]

Proper assessment of a proposed solar technology should include a determination of the system's net energy production. In 1978 Peter Knudson described this as follows: "Net energy analysis, in its broadest sense, attempts to compare the amount of usable energy output from a system with the total energy that the system draws from society."[7] I offer my own definition: it is the magnitude of the solar-energy-derived output minus the non-renewable energy drawn from the Earth needed to make and operate the solar energy system.

There are calculations showing that the net energy of solar collection and distribution systems in some cases is negative. Also, at the end of their useful lives they have to be dismantled and recycled (with additional expenditures of energy).[8]

If the net energy output of a solar technology is negative, logic leads to the question, "Why bother?" In such a case, wouldn't it be better to use the fossil energy directly rather than lock it up in an inadequately producing solar energy system?

This is a controversial topic. Even if the calculations are correct for some situations, there can be value in storing present day (less expensive) fossil energy in solar collection devices, as a hedge against future depletion. Continuing with this argument, since we are going to use up fossil fuels anyway, why not invest that energy in the manufacture of renewable energy systems, so they can go on producing power when the fossil fuels are depleted? Ultimately we would like to remove the nonrenewable energy inputs from the manufacture of solar energy systems altogether.

This leads to the idea of a solar “breeding” system—using solar energy in the mining and processing of ore and the manufacture of solar energy systems, thereby reducing or eliminating the fossil fuel subsidy. Solar energy systems produced by such a system will be strong net energy gainers. For such a strategy to be successful, the solar-powered mining and manufacturing industry must be completed before the fossil fuel sources are gone (or before they become exorbitantly expensive). This might enable the establishment of a society based solely on solar energy, using solar energy alone to recycle worn out solar systems. Ultimately we might even be able to develop a completely sustainable process not requiring the extraction of further minerals or fossil fuels from the Earth to keep it going, as long as requirements for ‘fresh’ inputs are continually reduced. Of course a fundamental presumption of such proposals is that Earth’s human population is reduced to a sustainable level, one supportable by totally renewable energy systems alone.

Solar Pollution

The issue is not just about the non-renewable energy subsidy required to make and operate solar energy systems. The degree of environmental destruction associated with an energy consuming or producing system of any kind is also critical. As Baron pointed out in 1981, “Even more serious would be the impact upon public health and occupational safety if solar energy generates its own pollution when mining large quantities of energy resources and mineral ores.”[6] Some solar energy manufacturing processes produce toxic or otherwise undesirable waste products which have to be recycled, discarded, or otherwise rendered benign. Clearly, we’ll have to pick and choose amongst the solar alternatives to find the least environmentally impacting ones, and work hard to improve all the rest.

Solar Limits

There are physical limits to the production of energy from direct solar radiation. In the absurd limit, we clearly could not cover all available land area with solar collectors. A more reasonable limit would be to fill existing and future rooftops with solar collectors. From data provided by the U.S. Energy Information Administration, I estimated the total combined commercial and residential building roof area in the United States in the year 2000 at 18 billion square meters. From a National Renewable Energy Laboratory web site, I found that the approximate annual average quantity of solar energy falling on a square meter of land area in the United States is about 4.5 kWh of energy per square meter of area per day. Multiplying this by 365 days in a year and by the 18 billion square meter roof area figure, yields the total energy received by rooftop solar systems in this scenario: 2.46×10^{13} kWh per year, or 84 Quads per year. This is just a bit below the 102 Quads per year U.S. primary energy consumption figure.

Not all roof area is usable, however. Roofs sloped away from the sun’s strongest radiation, shaded by trees and other buildings, having interfering equipment, or insufficiently strong to support solar equipment, are either not practical or not possible for this utilization.

The conversion from primary to end use energy is not perfectly efficient in either the renewable or the nonrenewable cases. Both the 102 and the 84 Quads of primary energy must therefore be reduced when converting them to actual end use energy. It is difficult to determine accurate average conversion efficiencies for all technologies in both categories, but they are not likely to be widely different. Thus the conclusion should remain valid that meeting total U.S. energy needs with 100% direct solar energy would require about *every single square foot* of roof area, of all commercial and residential buildings in the country.

Since most of the current roofs were neither designed nor built to carry the loads of (and wind loading on) solar collectors filling them, nor are they all exposed adequately to the sun, it is very unlikely that the U.S. could achieve the goal of a 100% solar economy in this manner. For every acre of existing roof tops which cannot be filled with solar collectors, an equivalent acre would have to be found elsewhere. And renewable energy from other sources would be needed. If U.S. population continues to grow, pressure will continue mounting to expand developed land areas into what are currently agricultural and wilderness areas. If the plan is to convert as much as possible of the U.S. energy economy to direct solar energy, solar collector farms will join in the competition for new lands to be opened up for this development.

In order not to have to convert agricultural or natural habitat areas to areas for engineered solar production, one would have to find other, already developed areas for erecting these solar collectors, such as street and highway corridors and parking lots. While the shaded areas might be attractive to persons having to drive and park in the hot sun, it is probably not economically feasible under current financing conditions. A number of other objections to this possibility can be expected, leading to pressure to convert agricultural and wilderness areas to solar production 'farms'.

What About the Deserts?

Solar's need for large land areas is a serious problem, if you wish to power the world with it. We have learned from other experiences about the adverse environmental and social impacts of growth and land development. Solar energy is unlikely to be completely exempt from all these impacts. A common reaction to the problem of needing areas for large solar energy collection systems in forests, on farms, or in developed areas is to point out the vast "unused" desert areas around the globe, suggesting that these would be good places for solar collectors. Surely some desert areas can be used for renewable energy technology, but there are limits. Deserts are not devoid of wildlife; they contain varieties of flora and fauna, adapted over millions of years to desert conditions. There is a limit to how much desert we can or even want to cover with solar collectors.

Indirect Solar — Renewable Energy Technologies

In addition to the solar energy which can be collected directly there are several indirect sources of this important resource. They include the *wind*, powered by differential heating of the Earth's surface, *ocean currents* (produced by a similar mechanism), *hydroelectric*, powered by solar-powered water evaporation and condensation into rivers, *tidal currents*, *ocean thermal energy conversion* (based on solar heated surface layers of the tropical oceans), and ocean *waves*, driven by the wind and carrying energy with them as they approach the shoreline.

Waves and thermal-driven currents offer a degree of natural solar concentration. Tidal currents are also concentrated in some locations. Solar-derived wind, pushing the sea over large distances, increases wave heights and their energy content. This energy can be extracted downwind, where the waves are most intense. Thermal currents can be focused between land masses, thereby concentrating the speed and energy content of the moving fluid. *Geothermal* is another possible source of energy. It uses the heat from deep below the Earth's surface to produce electricity. Let's take a look at each of these renewable technologies.

Wind power has now become economically viable for areas experiencing adequate average wind speeds. Wind turbines are being erected on the land in many locations around the world. Due to the difficulty of finding onshore sites and other factors, they are increasingly being sited offshore as well. The February 2002 issue of *Renewable Energy World* describes an example.

> Offshore wind farms promise to become an important source of energy in the near future; it is expected that within 10 years, wind parks with a total capacity of thousands of megawatts will be installed in European seas – the equivalent of several large, traditional coal-fired or nuclear power stations. Plans are currently advancing for such wind parks in Swedish, Danish, German, Dutch, Belgian, British, and Irish waters. Outside Europe there is serious interest in such developments on the US East Coast, and in Australia the resource off the Tasmanian coast seems to be attracting attention, also.[9]

Many wind proponents claim that wind farms on land can co-habitate with agriculture and that leasing such land can be a valuable source of income for the farmer. A substantial number of wind turbines have been installed in windy desert areas, and more are expected. Wind is generally variable in its speed, however, so it is not the most suitable source for what is called "baseload" electricity generation, that nonvarying core power component that forms the backbone of electric utility operations.

Ocean currents, such as the Florida Current, the part of the Gulf Stream flowing northward past the Florida peninsula, carry enormous quantities of kinetic energy in their motion. There have been several proposals to develop this resource, to place ocean turbines in the strongest currents and feed the energy generated to population centers onshore. According to Practical Ocean Energy Systems Management, Inc., "The first large ocean-system proposal is for a 2.4-mile system that would link Samar and Dalupiri islands in the Philippines. The Dalupiri project is now estimated to cost $2.8 billion, produce 2,200 megaWatts (MW) at tidal peak, and offset 6.5 million tons of carbon dioxide a year.[10]

A number of years ago I made a "back of the envelope" type calculation of the available energy in the Florida Current, that portion of the Gulf Stream flowing through the Florida Straits. The kinetic energy transported through a cross sectional area by a fluid of known mass density is the product of its kinetic energy per unit mass of moving fluid and the mass flow rate through that cross-sectional area. The energy flow rate, per unit area, is proportional to the *cube* of the current speed. All the kinetic energy contained in the flowing water cannot be usefully extracted or the flow would cease. It should be possible to extract enough energy to slow the stream by about 50% or so. In this case, approximately 88% of the available kinetic energy would be extracted.

I estimated the electrical generation potential of the Florida Current, between Miami and the Bahama Islands. The Gulf Stream flows northward through the straits at a speed ranging from two knots at the edges to over four knots in the middle of a 20 nautical mile (37 kms) width off Miami. This yields an approximate average kinetic energy per unit cross-sectional area transported by this current on the order of 2000 W m^{-2}. If we assume an 88% conversion efficiency (slowing the current by a factor of two in velocity) and that we extract this energy from the surface down to a depth of 10 meters over the 37 Km width of the current (370,000 m^2), then the total electrical power output for a 100% efficient electricity generator would be on the order of 0.88 x 2000 x 370,000 = 651 MW. If we choose a 30 meter depth, the power generation would be three times larger, or 1.9 GW, a large electrical generation capacity.

According to Practical Ocean Energy Management Systems, Inc.[10], ocean currents are one of the largest untapped renewable energy resource on the planet. Preliminary surveys show a global potential of over 450 GW, representing a market of more than US$550 billion.

The *Proceedings of the MacArthur Workshop on the Feasibility of Extracting Useable Energy from the Florida Current* [11] can be consulted for more information about the resource potential of the Gulf Stream. The U.S. Department of Energy in 1979 funded a study of the Florida Current energy potential that used a much larger cross-sectional area across the Straits of Florida, involving 132 turbines with duct exit areas of 22,900 m^2, for a total cross-sectional area exceeding 3 million square metres, and having a maximum rated electrical output of 10,000 MW from the 2.3 metre/second current. The study estimated that in the presence of variations of current strength, the total effective power output would range from 2,000 to 6,000 MW, equal to the output of several large conventional power stations. It is doubtful, however, that the economic value of the electricity that might be generated, though large, would be sufficient to offset the huge costs of construction, including anchoring underwater structures in strong current in deep water, and dealing with whatever environmental consequences might be produced (including potential impacts from diverting the current's warm water away from NW Europe with unpredictable climatic effects).

Tidal Energy can be extracted by placing turbines or other current energy extractors in or across the mouths of estuaries experiencing large tidal excursions. Energy in the flow of ocean water in and out of the estuary can be extracted and turned into electricity. A working power plant of this type is located in France. It produces 240 MW of power via a "barrage" across the estuary of the river Rance, near Saint Malo in Brittany. The plant went on-line in 1966 and supplies about 90 percent of Brittany's electricity. This is a fairly unique installation. It is doubtful that it could be duplicated at reasonable cost many places around the world.

For tidal differences to be harnessed into electricity, the difference between high and low tides should be at least five meters, or more than 16 feet. There are only about 40 sites on the planet with tidal ranges of this magnitude.

Tides of less magnitude, however, could be used to produce usable power. Turbines placed under the water, grounded on the bottom, could allow shipping to pass overhead while still generating power. Currently, there are no operational tidal turbine farms of this type. But European Union officials have identified 106 sites in Europe as suitable locations for such farms. The Philippines, Indonesia, China, and Japan also have underwater turbine farm sites that might be developed in the future. The costs of such massive undersea structures are likely to be high. It is a real question whether future increases in petroleum costs will justify extensive exploitation of the tidal resource.

Ocean Thermal Energy is another potential source. The sun heats the surface waters of the tropical oceans, making them considerably warmer than water at great depths. It is possible to run a heat engine between these two thermal regions. A working fluid, such as ammonia, placed in a partial vacuum, is evaporated by heat taken from the warm surface water, the evaporated gas expands against a large turbine, making it spin to produce electricity. The gas is condensed after passing through the turbine by cooling it with deep ocean water. Since the temperature difference between the two heat reservoirs is modest, in comparison with a fossil fuel steam power plant, the efficiency of conversion to electricity is quite low. On the other hand, the "fuel" (solar heated water) is free for the taking, so that such a plant should eventually pay for itself over time. So far no commercial OTEC plant has been built, mainly for reasons of too long payback times. As energy prices increase, payback times shorten, generally leading to the opening of new markets.

Ocean waves carry a large amount of energy. According to the U.S. Department of Energy, the total power of waves breaking on the world's coastlines is estimated at 2 to 3 billion kiloWatts (2-3 TW). In favorable locations, wave energy density can average 65 MW per mile of coastline.[12] Of course, due to environmental problems, land use conflicts, hazards to navagation, and other reasons, only a small fraction of this power can be extracted for human use. Wave power devices extract energy directly from surface waves or from pressure fluctuations below the surface.

Wave power can't be harnessed everywhere. Wave-power rich areas of the world include the western coasts of Scotland, northern Canada, southern Africa, Australia, and the northeastern and northwestern coasts of the United States. Wave energy utilization devices have been built and operated in a number of locations around the world. Several European countries have programs to deploy wave energy devices.

Hydroelectric power generation is used extensively around the world. United States hydropower facilities can generate enough power to supply 28 million households with electricity, the equivalent of nearly 500 million barrels of oil per year. The total U.S. hydropower capacity—including pumped storage facilities—is about 95 gigawatts. There are probably a number of sites around the world where rivers can be dammed and hydropower developed, but the environmental impacts can be huge. Thus, the potential for energy from this source is limited.

Geothermal energy comes from the interior heat of the Earth. A fluid is heated below the surface, brought up, and used to generate electrical power. There are many ways this can be accomplished, and geothermal energy is already supplying power in many countries around the world. The Inventory of accessible geothermal energy is sizable. According to the Geothermal Education Office[13], "using current technology geothermal energy from already-identified reservoirs can contribute as much as 10% of the United States energy supply. And with more exploration, the inventory can become larger. The entire world resource base of geothermal energy has been calculated in government surveys to be larger than the resource bases of coal, oil, gas and uranium combined. The geothermal resource base becomes more available as methods and technologies for accessing it are improved through research and experience." It is possible to access geothermal energy anywhere on Earth, but in most places it lies very deep. In special geological areas, however, it is closer to the surface and more economically available.

If we combine the energy production potentials for all the sources mentioned above, we could supply all the world's energy needs, probably several times over. There are limits, however, discussed in the next section. For more information on renewable energy developments around the world, a good source is the periodical *Renewable Energy World*, published by James & James, Ltd., 8-12 Camden High Street, London, NW1 0JH, UK.

Problems with Renewables

Though promising, renewable energy sources are not unlimited, nor without their environmental impacts. At the current minuscule level of renewable energy generation, what little environmental consequences might result from renewable systems is pretty much a drop in the bucket compared with those of fossil fuels. However, as fossil fuels switch roles with renewables, the relatively minor impacts experienced now can grow to a substantial size.

MTI describes some of the problems with renewables:

> Despite their benefits, renewables present important issues that need to be addressed. The main constraints on their use are the costs of the energy they produce and the local environmental impacts of renewable energy schemes. Currently, the cost of energy from renewables is generally higher than that produced by "conventional" energy sources. However, as renewables become more established and the benefits of mass production take effect, the gap will reduce. Indeed, in the case of wind power and some other technologies, this is already happening.[14]

As energy prices rise with the decline of oil, the cost effectiveness of the renewable options should increase. The *impacts* of renewable energy technologies, I believe, can only increase. These impacts are many and varied. A short list follows.

Wind turbines have been shown to be hazardous to birds in some locations. Though the problems are relatively minor at present, if the landscape is covered with these large devices, more problems can be expected. The few wind farms presently in operation are something of a curiosity and generally well tolerated by most local residents. If the areas covered by them increase a hundred-fold, however, opposition on visual and amenity grounds can be expected to increase. Some of the turbines are noisy. This can be minimized with better technology, but noise pollution is likely to remain as an impact for local human settlements.

Offshore wind turbines have some advantages, mainly through being distant from populations served by them. "Out of sight" means "out of mind," unless serious problems develop. The hazards due to offshore wind 'farms' include dangers for navigation and disturbance of local marine fauna. Often when human structures are placed near the coastline, they are heralded as "artificial reefs" capable of increasing populations of a variety of marine species, generally considered a good thing, but a possible problem when huge areas are concerned.

Undersea current energy extractors have much potential in regions where conditions are right. They do, however, slow (and possibly redirect) the currents from which the energy is extracted, with possibly adverse consequences for marine life and for human shorelines, if the changes lead to significant alteration of geologic features and habitats. For example, if a sufficient number of current energy extractors were placed across the Straits of Florida, the Gulf Stream's surface waters will be slowed by some amount, possibly altering the flow of this warm current, which is partly responsible for moderating the winter climate of Northern Europe. Though some undersea turbines have been designed to turn at relatively slow speeds, slow enough for marine animals to easily avoid collision, extensive experiments to validate this claim have not been completed.

The environmental consequences of slowing the Gulf Stream by a significant fraction, even if only at the surface, and the enormous cost which would be inherent in such an effort would clearly not be justified by the relatively small part of Florida's future electrical energy use that could be supplied from this source. (Florida is growing at a rate of 2.35% annually, corresponding to a doubling time of thirty years. That is a faster rate of growth than Haiti at 1.73%, India at 1.8% and Mexico at 1.95%.)

Extraction of energy from other ocean currents may be more feasible, but the potential environmental impacts could be very large. The resource is so huge, however, that limited use of ocean currents will probably become desirable, as we search for alternatives to the fossil fuels.

Tidal Energy also has a large potential, but is restricted to the estuarine areas experiencing significant tidal swings. Tidal power plants that dam estuaries can impede sea life migration, and silt build-ups behind such facilities can impact local ecosystems adversely. Tidal "fences" may also disturb sea life migration. Newly developed tidal turbines may prove ultimately to be the least environmentally damaging of the tidal power technologies because they don't block migratory paths, however the future economic feasibility of these huge underwater structures, anchored to the bottom, has not yet been proven.

Ocean wave energy has a very large energy potential, but also many environmental and technological hurdles to overcome. Impacts include:

- Hydrological effects of structures could alter the shoreline and adversely affect shallow areas, and the plant and animals life in these areas.
- There are potential navigation hazards. This might be mitigated with proper signaling devices, such as reflective paint, radar reflectors, and sound sources, but this hazard would remain.
- Some devices can be very noisy. The potential for damage to marine mammals is relatively unknown, but many species utilize sound waves for a variety of communication purposes. For humans, this problem is likely to be little more than an annoyance.
- When located on or close to shore, significant visual effects are likely.
- Some recreational uses of affected areas can be impacted, in some cases significantly.
- The installation of ocean wave energy conversion devices, and the laying of electrical cables will damage and affect species on the sea bed and in the water column.
- Marine mammals will also be affected in several ways during the installation, and possible in the operation of devices.

The environmental consequences of extracting substantial fractions of the wave energy incident upon a shoreline can be very significant. The natural processes involved in beach erosion and replenishment are many and complex. The placement of a wave machine directly in or just offshore from the surf zone of a beach could have drastic consequences on beach formation dynamics, habitat destruction, and recreational use. Offshore sites may not have the same impacts, but if the wave regime approaching a coast is altered significantly, there could still be serious affects. Wave energy system planners will need to choose sites that preserve scenic shorefronts and avoid areas where wave energy systems are likely to significantly alter sediment flow patterns on the ocean floor and littoral drift along the shoreline.

Hydroelectric power has a number of potential environmental impacts. In addition to the flooding of valleys and destruction of upland habitat, hydropower technology can have additional environmental effects, such as fish injury and mortality from passage through turbines, as well as detrimental effects on the quality of downstream water. A variety of mitigation techniques are now being used to address these environmental issues, and environmentally friendly turbines are under development. The flooding of large areas of land, however, constitutes a conversion of that land from its current use to an aquatic ecosystem. This has obvious societal impacts, and serious ecological ones as well.

Geothermal energy seems a relatively clean option, however there are some environmental and social impacts. According to the Geothermal Education Office[13], "hydrogen sulphide gas (H_2S) sometimes occurs in geothermal reservoirs. H_2S has a distinctive rotten egg smell that can be detected by the most sensitive sensors (our noses) at very low concentrations (a few parts per billion). It is subject to regulatory controls for worker safety because it can be toxic at high concentrations. Equipment for scrubbing H_2S from geothermal steam removes 99% of this gas."

"Carbon dioxide occurs naturally in geothermal steam but geothermal plants release amounts less than 4% of that released by fossil fuel plants. And there are no emissions at all when closed-cycle (binary) technology is used. Geothermal water contains higher concentrations of dissolved minerals than water from cold groundwater aquifers. In geothermal wells, pipe or casing (usually several layers) is cemented into the ground to prevent the mixing of geothermal water with other groundwater."

"No power plant or drill rig is as lovely as a natural landscape, so smaller is better. A geothermal plant sits right on top of its fuel source: no additional land is needed such as for mining coal or for transporting oil or gas. When geothermal power plants and drill rigs are located in scenic areas, mitigation measures are implemented to reduce intrusion on the visual landscape. Some geothermal power plants use special air cooling technology which eliminates even the plumes of water vapor from cooling towers and reduces a plant profile to as little as 24 feet in height."

This brief review shows that despite the attractive energy potentials of the world's wind, waves, ocean currents, tidal currents, and geothermal sources, extracting significant portions of this energy presents environmental, economic, and social problems. Fortunately most are relatively easy to overcome when the power plants are small or widely separated. Modest use of these renewable technologies may be easily tolerated. However, considering the growth in world population and rising expectations for plentiful energy, the future demand will put great pressure on developers to capture as much of each resource as possible, perhaps with terrible environmental consequences. A judicious use of all the profiled renewable energy sources should be able to meet the energy needs of a smaller world population with minimal environmental impact, thereby making the goal of a fully sustainable society realizable.

Conservation Limitations

Energy conservation is another important strategy, almost like having a new source of energy, because energy freed up from one use is available for other uses. There are a number of technologies for conserving energy, including such things as compact fluorescent light bulbs and energy-efficient buildings (and their efficient heating, refrigerating, and cooling equipment, as well as more energy-efficient appliances). The potential for energy savings through technologically-based conservation methods is deemed huge by thoughtful analysts. Improved energy efficiency in transportation systems is also possible, but not without massive redesign of transport vehicles and systems.

Under any hypothesis, efficiency must be a component of any strategy for meeting future energy needs. With the exceptions of ocean waves and ocean currents, solar energy in all its forms is a relatively dilute form of energy. The equipment needed to collect it and convert it to a more useful form is generally expensive and burdened with serious environmental impacts when utilized on a large scale.

Energy conservation is a very important adjunct of any solar energy conversion technology. Reducing one's energy needs reduces the size of solar system needed, and hence its cost and environmental impacts, making solar a more socially and economically viable option. When you reduce energy consumption considerably, with radical energy efficient design and construction, capital costs for that solar energy system will be reduced as well.

The problem is that efficiency by itself is just a multiplier. As pointed out by my colleague, Paul Jindra, no matter how "efficient" our energy-consuming processes are, and in complete compliance with the first and second laws of thermodynamics, a finite Earth still gets consumed. With continued growth of population and affluence, and with overall consumption out-stripping energy conservation, our energy and environmental crises are sure to remain with us a long time.

Conclusions

It is clear that attempts to solarize the world economy are fated to run into serious obstacles, unless population and per capita energy consumption are drastically reduced. A major commitment to solar energy is likely to transform landscapes and seashores, bringing forth many new environmental problems, while demanding very large capital spending.

Renewable energy cannot be considered a complete panacea for all our energy problems. There is a fallacy in believing that energy conservation and solar energy alone can save our energy future. Stuart Gleman once said that "solar provides just enough," but not enough that we can be wasteful with it.[15]

With a reduced population per capita demand, energy conservation and solar energy should be sufficient to support a sustainable and sizeable human population. Further, conservation and solar are needed now to conserve the valuable complex molecules of fossil resources for more durable and more important uses later. Every country in the world should be funding research and demonstration projects, and promoting solar and conservation vigorously.

Unfortunately, however, most are not. A reason is that many renewable energy technologies are perceived as not economically competitive with fossil fuels. In some cases this is true, but renewables have proven their worth. In many cases they are already a cheaper source of energy than certain fossil fuels.

Economic analysis and financial costing remains tilted against renewable energy– the playing field is far from level. Renewables are still held back. Government subsidies to the fossil fuel industry are not matched for renewables. Existing electricity systems and laws often make it extremely difficult for renewables to gain fair access to national markets. Fossil and nuclear power in the EU are publicly subsidized to the tune of 15 billion Euro per year. In addition, the European taxpayer picks up the environmental and human health bill for acid rain, for NO_X emissions, for particulates, and for the 'natural' disasters caused by climate change, itself triggered by fossil fuel burning.

Perhaps the most serious problem is that current "free" market practices offer no mechanisms for including non-monetary benefits, along with the energy savings of a given technology. Such "green" technologies are therefore undervalued in the market and underutilized in consequence.

Despite these obstacles, the market for renewables is growing. The jobs, income, and energy security that will result from building market dominance for renewables are undisputed. The only question is how fast it will happen.

If world population and per capita use of energy continue growing at current rates or higher, our demand for energy is likely to grow faster than our ability to supply it from renewable sources. Also, as supplies of non-renewable sources dwindle it will become increasingly expensive to supplement solar or back it up with non-renewables. This reminds us of Bartlett's Second Law of Sustainability: "In a society with a growing population and/or growing rates of consumption of resources, the larger the population, and/or the larger the rates of consumption of resources, the more difficult it will be to transform the society to the condition of sustainability."[16]

It seems inescapable that the industrial nations of the world, as well as those working to industrialize (mainly along the western model), must implement policies to stop population growth, reduce per capita energy demand, conserve valuable fossil resources for more durable uses, and aggressively promote the use of renewable energy while working hard to reduce environmental impacts. There indeed are limits to growth, and the human species is now approaching them (or has exceeded them according to some observers). In order to achieve the goal of a sustainable global human society, considerable education, discussion, and rethinking of priorities will be needed. Let us begin.

Figure Captions

1. Exponential growth of world population.
2. Illustration of the link between food production and fossil fuel subsidy in the U.S. Abundant food makes the large human population possible. Food is abundant largely because inexpensive fossil fuels are abundant. After Steinhart and Steinhart.[4]
3. Long term growth of world energy use. Source: UK Atomic Energy Authority. http://www.ukaea.org.uk/

4. World Energy Consumption by Region, Report DOE/EIA-0484(2002), March 26, 2002, U.S. Department of Energy/Energy Information Administration.
5. U. S. Energy Transitions. Source unknown.

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Key words for indexing

Energy
Environment
Renewable energy
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Air pollution
Water pollution
Fossil fuel depletion
Public policy
Solar energy
Population
Population growth, expansion
Industrial revolution
Population growth
Dieoffs
Fossil fuel subsidy

Irrigation
Urbanization
Agricultural productivity
Famine and poverty
Food and Agriculture Organization
Hunger and malnutrition
Cropland
Food energy
Terrorism
Resource wars
Peak Oil
China
India
Energy transitions
Hydrogen
Net energy
Solar breeder
Solar limits
Solar deserts
Wind
Ocean currents
Hydroelectric
Tidal currents
Ocean thermal energy conversion
Ocean waves
Geothermal
Marine mammals
Energy efficiency
Sustainability

Figures

Figure 1.

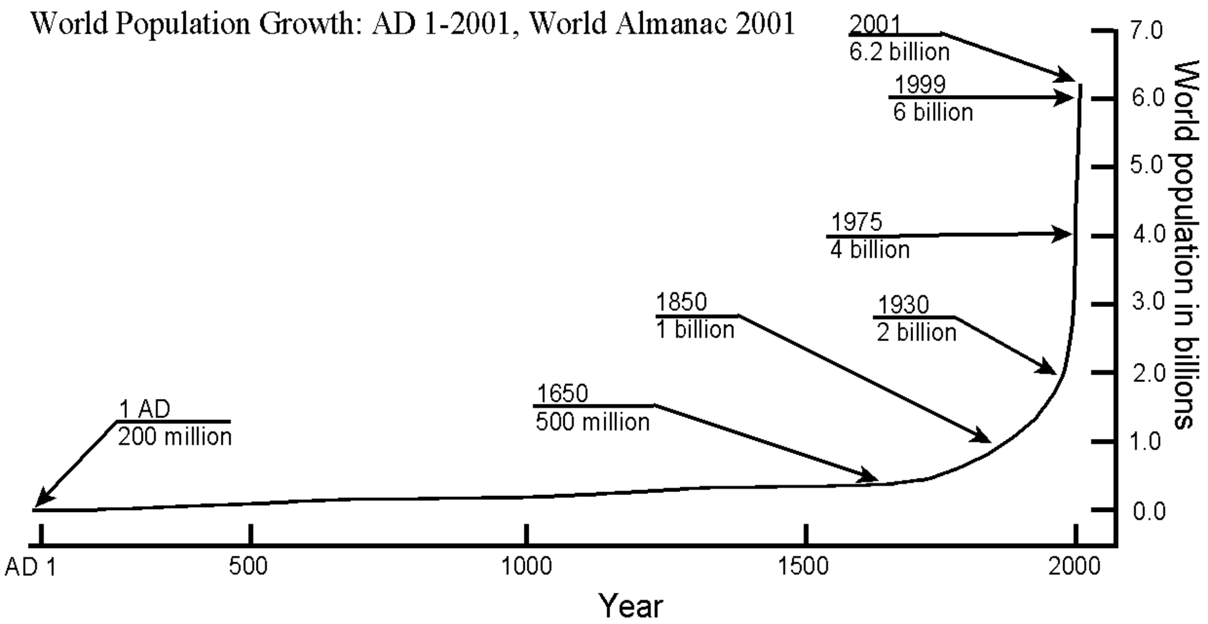

Figure 2.

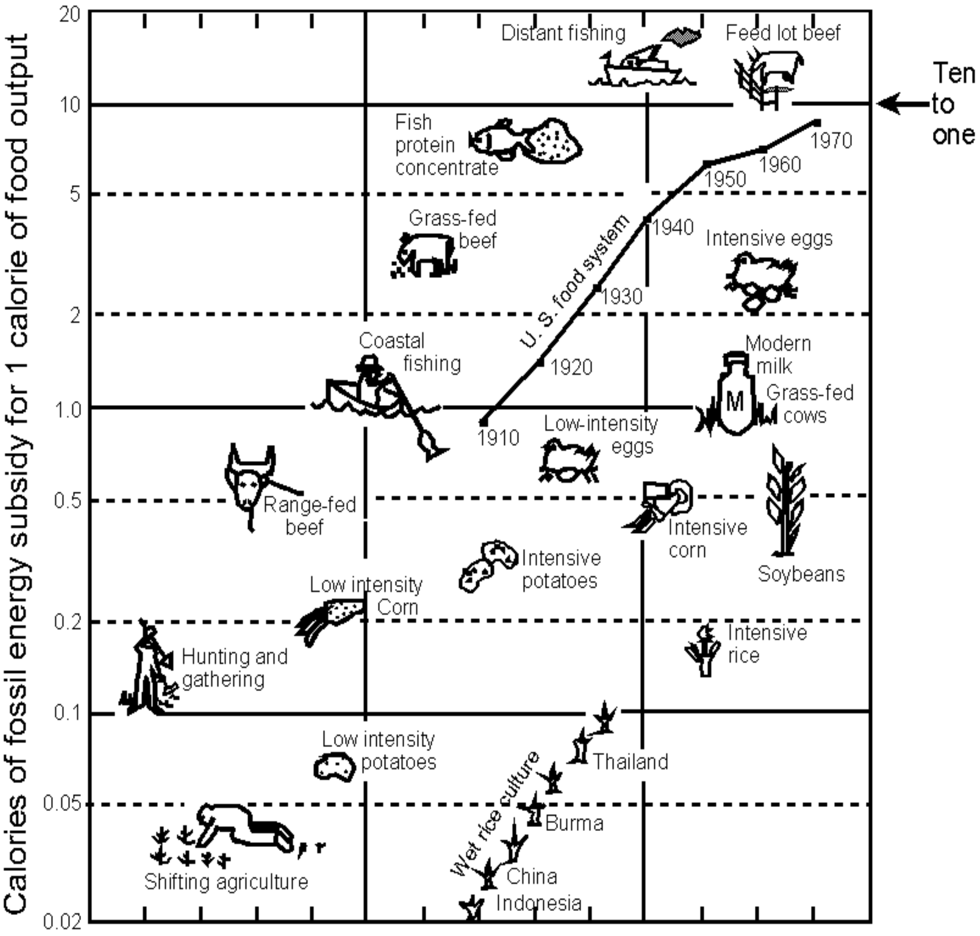

Figure 3.

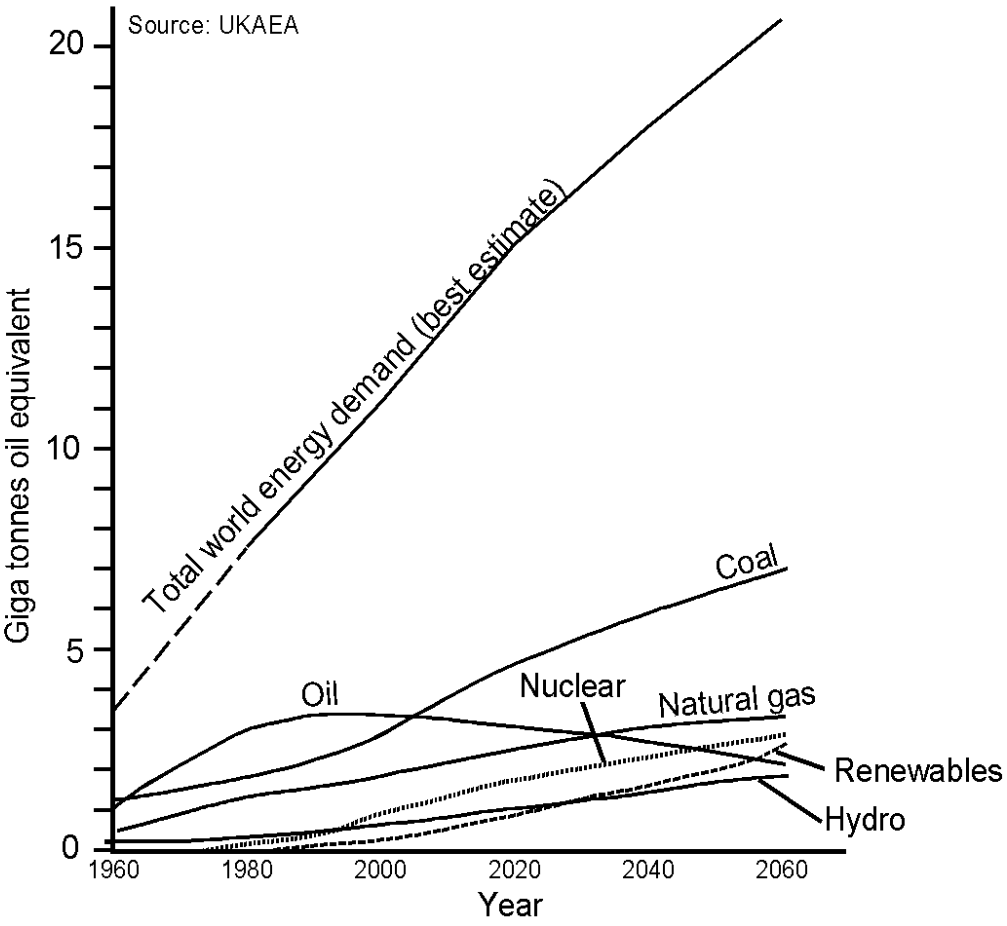
Source: UKAEA
Giga tonnes oil equivalent
0
5
10
15
20
1960
1980
2000
2020
2040
2060
Year
Total world energy demand (best estimate)
Coal
Oil
Nuclear
Natural gas
Renewables
Hydro

Figure 4.

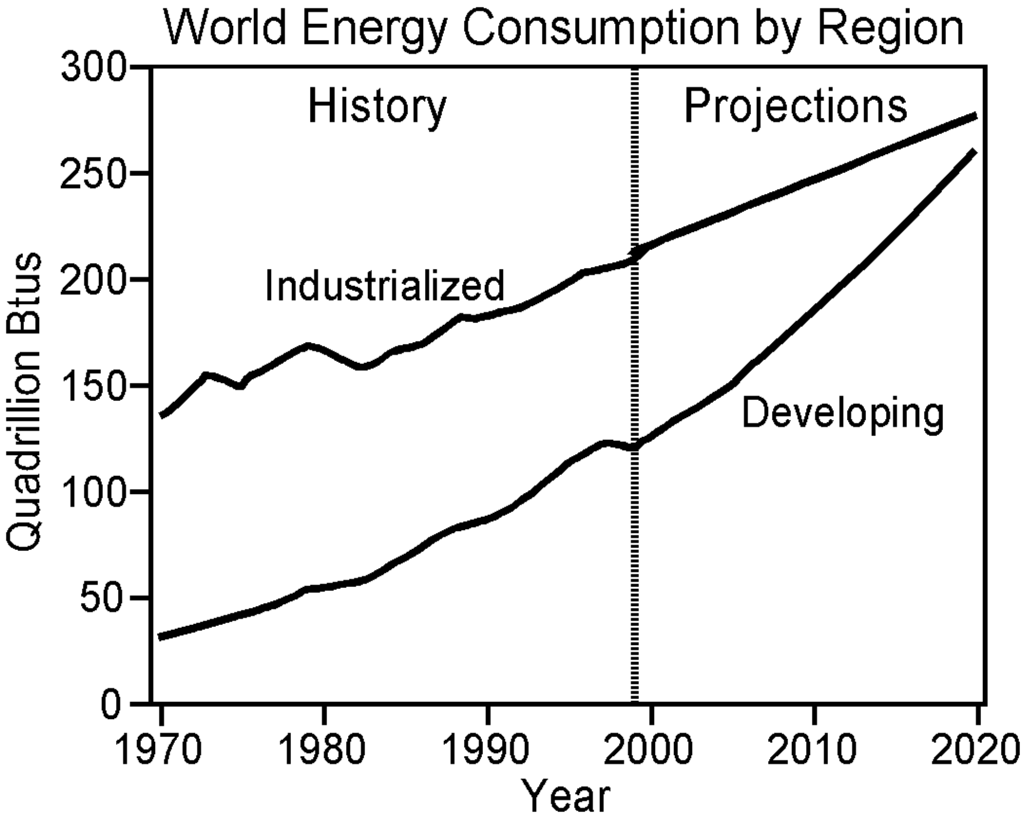
World Energy Consumption by Region
History
Projections
Industrialized
Developing
Quadrillion Btus
0
50
100
150
200
250
300
1970
1980
1990
2000
2010
2020
Year

Figure 5.

U. S. Energy Sources