Global Change and the Energy Crisis

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ABSTRACT

We discuss the pros and cons of biofuels, photovoltaics, wind, ocean currents, ocean waves, geothermal heat, tides, hydroelectric generation, nuclear fusion, and nuclear fission as alternative energy sources to fossil fuels. Photovoltaics hold promise as a long-term resource if costs can be driven down enough so that their installation on a large scale does not eat up half of worldwide GDP. However, reliability as the base load dictates nuclear power to be the only viable, carbon-friendly, choice possible for Taiwan. Only an aggressive expansion of nuclear power plants can meet, and even exceed, the G8 goal of halving the human emission of CO_2 by 2050. A switch from a plutonium to a thorium economy can address legitimate concerns about the cost, safety, waste, and potential for weapons proliferation of nuclear power. A coherent energy strategy exists that can appeal to both developed and developing nations, but nuclear activists and environmentalists need to work together to achieve a safer and healthier world.

The Grand Challenge of the 21st Century

Figure 1 presents a map of the whole world that shades different regions in the amount of their per capita usage of energy. This map shows a clear correlation between wealth and energy consumption. Fabled in their wealth, North America and the Middle East are also leaders in their consumption of energy, largely in the form of burning fossil fuels. Taiwan's consumption per capita is comparable to many countries in Europe. However, Taiwan does not have the standard of living of Europe because its usage of energy is less efficient. There are also vast regions of the world where the per capita consumption of energy is quite low. However, the situation is changing rapidly in developing, populous nations such as China and India. This development exacerbates the Grand Challenge of the 21st Century, which is global warming and the energy crisis.

World population will likely increase to 9 billion in 2050. If the average per capita usage of energy were one-half of the United States (11 kW in 2008), i.e., living standards comparable to that of Taiwan today, then the required worldwide power would be 50 TW

Figure 1. Per Capita Energy Consumption in 2007 (Tonnes of Oil Equivalents)

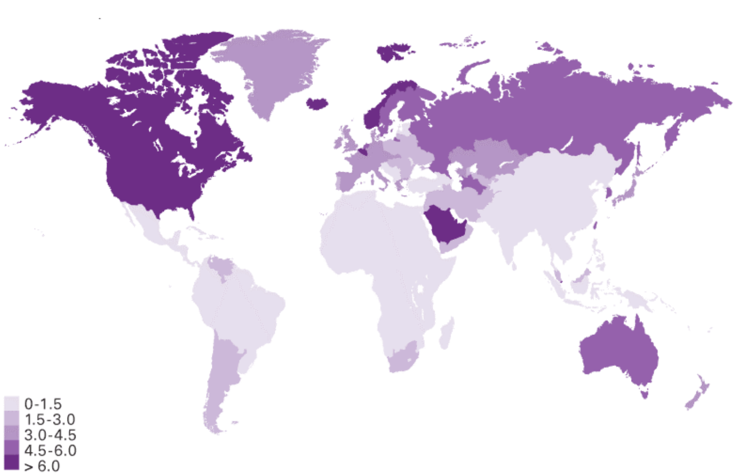
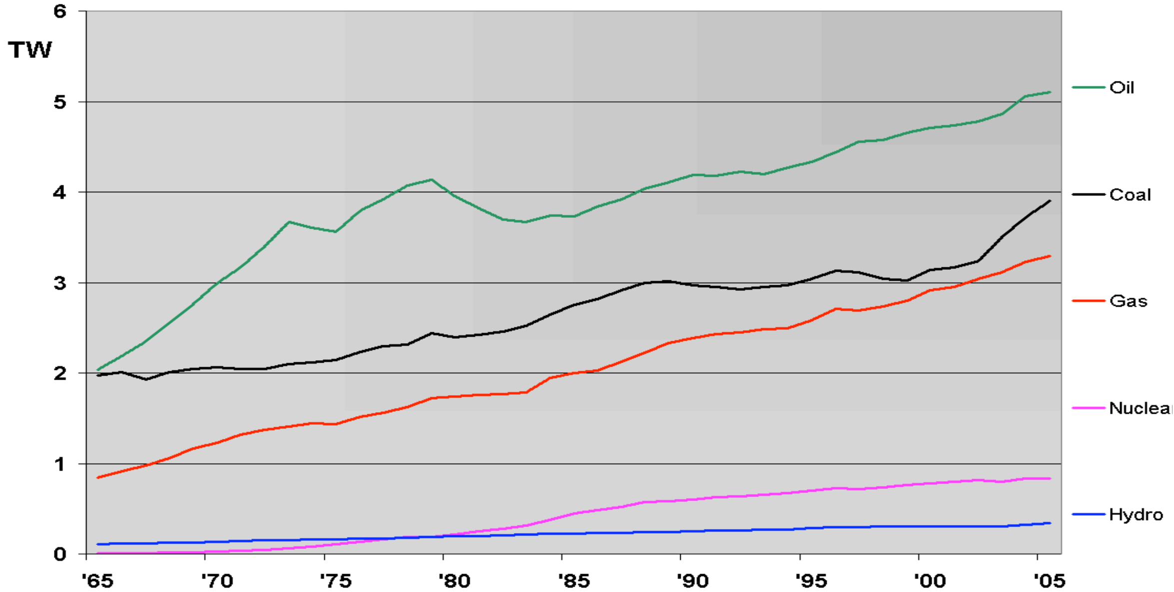


Figure 2. Worldwide Mix of Power Generation from 1965 to 2005



(1 TW = 10^{12} watt). Figure 2 shows the mix of primary resources used to generate this power in the four decades between 1965 and 2005. At present, hydroelectric plus nuclear accounts for about 1 TW; natural gas, coal, and oil supply the rest of the 15 TW used in 2008. Of all forms of power consumption, the steepest rising is coal, which is the absolute worst thing to burn in terms of CO_2 emission.

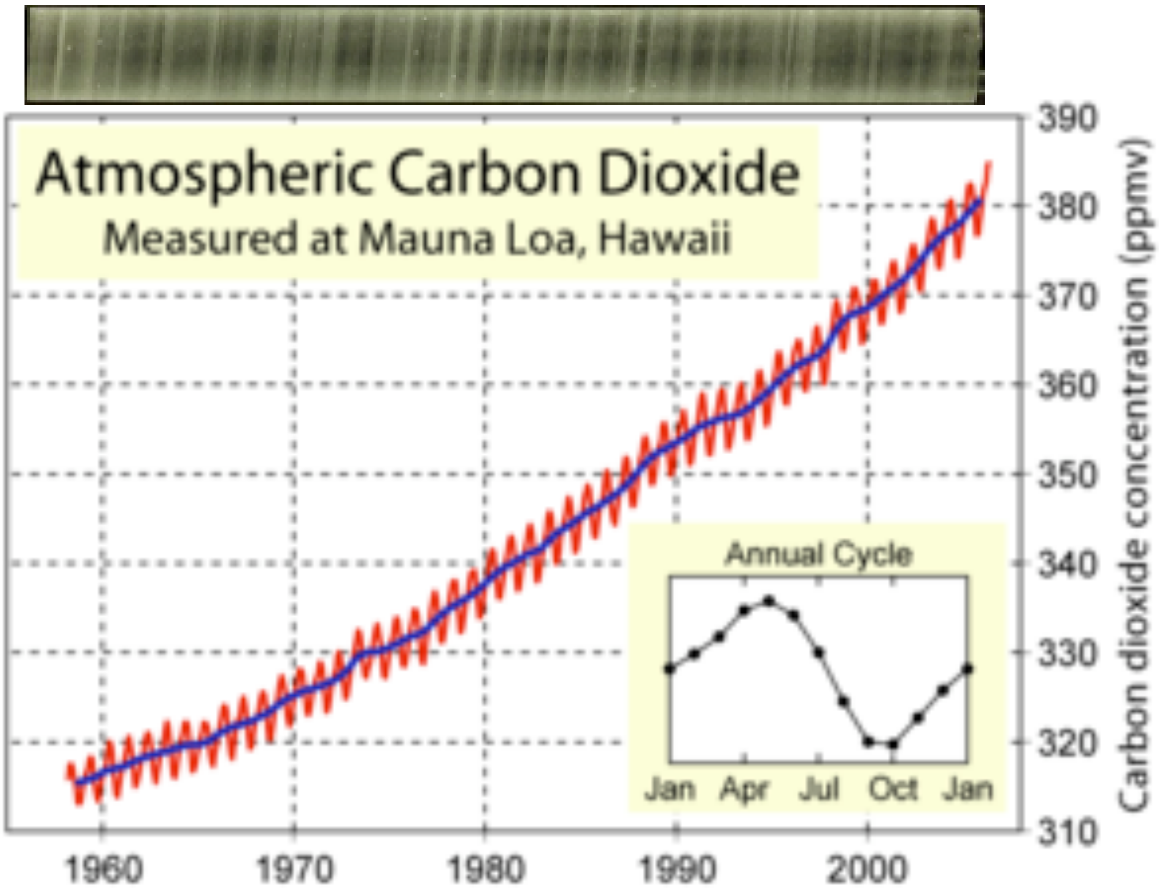
Figure 3 shows that the burning of fossil fuels has led to an unprecedented rate of rise of atmospheric CO_2, as directly measured at Mauna Loa in Hawaii. The annual variations seen in the data reflect the difference in the response of vegetation in the Northern and Southern hemispheres to the change of months. If we smooth over such annual variations, the part per million (ppm) by volume of CO_2 in the Earth's atmosphere has steadily increased from 315 ppm in 1960 to the present 390 ppm in 2008.

Carbon dioxide is a greenhouse gas (GHG) that increases the optical depth τ for infrared radiation emitted by the ground to traverse through the atmosphere. Let T_g be the mean temperature of the ground and T_E the effective temperature at which the energy of sunlight absorbed by the Earth is reradiated to space. A simple model of the greenhouse effect gives the relationship among T_g, T_E, and τ as

$$T_g = T_E \left(\frac{3}{4}\tau + \frac{1}{2} \right)^{1/4} .$$

A fraction (about 80%) of the energy flux f of sunlight intercepted by the Earth is absorbed when we average over latitude, day and night, and seasons. This leads to T_E = 250 K, giving a value for T_g = 290 K at sea level that is above the freezing point of water, 273 K, when we account for the term in the parenthesis representing the warming effect of GHGs in the atmosphere (principally, methane, water vapor, carbon dioxide, and ozone). The atmosphere acts as a blanket to trap some of the reradiated infrared radiation,

Figure 3. Bottom: increase of atmospheric carbon dioxide measured at Mauna Loa, Hawaii; top: section of Antarctic ice core.

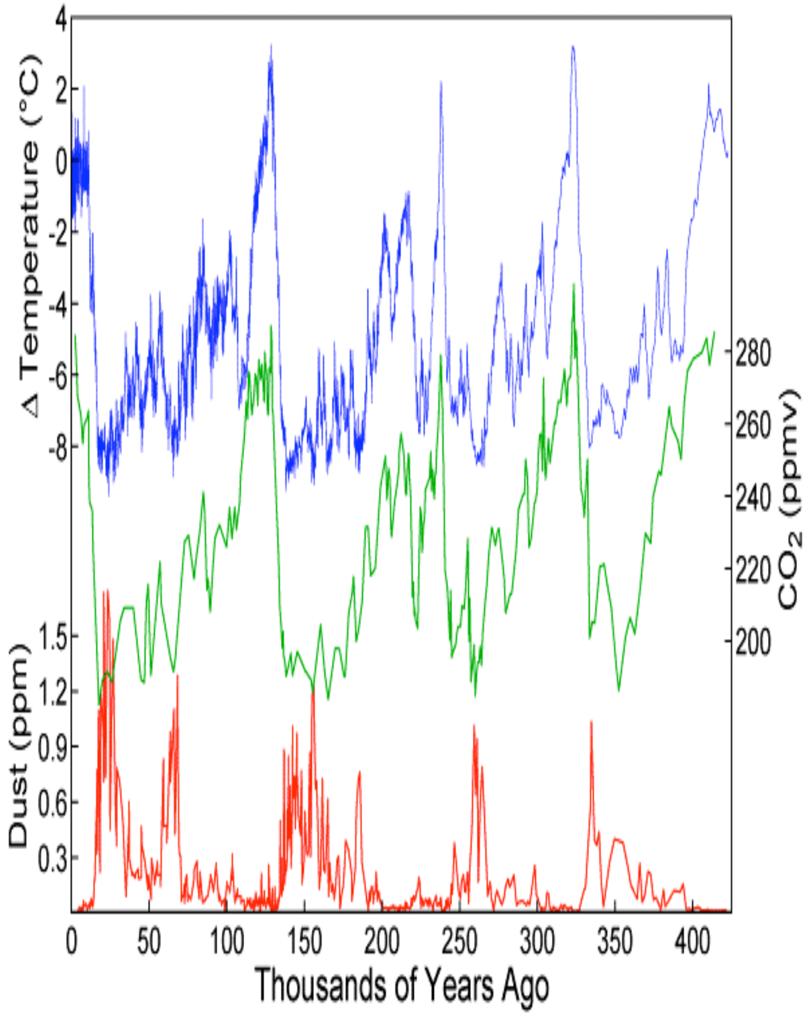


yielding a ground temperature that is higher than the amount without an atmosphere. The process resembles, for a given rate of metabolism, a sleeping person's elevation of her body temperature by covering up with a thick blanket at night. Global warming of the Earth occurs when its atmospheric blanket gets thicker with the passing decades.

Antarctic ices cores, shown at the top of Figure 3, can be used to extend the historical record prior to when direct recordings were first taken by the geophysicist Roger Revelle. The stripes in the ice core represent translucency variations in the ice compacted from snow that falls in the Antarctic summers and winters. Counting the number of stripes provides a simple method to date the ice. Analysis of the oxygen-isotope variations calibrates the air temperature – snow that falls during higher air temperatures has greater proportions of O-17 and O-18 relative to O-16. Air bubbles trapped in the ice then allow correlations to be established with the atmospheric CO_2 content that is in the air bubbles. In this way, the air temperatures and carbon-dioxide concentrations can be inferred for epochs where we do not possess measurements from Mauna Loa.

Figure 4 yields the results when plotted against thousands of years into the past. For our purposes here, let us just focus on the two upper plots, which give the CO_2 volumetric

Figure 4. Inferences from Antarctic Ice Core Data



concentration in ppm and changes of the air temperature from some fiducial norm in degrees Celsius.   On time scales of 10^3 years, CO_2 concentration changes are well correlated with, but *lag*, temperature variations. Evidently, both are driven by something else. In fact, the temperature driving is associated with the *Milankovich cycle*, where the closest distance of the Earth from the Sun and the tilt angle of its spin axis with respect to the orbital plane experience periodic change because of near-resonant interactions with the other planets of the solar system. The immediate effect is small, however. A process of amplification is needed to explain the large temperature excursions at the poles.

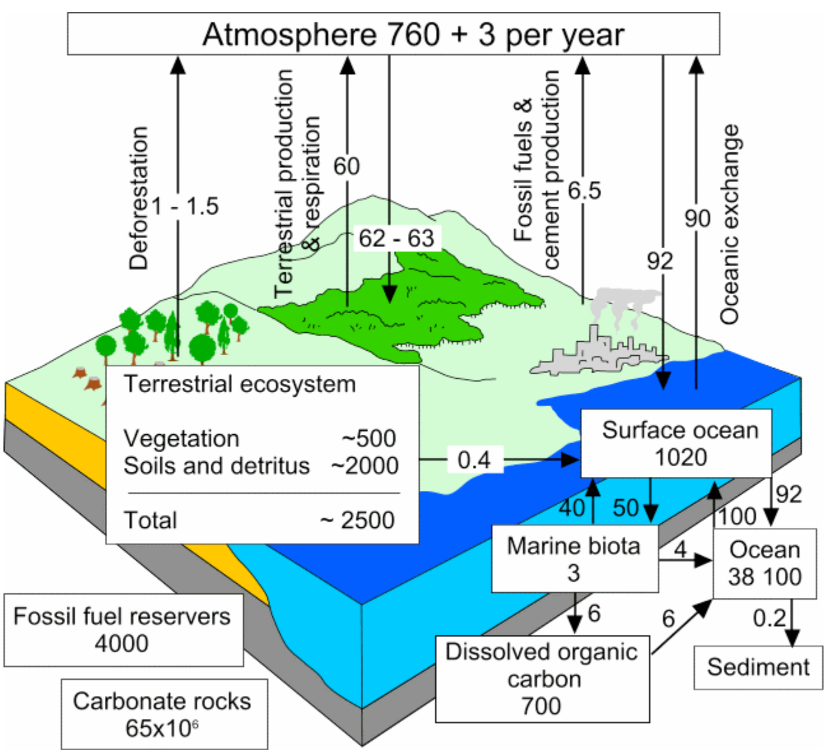
Two of the effects are believed to be the following. First, warming oceans release carbon dioxide after a time lag. Second, melting ice reflects less sunlight, accelerating the warming process. These amplification and feedback processes make especially frightening the projection that the CO_2 concentration in the atmosphere may double from the 280 ppm value at the end of the last ice age to 560 ppm in 2050.

To appreciate the magnitude of such a change, recall that 50,000 years ago, enough of the oceans' water was locked up in ice as to enable people to walk from Borneo to Australia to become the aborigines of that country. And 14,000 years ago, Asians crossed by land bridge to North and South America and became the Native Americans of those two continents. But when the CO_2 rose from 200 ppm to 280 ppm, the glaciers melted, the seas rose, and the land bridges disappeared. What lands (or islands) will the seas submerge when they rise in response to an increase in atmospheric CO_2 from 280 ppm (end of last ice age to beginning of the Industrial Age) to 380 ppm (in 2005) to 560 ppm (in 2050)? Do we still wish to debate whether global warming is caused by humans? Or should we stop conducting uncontrolled experiments on our own atmosphere and oceans?

Carbon Cycle and the G8 Resolution of 2008

Figure 5 shows that the carbon budget of the Earth has many large sources and sinks. Most of the natural processes are in equilibrium, so our concern is with the net annual release of CO_2 into the atmosphere by human activity. Burning fossil fuels and making cement adds approximately 6.5 gigatons of carbon (GtC) per year to the biosphere, whereas deforestation adds another 1 to 1.5 GtC, for a total of 7.5 to 8.0 GtC. Most of the carbon (about 65 million GtC) on Earth is actually locked up in carbonate rock (limestone). Grinding up and otherwise processing a portion of this limestone to make cement releases CO_2 into the atmosphere. The next large reservoir of carbon is contained in buried fossil fuels. Burning the entire reservoir, about 4000 GtC, would dwarf the total amount, about 760 GtC, currently in the atmosphere.

Figure 5. The Carbon Cycle



Roughly 40% of the additional 7.5 to 8.0 GtC released annually into the biosphere, or 3 GtC per year, is actually accumulating in the atmosphere. The other 60% probably goes into the oceans and acidifies it, a reason why coral reefs are disappearing worldwide. Climate models suggest that if atmospheric CO_2 rises unabated to the end of the century, the average temperature may increase by about 4 C. The next time there is a heat wave in Taiwan, imagine how much hotter it will feel with another 4 C of temperature.

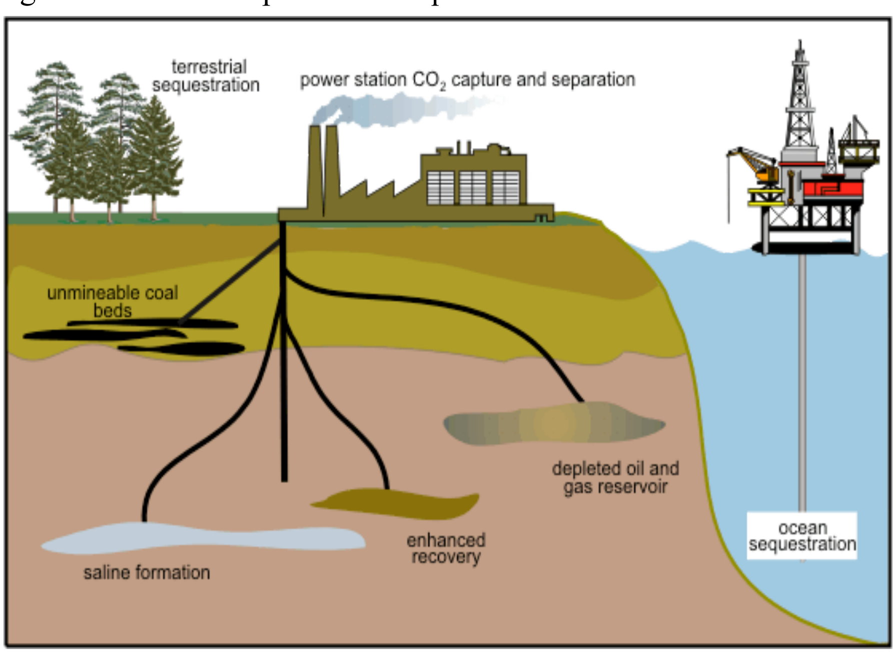
These figures spurred the G8 nations to issue its resolution of 2008, which is to halve human CO_2 emission by 2050. Unfortunately, G8 did not specify the baseline year, so most analysts assume a halving of the CO_2 emission of 2008, which would bring the level down to those of 1973. However, such a level of CO_2 emission was not sustainable in 1973 (see Fig. 3), and it will not be sustainable in 2050. Perhaps the world should aim for *zero* CO_2 emission by 2050. What is the point of procrastinating another 42 years?

At issue is an important psychological factor. How will people, especially young people, react if we tell them that they must sacrifice during the coming decades to achieve a certain goal? What do we say when they ask, "What is our reward at the end of the sacrifice?" They may not respond well if we reply, "You will be a little less miserable." More worthy and inspiring is a goal that gives them a permanently cleaner and better environmental future.

Carbon Capture and Sequestration

To reach even the modest target set by G8, the 2008 document called "Energy Technology Perspective" released by the supporting International Energy Agency (IEA) relies on the so-called technology of "carbon capture and sequestration" (CCS). The central idea is to keep burning fossil fuels, but to capture the CO_2 released in stationary power generation and to lock it up in some safe geological repository (see Fig. 6).

Figure 6. Carbon Capture and Sequestration



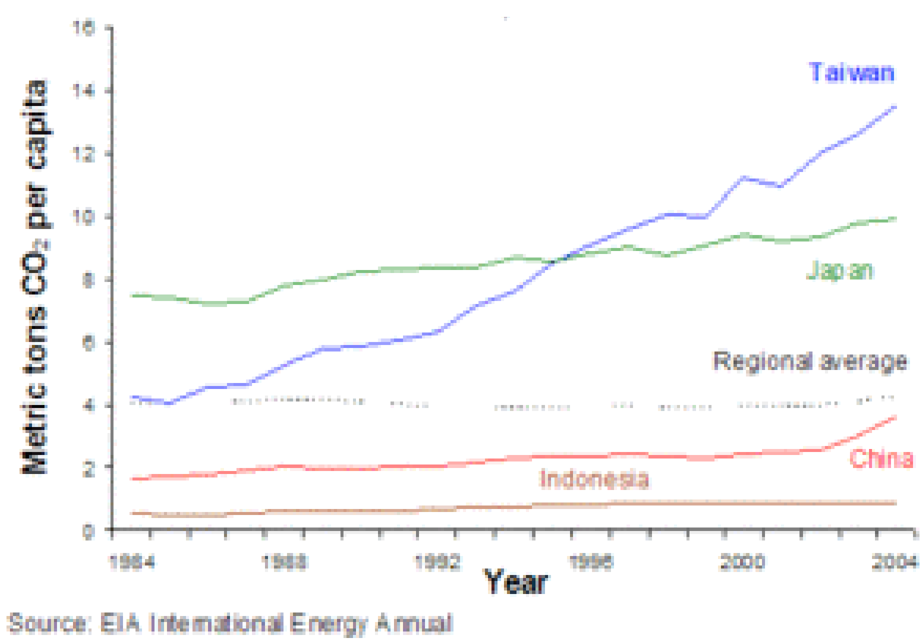
The simplest notion is to draw out oil or mine coal from the ground, and pump back the CO_2 generated by burning the liquid or solid into a gas. Even at high enough pressure to be in a supercritical state, a gas is more rarefied than a liquid or a solid. Thus, depleted oil fields, coal mines, and natural gas reservoirs cannot have the capacity to trap the CO_2. Saline formations are another possibility, but their ability to retain CO_2 is unproven. Ocean sequestration may become the default option, but ocean sequestration is hard to monitor for leakage. Any leakage would further acidify the oceans, as well as lead to an eventual release of the CO_2 into the atmosphere when the oceans become warmer.

Apart from such worries, there is the added element that CCS is an expensive technology. Enough research has been done on the problem that it is now known that just the capture and separation part would cost 30% of the energy released in burning coal. As a consequence, in 2008 the US government canceled its demonstration CCS power plant FutureGen because of cost overruns. Moreover, all US utilities, except one, have stopped investigations into coal gasification, which would have reduced, but not halted CO_2 emission at coal-burning plants. If a rich country such as the USA is unwilling to invest in CCS, how can poorer nations be expected to do it?

In any case, CCS is difficult to impossible for the transportation sector, which uses 22% of the total energy consumed by humans. This 22% is divided globally into 14% for passenger cars, and 8% for trucks, trains, boats, and jets (hereafter abbreviated as t, t, b, j). The two categories have quite different energy needs. Electrification and batteries are a possible solution for passenger cars. For t, t, b, j, that need more intense sources of power, liquid fuels are probably indispensable for the foreseeable future.

Conservation and Wise Energy Choices

Figure 7. Per Capita CO_2 emission in a few selected Asian countries in 1984-2004



If CCS is not an option, we are left with conservation and wise energy choices. Figure 7 shows that room exists for conservation in Taiwan's use of energy. The CO_2 emission per capita of Taiwan is currently greater than Japan, China, and Indonesia. In particular, Japan is more advanced than Taiwan in its usage of energy. Reaching Japan's level should be possible through conservation, allowing reductions by a third, say, in Taiwan's per capita CO_2 emission.

Less developed Asian regions like China and Indonesia look good in Figure 7 because the numerator (total CO_2 emission) is small relative to the denominator (total population). Thus, China and India have a point when they claim that they do not contribute nearly as much per capita to the problem of global warming as an advanced nation like the United States. However, plotted in a different way – total CO_2 emission over total energy used, which measures how wisely one chooses the energy source that one uses – China does not come out so well (Fig. 8). India does a little better, Japan does significantly better, and France does a lot better. It may be surprising that the USA comes off so badly in Figure 8. What happened in history that caused France and the United States, who had similar records up to the early 1970s, to diverge so much in the 1980s and 1990s?

Late in1973, in the wake of the Arab-Israeli War, came the first oil shock. France, under President Pompidou, made a decision to achieve less reliance on foreign oil, and began an aggressive program of expanding the number of its nuclear power plants. This epochal decision paid off in the unanticipated dividend of dramatically decreasing France's carbon footprint in the world. In contrast, the United States did nothing in the face of the first oil shock, and therefore its carbon footprint remained roughly level throughout the rest of the 1970s. Then in 1979 came the nuclear accident at Three Mile Island (TMI). The reaction in the USA was essentially to put a freeze on the further construction of additional nuclear power plants. With an expanding economy, the vacuum was filled by a corresponding increase in fossil-fuel power plants. The result of this unwise choice was a rising trajectory in the carbon footprint of the United States, until today, it does not have a much better record in this regard than India.

Figure 8. Carbon intensity: total CO_2 emission over total energy used

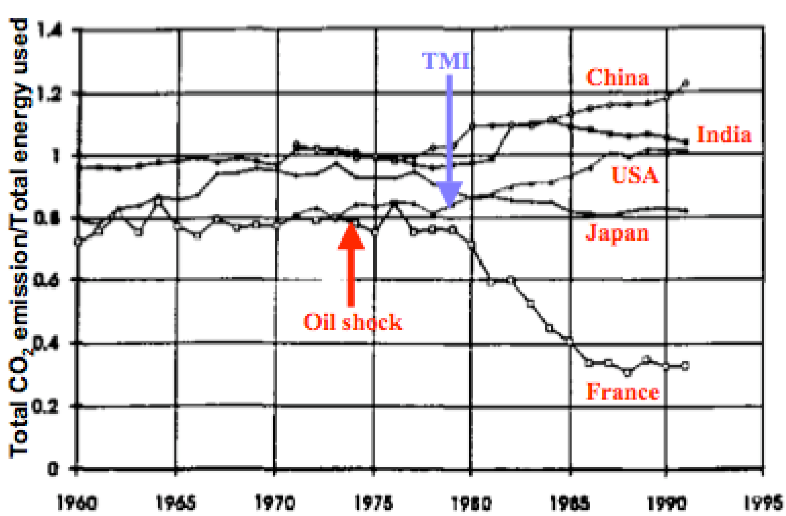
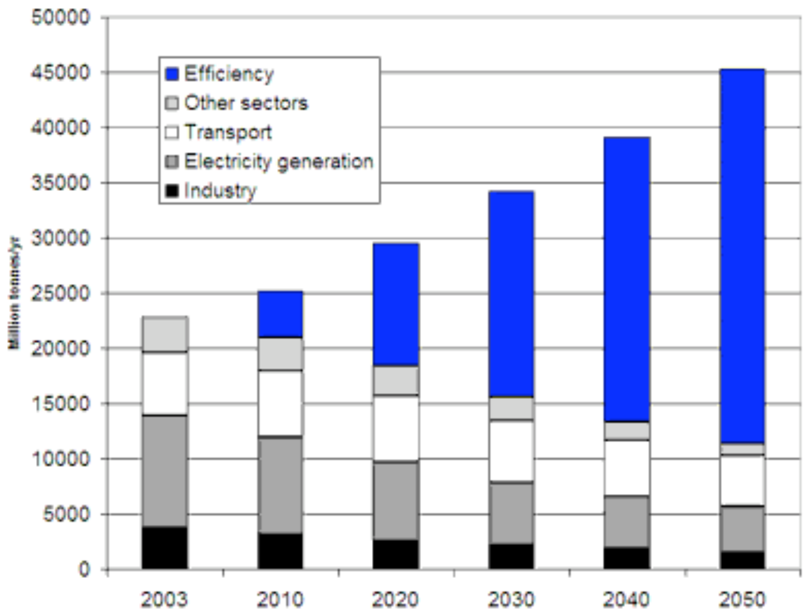


Figure 9. World Energy Outlook of IEA 2008 Study



Thus, through conservation and wise energy choices, it should be possible for the world to decrease its power demand in 2050 from our initially estimated 50 TW to a figure, 29 TW, more in line with the IEA's World Energy Outlook of 2008. In Figure 9, the IEA projects optimistically, in support of the G8 resolution of 2008, that world needs of power generation in 2050 can roughly double the usage of 2008, while halving the total CO_2 emission. According to this projection, "efficiency" can make up the difference. Efficiency entails many things. A skeptic might enquire if 75% of the total energy usage can be made carbon-free by "efficiency," then why not 100%? The rest of this article explores what the nature of this magical "efficiency" might be.

Projections of Energy Needs in a Sustainable Future of 2050

In the previous section, we argued for a figure of 29 TW of carbon-friendly energy usage for the whole world in 2050. Taiwan's share of world population is 0.3%. A reasonable target for Taiwan is thus 0.3% of 29 TW, or 86 GW (1 GW = 10^9 watts). The bottom row of Table 1 then summarizes the two targets for clean power usage: 29 TW for the world and 86 GW for Taiwan. To get to this bottom line, we have to add the contributions from two basic categories: liquid fuel for t, t, b, j; and clean electricity generation for all other purposes (including passenger cars).

Carbon-friendly liquid fuels include biofuels made by biological means, synfuels made by chemical means (through the heat of other power generation mechanisms), and natural gas diverted from electricity-generation plants. In 2050 the propulsion of trucks, trains, boats, and jets will probably require 3 TW for the whole world and 7 GW for Taiwan. Coincidentally, these levels are the natural gas usage in 2004, respectively, for the world and Taiwan. Thus, if the supply of biofuels and synfuels is inadequate still in 2050

Table 1. Sustainability Targets for Power Generation in 2050

Type	World (TW)	Taiwan (GW)
Biofuel Synfuel Natural Gas	3 t, t, b, j ~ 2004 NG 0-10% CO_2	7 t, t, b, j ~ 2004 NG 0-3% CO_2
Clean Electricity	1 installed 25 new	9 installed 70 new
Total	29 TW	86 GW 0.3% world

to meet the demand, natural gas at 2004 prices should be able to make up the slack. If biofuel and synfuel are able to handle the load, then the reduction of net carbon emission would be complete; whereas, if liquefied natural gas or its fossil-fuel equivalent were to assume the entire load, we would still see a reduction of total CO_2 to 10% and 3%, respectively, of the world's and Taiwan's emission levels of 2008. These latter figures assume that the remainder of the power needs of society come from clean methods of generating electricity. Installed capacities of hydro plus nuclear are 1 TW for the world and 9 GW for Taiwan (hydro plus nuclear plants 1, 2, 3, 4). To sum to 29 TW and 86GW then requires an additional 25 TW and 70 GW of new clean-electricity capacity for the world and for Taiwan, respectively. Since electric motors are generally more efficient (as well as cleaner) than those powered by liquid fuels, the 25 TWe or 70 GWe (the suffix "e" denotes "electric") imply a higher level of utility than if they were the same numbers in TW or GW of fossil fuel/biofuel/synfuel. Part of the meaning of "efficiency" is obtaining a higher standard of living by doing more with less (e.g., 3 TW + 26 TWe instead of 50 TW).

Good Ideas

To reach the goals of an additional carbon-friendly power-generation of 25 TWe for the world, and 70 GWe for Taiwan, we need to enlist good ideas. Some fall into the category of conservation; others, alternatives to fossil fuels.

In the category of good conservation ideas, we may list:

1. solar heating of water, air conditioning by photovoltaics;
2. more efficient appliances, more telecommuting;
3. electrification of personal vehicles; biofuel/synfuel for t, t, b j.

In the category of alternatives to fossil fuels, we should resolve to keep an open mind to all possibilities. But we should also achieve an understanding of their limitations before we push to any large-scale deployment. The list of fossil-fuel alternatives that are commonly discussed include:

1. biofuels (Sun),
2. photovoltaics (Sun),
3. wind (Sun, secondary),
4. ocean currents (Sun, secondary & tertiary),
5. ocean waves (Sun, tertiary),
6. geothermal (Earth),
7. tidal (Moon),
8. hydroelectric (Sun, secondary),
9. nuclear fusion (Big Bang),
10. nuclear fission (Supernovae).

The parenthetical comments at the end of each listing provide the key to understanding the energy potential of these ten items: the underlying sources are all astronomical. Thus, growing plants (biofuels) and solar cells (photovoltaics) are primary recipients of the Sun's energy output. Wind is a secondary outcome, for it arises from uneven solar heating, making some areas higher in temperature and pressure than other regions, thereby generating wind through the resulting pressure differential. Ocean currents are the winds of the sea, obtaining their energy through a combination of the secondary effects of uneven solar heating of the oceans as well as the tertiary effects of the wind's long-term drag on ocean surfaces. Ocean waves are a tertiary effect of the Sun's power, arising because of instabilities created at the interface between the sea's surface and the wind blowing above it. Geothermal taps into the residual heat of the Earth's formation process; tidal, into the differential height of ocean water raised by the Moon's gravitational pull. Hydroelectric power generation occurs as a secondary effect of the Sun evaporating water from the oceans, the water vapor condensing into rain over mountains, the rain washing down mountains to become streams and rivers, and humans damming the rivers to cause water to fall through turbines to generate electricity. Fusion involves combining light elements, like the deuterium created in the Big Bang and found in seawater, into heavier elements and releasing the difference in nuclear energy. Fission induces the splitting of very heavy elements, like the uranium created in Supernova explosions and found in common forms of Earth rocks, into smaller fragments (fission products), thereby releasing the difference in nuclear energy.

The Big Bang and Supernovae are intrinsically much more powerful than the Sun. But we are much closer in space and time to the Sun than we are to the Big Bang and Supernovae, so these three contributors may make comparable contributions to the solution of the energy crisis. In contrast, the Sun is more powerful than the Earth, which is, in turn, more powerful than the Moon. Thus, primary receptors of solar power are likely to be more important than primary employment of the Earth's internal heat or of the Moon's tidal pull. On the other hand, inefficiencies at every intermediate step of the process make secondary and tertiary receptors of the Sun's energy less powerful as natural resources than the primary receptors.

Quantitative estimates bear out the above qualitative reasoning. Detailed numerical estimates give the following results (see Appendix):

1. biofuels (1.6% land for t, t, b, j),
2. photovoltaics (0.3% land for everything, also ½ GDP),
3. wind (2 TWe maximum),
4. ocean currents (6 TWe maximum),
5. ocean waves (0.24 TWe maximum),
6. geothermal (0.4 TWe maximum),
7. tidal (0.003 TWe maximum),
8. hydroelectric (3 TWe maximum),
9. nuclear fusion (as much as needed),
10. nuclear fission (as much as needed).

If we want to make large-scale deployments, we should focus on the resources that are big and reliable. At maximum (using all the shorelines of the world, or drilling for all the heat from plausible hot spots beneath the continents, or all tidal energy impingent on all the ocean bays of Earth), items 5, 6, 7 yield relatively small resources in comparison with the global need, 25 TWe. Therefore, to avoid distraction, let us dismiss their serious use.

Let us now consider the popular alternative, number 3 on the list, wind. The maximum that one gets, without one windmill blocking another, if one taps all the wind on continents within 80 meters diameter of the hub height off the ground is 2 TWe. To many, wind seems an attractive resource contributor to the total energy mix. However, wind is notoriously fickle and hard to use without energy storage, as we shall discuss later, so let us tentatively also remove it from our list.

Unlike wind, ocean currents are steady and predictable. They arrive at this state by taking a long time to be established. Exploiting them on too large a scale could cause serious climate disruptions, for example, the cooling of Europe if the Gulf Stream is diverted for energy purposes. Since the oceans occupy roughly three times the area of the continents, and since the wind blowing over oceans is a primary driver of ocean currents, we can estimate the maximum safe amount of electric power that can be tapped from ocean currents at 3 times the wind value over continents, or 6 TWe maximum. In practice, it is difficult to anchor turbines in the deep oceans, so it is possible in shallow waters to tap only a small fraction (1%?) of the 6 TWe. For example, National Taiwan University has a proposal to generate 1 GWe of power by placing 1000 MWe marine turbines in the Kuroshio Current that flows off the eastern shores of Taiwan. Such levels of electricity generation make an interesting but small contribution to the total that is needed (70 GWe of new clean electricity for Taiwan). To avoid distraction, let us therefore also remove ocean currents, number 4 on our list, from our focused discussion.

Consider next hydroelectric power. As a secondary solar resource, it is reasonably large as well as cheap and reliable to use. However, of the 3 TWe that is theoretically possible to tap if we dam all the rivers of the world, humans have already used all the easy possibilities. Hydroelectric is an exploited technology of the 20th century; its expansion in the 21st century will bring diminishing returns relative to the environmental impact (more later). Let us therefore also remove item 8 from our list of possible *new* resources.

This pruning leaves us with the big four: biofuels, photovoltaics, nuclear fusion, and nuclear fission. Biofuels from cellulosic ethanol is a much discussed option, and our list above indicates that devoting 1.6% of all the land of Earth to farm this resource could fulfill the energy needs of trucks, trains, boats, and jets. However, this option assumes that we can genetically weaken the cell walls of plants like switchgrass enough to achieve the sought-after factor of 5 increase in ethanol extraction over corn, and that no organics are returned to the soil. These assumptions make us hesitant to choose this option definitively over other alternatives, such as synfuels for t, t, b, j made, say, from reactor heat.

Photovoltaics have a large efficiency advantage compared to plants in converting solar energy to useful power. Thus, devoting only 0.3% of all the land area of Earth to photovoltaics could, in principle, satisfy the additional need for 25 TWe of clean electricity generation. This represents only 10% of the land devoted to world urban use. Although there are not enough rooftops in a congested area like Taipei City for it to generate a self-sufficient amount of electric power, one can contemplate using (semi-transparent) solar cells on windows too.

Excessive land use is therefore not a problem with photovoltaics. More problematic are intermittency and cost. Intermittency refers to the fact that not every day is sunny; indeed, in Taiwan, the days are often cloudy. One cannot do without electric power on such occasions. Thus, solar cells without an additional energy storage mechanism (e.g., batteries or capacitors, or the electrolysis of water) cannot serve as the base load of any electrical grid. Adding energy storage to photovoltaics would further increase its associated cost. It is the experience of many municipalities that the unsubsidized lifetime cost of electricity generation by photovoltaics is 0.30 USD per kWh. Since the per capita power use in Taiwan is 5.8 kW and there are 8,760 h in a year, it would cost 470,000 NTD per person to pay for the average person's annual energy consumption. Most families in Taiwan cannot afford energy at such rates. The same conclusion applies to the world as a whole: 66 TUSD would be needed to pay the annual bill in 2050, if 25 TWe is the output from photovoltaics. In 2050, the figure of 66 TUSD will be about ½ of the world GDP. Clearly, photovoltaics is too expensive, and solar energy generation, too variable, for it to be relied upon, *at present*, as the primary solution to the energy crisis.

What about thermonuclear fusion? Plasma physicists aim for a working prototype of fusion power generation in thirty years. However, they have been too optimistic in their estimates before. It could be another century before electricity generation by plasma fusion becomes *commercially* viable. In the interim, the world is getting warmer.

The only energy source commercially available now that can supply as much power as we need is number 10 on our list, nuclear fission. The fallback position is therefore 25 TWe worldwide by nuclear (fission) power plants, and perhaps an additional 3 TWt ("t" for "thermal") if separate high-grade reactor heat is required to produce synfuel (for example, hydrogen from the breakdown of water). Hereafter, we take 25 TWe for the world and 70 GWe for Taiwan as the baseline targets for nuclear power generation in 2050. *In other words, we plan for 100% of the needed energy generation to occur by nuclear power.* This planning does not imply that we wish to discourage the use of renewable energy sources, but rather that we wish to have an insurance policy in case all other efforts prove less promising than the initial enthusiastic estimates.

Empirical Evidence that Carbon Emission Can Be Reduced

Despite our pessimism about the potential of renewable energy sources to solve the problem of global warming, we do have empirical evidence that individual countries can drastically reduce their carbon emission. Figure 10 shows the cases of three advanced European countries: Denmark, France, and Sweden. We explained earlier the achievement of France as a triumph of its nuclear energy program. How did Sweden do even better? And why did Denmark do far worse?

The answers to these questions are contained in Figures 11a and 11b. Figure 11a shows that France achieved its present good performance by generating 77% of its electricity by nuclear power. Sweden has an even better performance because it has a balanced amount of electric power generation by hydro. Of the Scandinavian countries, Norway is the most green, because it is a lightly populated land with lots of topography and fjords, i.e., with lots of running water that can be utilized for hydroelectric power generation.

Figure 10. Carbon intensity of Denmark, France, and Sweden from 1965 to 1994

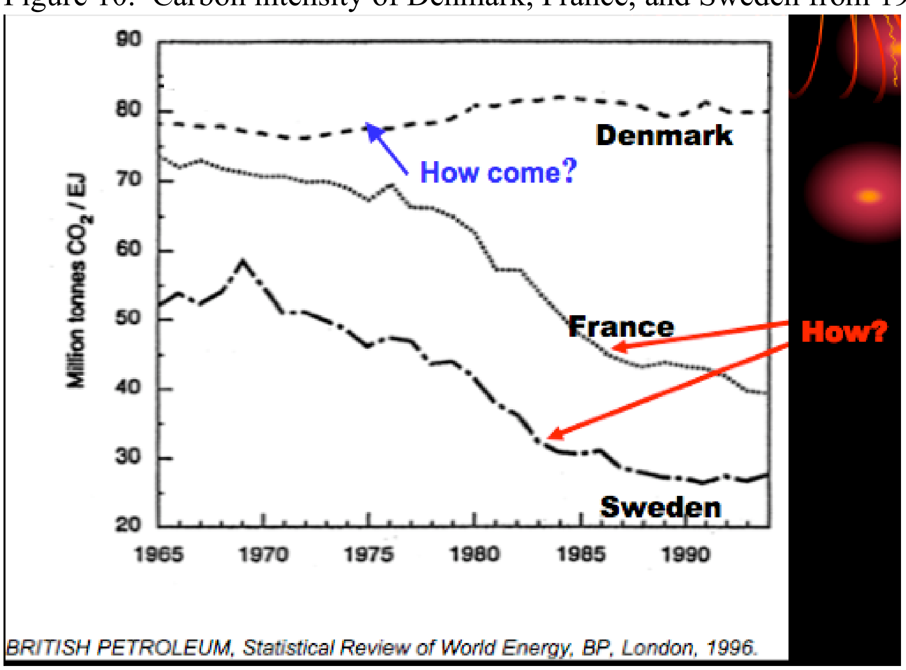
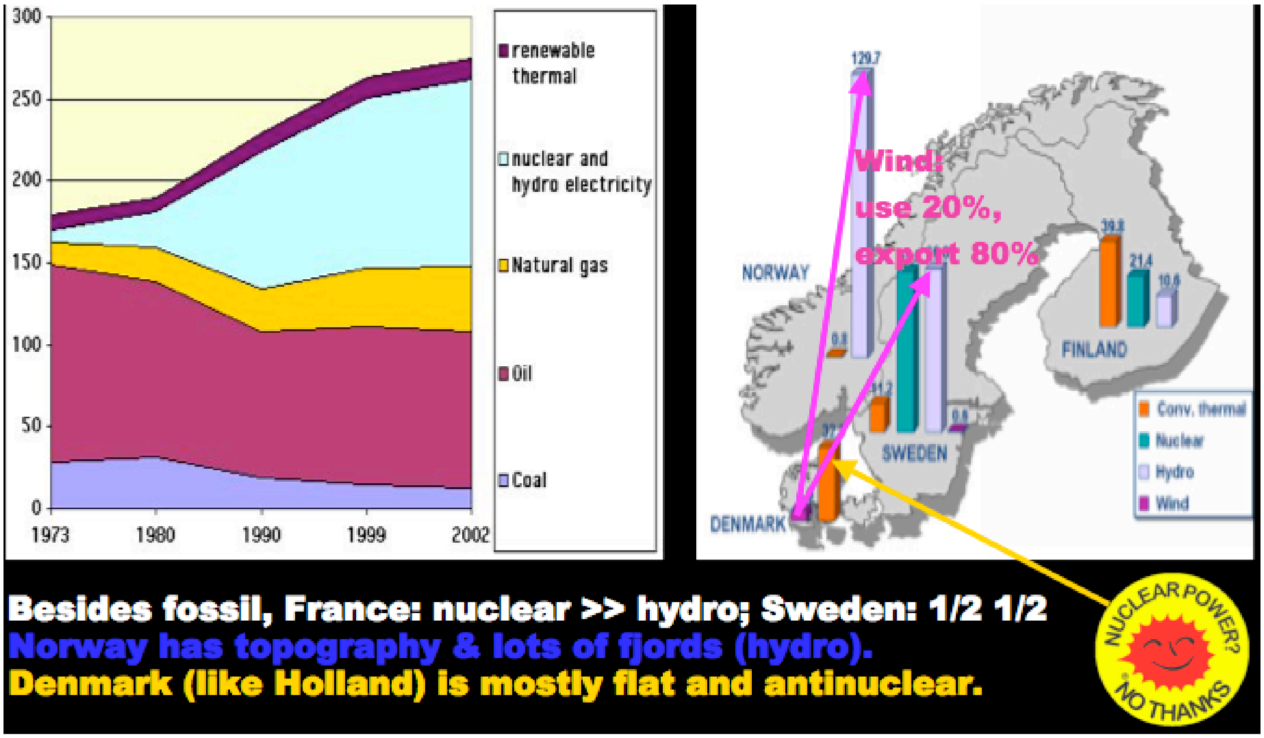


Figure 11a France's power mix. 11b. The power mix of the Scandinavian countries.



In contrast, Denmark, like Holland, is mostly flat (therefore, no hydro) and antinuclear (therefore, no nuclear). Indeed, the famous logo of worldwide antinuclear sentiment, "Nuclear Power? No Thanks," originated in Denmark. This attitude has led Denmark to generate its electricity mainly by conventional fossil-fuel plants. It also invested heavily in wind; Denmark has the largest percentage of total electricity generation by wind (about 20%).

However, wind is notoriously gusty. When the wind is strong, Denmark gets a lot of electricity generation through its modern farms of windmills. However, conventional fossil-fuel plants have considerable thermal inertia. They cannot turn off and on to suit the time scales when wind power generation is strong and weak. In such a system, the power grid cannot easily absorb wind electricity generation because the grid could crash from the fluctuations of the load. Thus, of the total electricity generation in Denmark by wind power, only 20% is actually used at home, 80% is exported to Norway and Sweden. These countries have vast hydroelectric plants where the water behind the dams can be released or not at will. They have no difficulties putting excess wind-generated electricity on their grids. When the wind dies in Denmark, Norway and Sweden can increase their hydroelectric power generation and send a portion back to Denmark. In this energy exchange, Norway and Sweden make a tidy profit from the investment that Denmark put into its windmill farms.

Energy Resource Summary

From the previous discussion, we may draw several conclusions:

1. Of renewable energy sources, only photovoltaics have the potential to be the global solution, but it is too costly and too intermittent to be the base load.

2. Wind energy is neither sufficient nor reliable enough to be highly useful unless it is coupled to some means for energy storage (feed capacitors, produce hydrogen, lift water).

3. Ocean currents are steady, took a long time to establish, and their large-scale exploitation has serious unexamined consequences.

4. Nuclear fusion is very far from practical commercialization.

5. Of the other large technologies, only hydroelectric and nuclear fission are cost-competitive with fossil fuels.

6. Hydro is cheap, but its utilization is nearly saturated (see Fig. 12).

7. In contrast, the rapid rise of nuclear fission flattened in the early and late1980s because of the occurrences of the TMI and Chernobyl accidents.

Figure 12. Share of global energy consumption

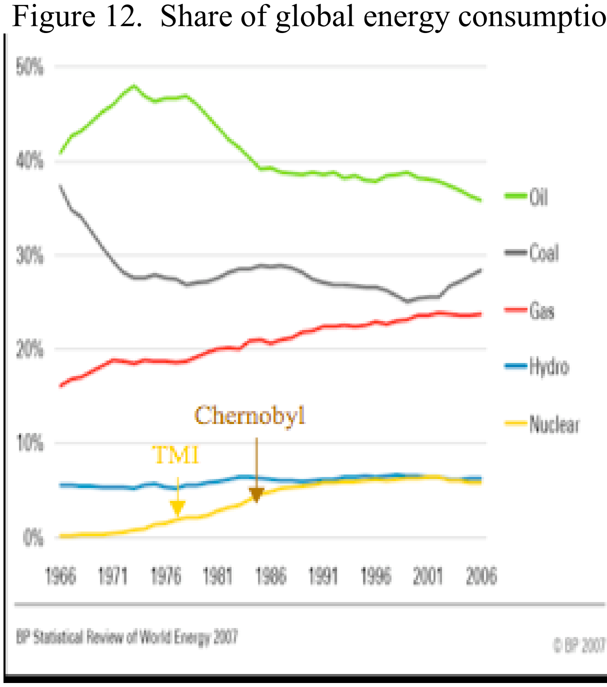


Table 2. Energy Plan of Greenpeace and EREC in Response to the 2008 G8 Resolution

	2003	2010	2050
Hydro (MW)	728,000	854,800	1,257,300
Biomass	48,030	110,000	504,610
Wind	30,280	156,150	2,731,330
Geothermal	10,170	20,820	140,010
PV	560	22,690	2,033,370
Concentrating Solar Power	250	2,410	404,820
Ocean energy	240	2,250	63,420
Total	**817,000**	**1,169,120**	**7,134,860**

At first sight, the previous conclusions seem diametrically opposed to those drawn by the 2008 response to the G8 resolution and IEA study given by Greenpeace and the European Renewable Energy Council (EREC). These two organizations gave their plan for achieving the G8 goal without any recourse to nuclear power. Instead, their projections are summarized in Table 2.

We do not wish to dispute the methodology by which Greenpeace and EREC extrapolate from current trends to reach their 2050 numbers. Nor do we deny that the choices made here are better than building coal-fired plants. Nevertheless, we still wish to examine the hidden assumptions of the 2050 numbers. For example, this plan increases hydroelectric power from 0.728 TWe in 2003 to 1.257 TWe in 2050. The last figure represents 42% of what we compute in the Appendix as the maximum achievable if we dam all the rivers of Earth. To put the matter into perspective, the Three Gorges dam at 22.5 GWe is the most powerful hydroelectric plant in the world (top left of Fig. 13). The increase in hydroelectric capacity in the Greenpeace-EREC plan represents a worldwide addition of 22 Three Gorges dams. Seen in this light, the recommended expansion of hydroelectric power has massive environmental costs. The same statement applies to the large-scale deployment of all renewable energy resources. “Renewable” does not equate with “green,” once the application goes beyond the small and picturesque.

Consider next the entry for biomass. The generation of 0.5 TW by cellulosic ethanol does not fill the liquid fuel needs of trucks, trains, boats, and jets. To do that requires planting 1.6% of the world’s land area (about 5 times my home state of California) with, say, switchgrass (2^{nd} picture of the top row of Fig. 13). Although switchgrass is not native to California, attempts are being made to introduce it, and similar varieties grow in rolling meadows. Every summer, lightning sets ablaze part of this grassland. If fuel-processing plants (3^{rd} picture of top row of Fig. 13) are sited close to the burning harvest fields, they may join the general conflagration. These infernos are followed by mudslides during winter rains on hillsides denuded of grass in the areas affected by the fires. These now-annual events in California may become familiar sights in many parts of the world if cellulosic ethanol production from switchgrass, or its equivalent, is adopted as a large-scale remedy to the global energy crisis.

Figure 13. Environmental Impact of Various “Green” Technologies

The 2.731 TWe generation from wind recommended in Table 2 has a different difficulty. This value represents 140% of the maximum amount that we computed as theoretically possible from windmills with 80-meter arms (near the maximum before metal flexure of the tower becomes a severe problem). How can one get 40% more than the maximum amount? Well, perhaps my estimate is in error. However, my estimate is probably not enough in error to reverse the conclusion that the plan must implicitly place a windmill wherever one can somewhere on the face of the Earth without “wind-shadowing” another windmill nearby. Such a coverage is quite different from the relatively modest Danish project in the North Sea depicted as the 4th picture in the top row of Figure 13. If one wants to greatly expand wind energy production as in Table 2, one cannot push the windmills farther out to sea – the water becomes too deep to secure the windmills. No, they will have to come ashore, where their great arms will loom in everyone’s view, and the noise they make when they turn will be disquieting.

The 0.140 TWe contemplated for geothermal energy generation is 35% of the maximum extractable from the hot geothermal sites of all the dry land of Earth (0.4 TWe, see Appendix). In other words, one is envisioning drilling to 35% of wherever there is evidence of hot underlying rock (bottom left of Fig. 13). Such an enhancement of the global heat flow has been imagined in an MIT study, but one wonders whether the citizens of Taiwan would like to see energy plants augmented by huge drilling operations on Yangmingshan or within the confines of Taroko Gorge?

What did Greenpeace and EREC have in mind for the 0.063 TWe generation by ocean power? Did they mean the construction of the equivalent of 250 tidal power plants of the scale of the currently largest one in La Rance, France (2nd picture of bottom row of Fig, 13)? Or did they mean to infest the entire Western seaboard of America with power generating buoys of the type displayed in the 3rd picture of the bottom row of Figure 13?

Solar collectors typically use 10 times the land that photovoltaics do to generate the same electricity. Thus, construction of 36,000 solar towers similar to the 11 MWe (peak) platform near Seville, Spain (4th picture on the bottom row of Fig. 13) to obtain 0.4 TWe of power seems an intrusion. The platforms look vaguely familiar because astronomers construct such light collectors too, but they do it to gather knowledge, not to boil water.

The only green part of the plan of Table 2 involves photovoltaics to produce 2.033 TWe of power. Such a project would use less than 0.03% of the total land area of the Earth and could be accommodated on the available rooftops of the world. In such a setting (last picture in Fig. 3), one is placing human-made devices on human-built structures, so there is no incongruity. The pattern of solar cells can even be creatively designed as to add architectural interest to what would otherwise be a rather bland roof.

In any case, even if all the projects in Table 2 were carried out, their total contribution to electric power generation would only be 7.135 TWe. This represents 29% of the target value of 25 TWe needed in 2050 to account for population growth and the economic aspirations of the poorer peoples of the world. Where is the other 71% coming from? If Greenpeace and EREC mean barely to fulfill the G8 resolution, without using CCS technology (as appears now likely) or nuclear energy, then they can access 14 TWt of natural gas (= 7.8 TWe at 56% modern-plant efficiency). The total of almost 15 TWe still falls short of 25 TWe. Moreover, use of natural gas at approximately 4 times present rates will drive up its world price, leaving the enlarged population considerably economically poorer on average in 2050 than now. Developing nations will probably not accept such a fate. They will turn inevitably to burning coal. They already have.

Environmentalists for Nuclear Power

Let us succinctly summarize the limitations of renewable energy resources. The human demand for energy has grown so large that burning fossil fuels to satisfy our appetite for energy wrecks havoc on the atmosphere and oceans of Earth. Switching the source of energy to some other natural resource, particularly those that have been tried before in human history and were later replaced by oil, will automatically damage that resource.

The limitations of renewables have caused many environmentalists to reconsider their original objections to nuclear power. Among those prominent in the environmental movement who now advocate an increased role for nuclear power are James Lovelock, the author of the Gaia hypothesis that the Earth as a whole can be considered a living organism; Patrick Moore, the cofounder of Greenpeace; and Christine Todd Whitman, the former head of the Environmental Protection Agency (EPA) in America under President George W. Bush (Fig. 14). Here is what they have to say on the subject:

James Lovelock (2004): " Nuclear power is the only green solution. We have no time to experiment with visionary energy sources; civilization is in imminent danger."

Patrick Moore (2006): Given that hydroelectric resources are built pretty much to capacity, nuclear is the only viable substitute for coal. It's that simple."

Christine Todd Whitman (2007): "Nuclear is the clear course for the future, because it is the only form of base power that produces no air pollution."

Figure 14. Left to Right: James Lovelock, Patrick Moore, Christine Todd Whitman

It is interesting to note that the EPA under Whitman's leadership attempted to define CO_2 emission as air pollution. Had the EPA succeeded in this endeavor, it would have been a landmark accomplishment because then the EPA would have been able to regulate CO_2 as a pollutant. As it was, President Bush did not agree, nor even more did Vice-President Cheney. Whitman thus resigned as head of the EPA over a disagreement with the Bush Administration on the importance of global warming.

Efficacy of Renewables plus Nuclear in Reducing CO_2 Emission

Figure 15. Anti-correlation Between CO_2 Emitted and the Use of Hydro plus Nuclear

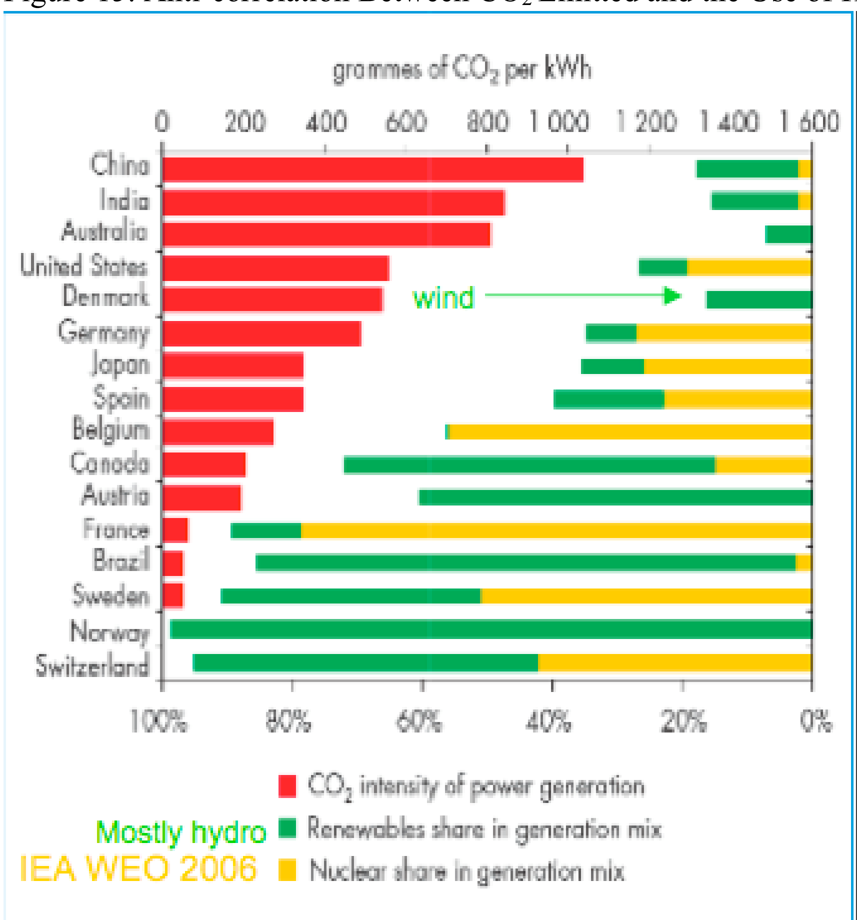


Figure 15 illustrates the anti-correlation between the amount of emission of CO_2 per kWh of electricity generation (red) and the percentages of nuclear (yellow) plus renewable (green) used to generate that kWh of electricity. "Renewable" here means mostly hydro. We may regard each set of bars as an experiment performed by a different country in the world. The complete set of experiments is then consistent with the following propositions:

1. Hydro and nuclear are the only proven reducers of CO_2 intensity.
2. The nuclear-free country that tried large-scale wind (Denmark) failed to reduce its CO_2 intensity, ending up not doing much better than the United States.
3. Countries that plan to go nuclear-free, e.g., Germany, are likely to increase their CO_2 intensity.
4. Advocates of a nuclear-free policy have a responsibility not merely to object, but to present realistic alternatives to nuclear energy.

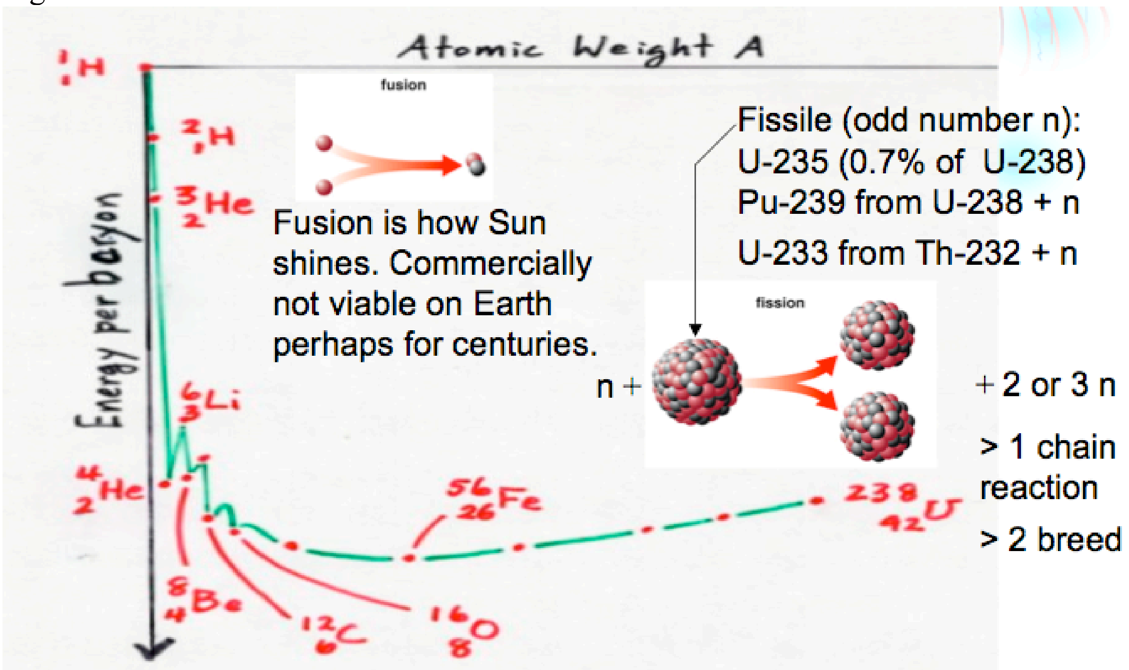
The Physics of Nuclear Power

Figure 16 gives the basic physics of nuclear power. When we plot the nuclear energy *E* per baryon (proton or neutron) of a nuclide against its atomic weight *A*, we find that the nucleus of an atom of iron-56 (atomic number = 26, atomic weight = 56; denoted ${}^{56}_{26}\mathrm{Fe}$) has the minimum energy. Thus, two nuclei lighter than iron-56 may undergo charged-particle fusion to become a heavier nuclei, and release energy; whereas a nucleus of a fissile atom such as uranium-235 (U-235) or plutonium-239 (Pu-239) or uranium-233 (U-233) may undergo nuclear fission when a neutron is added, splitting into two fragments that also release energy. Fusion is how the Sun shines, but commercially, it will come too late to stop greenhouse warming. Fission is exploited in present-day nuclear reactors.

Of the three forms of normally fissile material, only U-235 occurs naturally, being 0.7% of natural uranium. The other 99.3% consists of U-238, which can become fissile only by absorbing a neutron, turning it to U-239, which beta decays twice (turning two neutrons into two protons in the nucleus of the atom) and becomes Pu-239. Similarly, U-233 is not a naturally occurring form of uranium, but it can be made from thorium-232 (Th-232) through a neutron capture to make Th-233, followed by two beta decays to become U-233.

The fissile U-235 or Pu-239 or U-233 can undergo spontaneous fission when a neutron is added, yielding two lighter fragments (fission products) that have proportionally more neutrons in their nuclei than such elements like. Thus, an extra 2 or 3 neutrons are usually emitted as part of the fission process. Because the number of emitted neutrons is greater than 1, a chain reaction is possible, with at least 1 of the emitted neutrons causing another fissioning event when it is absorbed by a fissile nucleus, followed by the release of more neutrons, etc. If the emitted number of neutrons is greater than 2, then it is possible to breed a fertile nucleus, such as U-238 or Th-232, by adding a neutron to it and making it fissile (Pu-239 or U-233 after two spontaneous beta decays). One of the other neutrons in the fission process is then used to sustain the chain reaction.

Figure 16. Fusion and Fission



In this short discussion, it is important to note that

1. Taiwan has no known uranium deposits, but it does have beach sand that contains thorium, whose only naturally occurring isotope is Th-232.
2. U-233 has the most excess neutrons when it fissions, allowing a safe breeder that makes use of Th-232. Moreover, the Th-232/U-233 fuel cycle produces virtually no Pu-239, since Pu-239 is 7 nucleons away from Th-232, and something will generally happen before Th-232 captures 7 neutrons.

In order for the public to accept *any* nuclear fuel cycle, however, it must get over an irrational fear of radioactivity. Toward this end, we should note that, contrary to popular perception, inducing nuclear fission does not increase the total amount of radioactivity. Fission merely shortens the time scale over which the fission fragments decay and become safe. This time scale is governed by the half-lives of the radionuclides involved. Thus, U-235, U-238, and Th-232, have half-lives that are, respectively, 700 Myr, 4.5 Gyr (age of Earth), and 14 Gyr (age of universe). The half-lives of Pu-239 and U-233 are, respectively, 24,000 yr and 159,000 yr; that of common fission products, 30 yr or less.

To drive home the point that all radioactive waste eventually becomes safe, we note that everything heavier than iron was at one time radioactive (part of a supernova explosion that made a neutron star, which was prone to making heavy elements that are neutron-rich). For example, the gold in wedding bands was once radioactive but has since decayed and is now safe to handle (Fig. 17). Jewelers refrain from calling such items of enduring beauty by the pejorative, "radioactive waste."

Figure 17. The gold in wedding rings was once radioactive.

Why Nuclear Power Presents a Good Solution

Reacted completely, uranium and thorium are 2,300,000 times more powerful per kg than coal. The associated waste is thus much less. Even at the present fuel efficiency of only 1%, the accumulated world waste has a volume of only $(15\ m)^3$. Thus, the problem of nuclear waste is the duration of the radioactivity, roughly 10^5 yr for Pu, not its volume. No one can guarantee safe storage of the waste in a geologic repository for 10^5 yr.

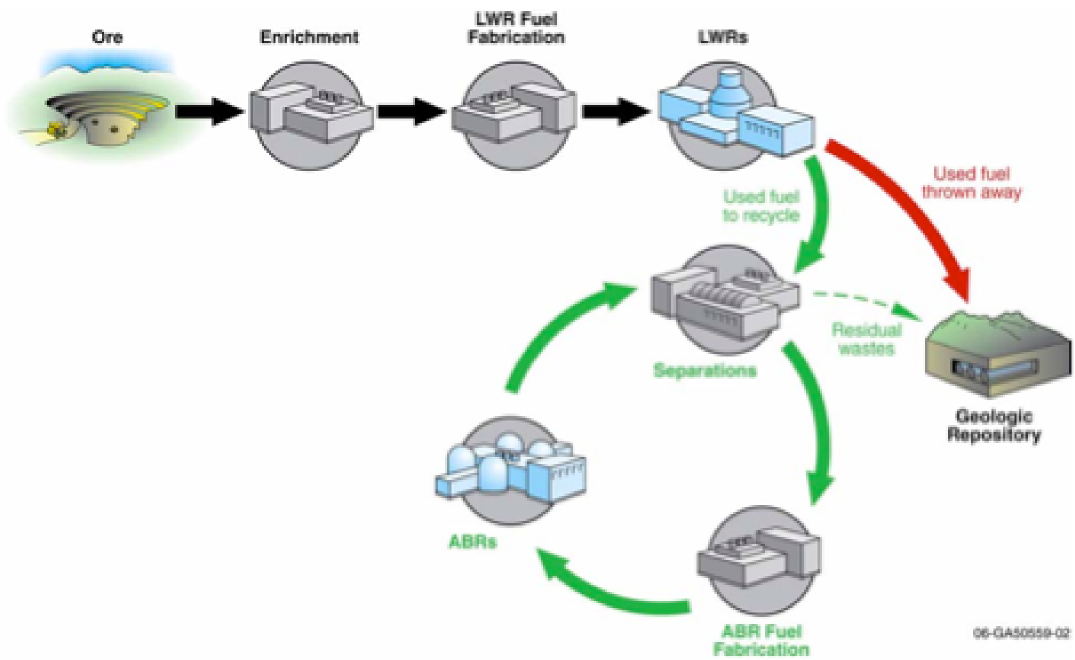
If it were not for the Pu in spent fuel rods, fission power would be the most environmentally friendly energy resource that we have now. Moreover, the fundamental fuel is abundant and cheap. There is enough high-grade uranium ore to last 200 yr (at 25 TWe if U-238 is bred to Pu-239). And since thorium is 3 to 4 times more abundant in Earth's crust than uranium, there is enough high-grade Th-232 to last at least 600 yr.

With fission power plants, there are legitimate concerns regarding the safety, the radioactivity of the waste, the cost, and the proliferation of nuclear weapons, but they can all be addressed. To begin, it is important to stress that radioactivity exists in the natural environment and contributes substantially to the generation of the interior heat of the solid Earth. Thus, uranium leaches by rain out of granite (the most common form of rock) into the oceans. Japanese scientists showed that this uranium is recoverable for fission purposes, and would last about 100,000 yr (at 25 TWe), adding only 10% to the current cost of nuclear power. Thus, while fission power is not renewable, it can last until we can harness fusion, where there is enough deuterium in the oceans to last over 10 Gyr. The climb of the solar luminosity over the next 5 Gyr as a main-sequence star implies that we should be prepared to leave the solar system if we survive another 1 Gyr.

Generation IV Reactors and Global Nuclear Energy Partnership (GNEP)

As an attempt to address the problems of sustainable development in a scenario where nuclear energy experiences much expanded deployment, the Department of Energy (DOE) of the United States organized a Global Nuclear Energy Partnership (GNEP) to analyze a suite of 6 advanced nuclear reactors, collectively called "Generation IV." Figure 18 shows the central feature of the GNEP program, which would shift away from a once-through (throwaway) fuel cycle to a breed and recycle approach.

Figure 18. GNEP would shift from an open throwaway fuel cycle (red arrow) to a closed recycle approach (green arrows).



The starting stages of the open and closed cycle approaches are the same. First, there is the mining of uranium ore. Second, this ore is taken to an enrichment plant where the U-235 is made a larger fraction of the uranium composition than its natural 0.7%. Natural uranium can self-sustain a chain reaction only in so-called “heavy water reactors.” With “light (or ordinary) water reactors”, abbreviated LWRs, the U-235 component needs to be somewhat enriched in comparison with its natural state. The enriched uranium is then fabricated into a solid pellet form that is loaded into fuel rod assemblies for burning in LWRs. This is where Taiwan enters in the nuclear enterprise; Taiwan does not have any of the three preceding steps: ore mining, uranium enrichment, or solid-fuel fabrication.

The once-through strategy currently followed by all LWR-using countries (the vast majority in the world) burns 1% of the total uranium fuel and throws away the spent fuel rods as “high-level nuclear waste” (red arrow in Fig. 18). GNEP proposes to use the 99% currently thrown away. This “waste” is composed of depleted uranium (mostly U-238 mixed in with only a bit of unburnt U-235) plus a small amount of Pu-239 (and other actinides) that resulted from the neutron irradiation of the U-238 in the now spent fuel rods. The Pu-239 with its awkward half-life of 24,000 years is mainly what makes final disposal of the high-level waste so difficult. If there were only 30-yr half-life fission products, one could store such waste below ground for 1000 yr, and the waste would drop below the background radioactivity level of the dirt under which it is buried. Four thousand years ago, the Chinese peoples already had technologies that can guarantee safe storage for a thousand years or more.

The GNEP proposal adds a recycle to the once-through approach. In the recycle (green arrows in Fig. 18), the remaining U-238 (most of the volume) in the spent fuel rods is bred into Pu-239. The Pu-239 (and remaining U-235) is sent through the reactor many times, until nearly 100% of the original uranium, U-235 and U-238, is burned.

Unfortunately, using the solid-fuel approach introduces problems in the recycle strategy. First, the fission products (which are unwanted neutron absorbers) must be separated from the mixed oxide fuel of uranium and plutonium (abbreviated MOX). The MOX separation process used by Europe and Japan could, in principle, divert separated plutonium from the uranium. Highly purified Pu-239 presents a relatively easy pathway to making atomic bombs. Although the Pu that one gets from civilian reactors is not weapons-grade, the USA is opposed to the MOX separation process.

Second, after the removal of fission products, solid-fuel refabrication is needed before one recovers fuel rods that are usable in reactors. Indeed, to achieve close to complete burn-up, the fuel has to be separated from the fission products and refabricated many times. Because the separation plants are large and the technology is sensitive, they are few in number and will generally not be located near the reactor sites themselves. Thus, the whole GNEP strategy requires multiple transportation of nuclear materials from reactors to separation/refabrication plants and back again. Such large-scale transportation of nuclear materials may not gain public acceptance. To reduce the number of such trips, the Generation IV concept envisages replacing LWRs with liquid-sodium fast breeders. The latter are perhaps four times as expensive as LWRs to build and operate.

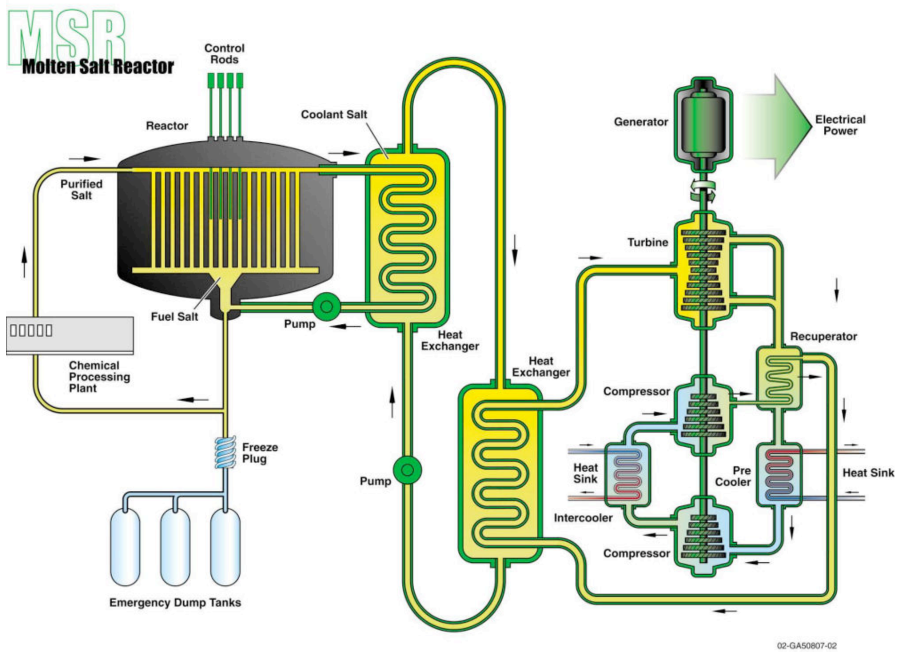
For these many reasons, the United States Congress requested the National Academy of Sciences (NAS) to study the GNEP strategy and to make recommendations. The report was issued in 2008, and the US NAS did *not* support the DOE's stewardship of the GNEP program. As a consequence, the whole GNEP concept is in shambles.

The Molten Salt Reactor

However, buried inside the Generation IV program is a little-known gem called the molten salt reactor (MSR). The MSR got started in the 1950s at Oak Ridge National Laboratory (ORNL) because the US Air force, following in the footsteps of the Navy's nuclear submarine, was interested in building a nuclear-powered airplane. If one thinks about this idea, it appears to have only one good feature – no other country would dare to shoot down a nuclear-powered plane over its own territory. Thus, the original Air Force reactor program was cancelled in 1956. At that point the ORNL turned its attention to a power-generation version of the MSR. The experimental version of this reactor, the MSRE, was a great success, ran for four years, 1965-1969, without incident, and showed, with great versatility, that it could burn all three fuel types, U-235, Pu-239, and U-233.

Figure 19 shows a schematic drawing of the MSR. The central idea is that the fuel, U-235 or Pu-239 or U-233, along with the breed stock, U-238 or Th-232, is dissolved in molten salt. A eutectic mixture of lithium fluoride and beryllium fluoride has the best properties for this purpose. The molten fuel salt is circulated through pipes of a special

Figure 19. The Molten Salt Reactor



Nickel alloy that is resistant to molten-salt corrosion. The fuel reaches a compact configuration within the reactor core where the aggregate achieves criticality. Neutron-captures then sustain a chain reaction, with some of the excess neutrons used to breed the U-238 or Th-232 into the fissile fuel, Pu-239 or U-233. In the original design, the breed stock is mixed in the same pipes with the fuel salt. In a modern breeder, the Th-232 or U-238 would be kept in a separate blanket salt. In either case, because the fuel is in molten form, it can be circulated essentially an infinite number of times, with only periodic, *on-site* processing to separate out the fission products and to rebalance the fuel mixture. The burn-up of U-238 or Th-232 can therefore be almost complete, with no unnecessary transportation of nuclear materials.

The design of the MSR furthermore allows the incorporation of many safety features. At the top of the reactor core are conventional control rods made of efficient neutron absorbers whose positions can be inserted more into the reactor core (to slow down the reaction rate), or withdrawn from the core (to speed up the reaction rate). This operation is done remotely and represents an active form of control. If the electric power fails, active control is lost, but the vertical positioning of the control rods guarantees that gravity will pull the control rods into the reactor core without operator intervention. The drop of neutron absorbers into the rector core then shuts down the reactor automatically.

If for some reason, the control rods still get accidentally stuck, and the fuel salt begins to get hotter, there is a second line of passive defense. A rising reaction rate in the reactor core will increase the temperature of the fuel salt, causing it to expand out of the reactor zone. The reaction rate of the molten fuel salt will then slow down, again without any active operator participation. This passively safe concept was tested in the MSRE, where all active pumping of the fuel salt was deliberately turned off. The reactor proceeded to shut itself down without human help.

Finally, if a mishap should cause both of the above safety mechanism to fail, and the fuel salt temperature continues to rise, there is a third passive line of defense. At the bottom of the fuel line assembly is a freeze plug, made of a non-eutectic mixture of salts that has a melting temperature equal to the highest at which one wants to operate the reactor. If the fuel salt exceeds this maximum, the freeze plug melts, causing the molten salt in the fuel lines to drain out automatically into waiting, sub-critical, emergency holding tanks.

There are also intrinsic safety features built into the materials used in the MSR. Foremost is the molten salt itself, which has a high heat capacity but a low vapor pressure. Thus, the reactor can be operated below atmospheric pressure (to blow radioactive gases inward not outward in case of a leak), with no expensive requirement of high-pressure containment vessels that need additional safety built in to prevent coolant explosions. The fuel salt is its own primary coolant, and a rupture of the pipes caused, say, by a strong earthquake carries both coolant and fuel away from the core. The fuel salt is designed to have a molten state, so there can be no associated "meltdown." Instead, outside the pipes, it will freeze into a solid after splashing into a pan embedded with neutron absorbers (not drawn). A TMI-style accident cannot occur with the MSR.

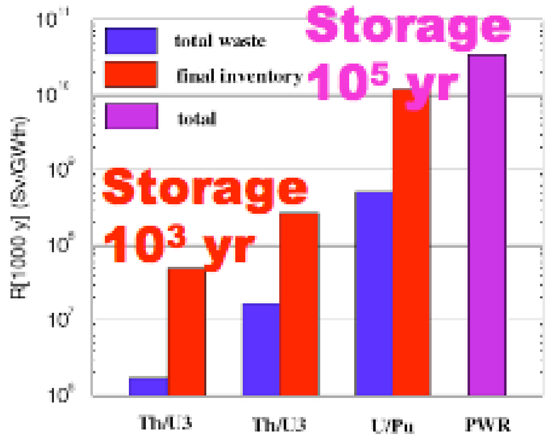
Furthermore, if the reactor is housed in a double-walled outer-containment structure, no release of radioactivities on the scale of the Chernobyl accident will occur, even in the event of a commercial jet crash or a strong earthquake. Given human nature, small accidents involving nuclear reactors are inevitable. On-site chemical processing will produce occasional spills. Proper engineering design must ensure containment. Such precautions can make the massive release of radioactivity into the neighboring environment highly improbable.

High-Level Waste

Figure 20 shows a bar graph of the relative amounts of high-level waste generated during 200 years of operation of different fleets of nuclear power plants that have the same power outputs. From left to right, the four reactor types being compared are the MSR using a Th-2333/U-233 cycle; a fast-neutron breeder using a solid-fuel Th-232/U-233 cycle; a fast-neutron breeder using a U-238/Pu-239 fuel cycle; and a pressurized light-water reactor (PWR) using conventional U-235/Pu-239 fuel. The amount of high-level waste is computed after 1000 years of unloading the spent fuel from the reactors.

Compared to PWRs, the direct volume of high-level waste (far-left blue bar) from MSRs is several thousand times smaller because of the complete burn-up of fuel. Even after contamination of the chemical processing equipment is taken into account, the final inventory for MSRs (far-left red bar) is smaller in volume by roughly a factor of 400. Moreover, instead of having to store the spent fuel rods safely for 10^5 years, the high-level waste from MSRs is mostly composed of fission products that can be safely disposed of, or mined for their rare elements, after only 10^3 years.

Figure 20. High –Level Wastes of Different Reactor Types



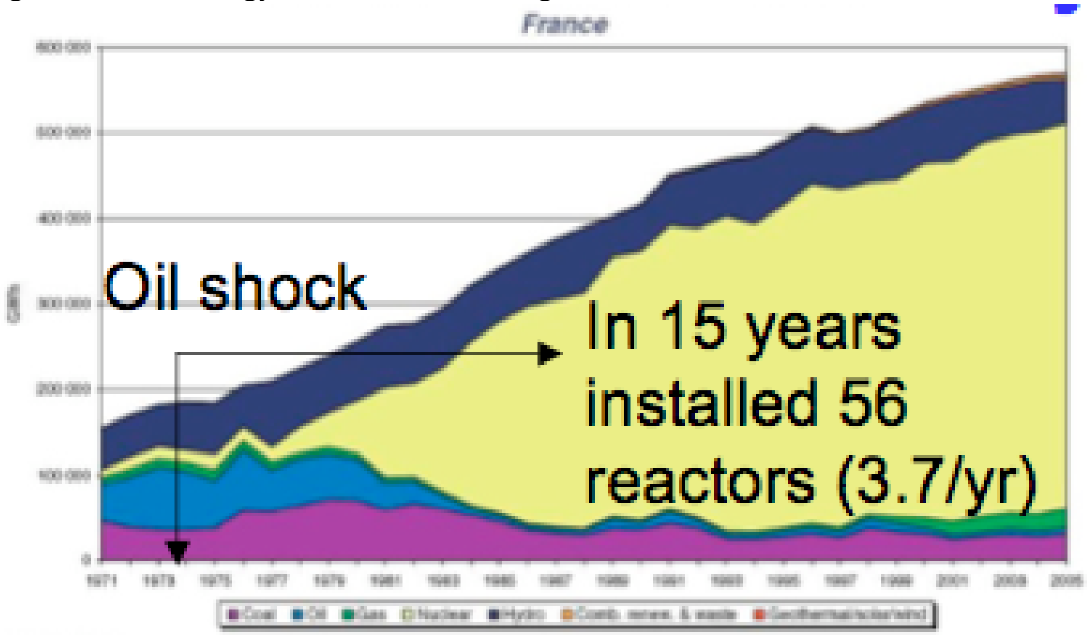
A Rational Energy Roadmap

Today, the world has 435 nuclear power plants with a total capacity of 0.37 TWe. If we wish to reach 25 TWe in 42 years, we would need to build 1 reactor unit a day, each generating 1.6 GWe. For Taiwan to acquire an additional 70 GWe generating capacity in 42 years, it would have to build 1 such reactor unit per year. These numbers are easy to remember: one per day for the world, one per year for Taiwan. We should add perhaps 10% to these numbers if we want separate reactors that produce synfuel for trucks, trains, boats, and jets via reactor heat.

Although commercial MSRs would not come online perhaps until after 20 years of R&D, it is possible to start enough of them on the accumulated plutonium/actinide stockpile in the world to make a complete transition by mid-century to a Th-232/U-233 fuel cycle. In other words, one can avoid building many additional (advanced) LWRs. On a time scale of decades, an adequate fleet of MSRs could rid the world forever of its dangerous stockpile of plutonium generated by civilian and military LWR programs. Because of the potential simplicity of the reactor design and lack of high-pressure containment vessels, estimates indicate that MSRs may be cheaper to build and operate than LWRs.

To aid weapons non-proliferation, in the reprocessing of LWR spent fuel, one should ensure that Pu-239 is never separated from the other actinides before these are all burned. The depleted uranium from LWRs, which has most of the volume, should be separated out by the molten salt technology and entrusted with the military, which can use such materials for armor and armor-piercing shells in conventional warfare. And in the Th-232/U-233 fuel cycle involving MSRs, one must ensure that U-233 is never separated from its sister isotope U-232. Some U-232 is always generated in the neutron irradiation of Th-232. Part of the decay chain of U-232 involves gamma radiation, and gamma rays are easy to detect, so a bomb would be difficult to conceal. Gamma rays also wreck havoc with any modern electronics associated with atomic weapons production. Thus, such an energy roadmap provides a satisfactory resolution of the issues of safety, cost, nuclear waste, and weapons proliferation that otherwise plague discussions of using nuclear power to solve the twin problems of global warming and the energy crisis.

Figure 21. The energy mix of France through the decades.



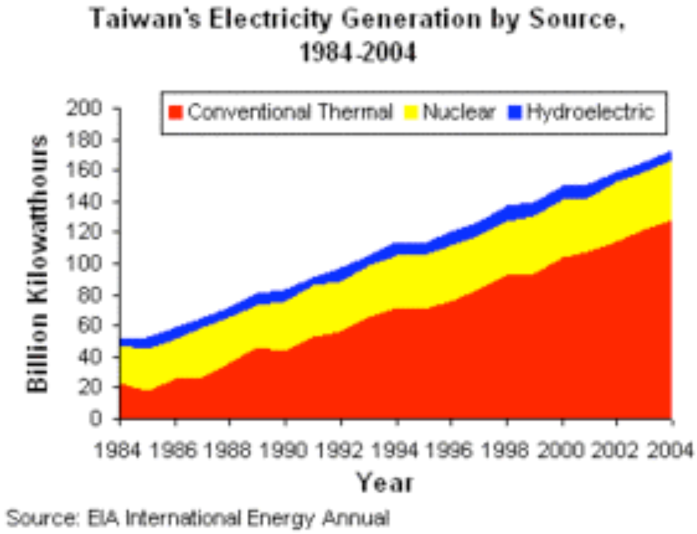
Still, the task of building one 1.6 GWe reactor per day for the world and one per year for Taiwan sounds daunting. The schedule is very ambitious. Can it be done? Figure 21 shows that not only can it be done, but also in some sense it has already been done.

Toward the end of 1973, the first oil shock motivated France to start a crash program of constructing nuclear reactors. Within four years, they began to see the fruits of their labors. Within fifteen years, they had built 56 reactors, for an average pace of 3.7 reactors per year. Now, France has 3 times the population of Taiwan, so a properly mobilized Taiwan should be able to reach a pace of 1 reactor per year (albeit, bigger than the ones being built in the 1970s and 1980s). After all, Taiwan is on schedule to build one large coal-fired plant per year. Why can it not replace these huge structures with one, relatively small, nuclear power plant per year?

France also has roughly 1% of the world population, so 100 times 3.7 reactors per year, or roughly 1 reactor per day, does not seem an impossible job for the whole world. After all, 35 years of progress have occurred since France managed its feat.

When one looks at a similar historical plot as Figure 21, but for Taiwan (Fig. 22), one cannot help but feel a twinge of remorse. In 1984, Taiwan and France had rather similar mixes for their energy portfolios, with nuclear power and hydroelectric accounting for about half of the total power generation. However, Taiwan followed a policy of not expanding its nuclear fleet during an era when its hydroelectric capacity had essentially saturated. The consequence was a steadily growing fraction of the energy mix being gained by the burning of fossil fuels as the economy expanded and energy consumption per capita increased. Looking back at this history, we see clearly that in energy policy, Taiwan would have been much better off today had it emulated France, and not the United States.

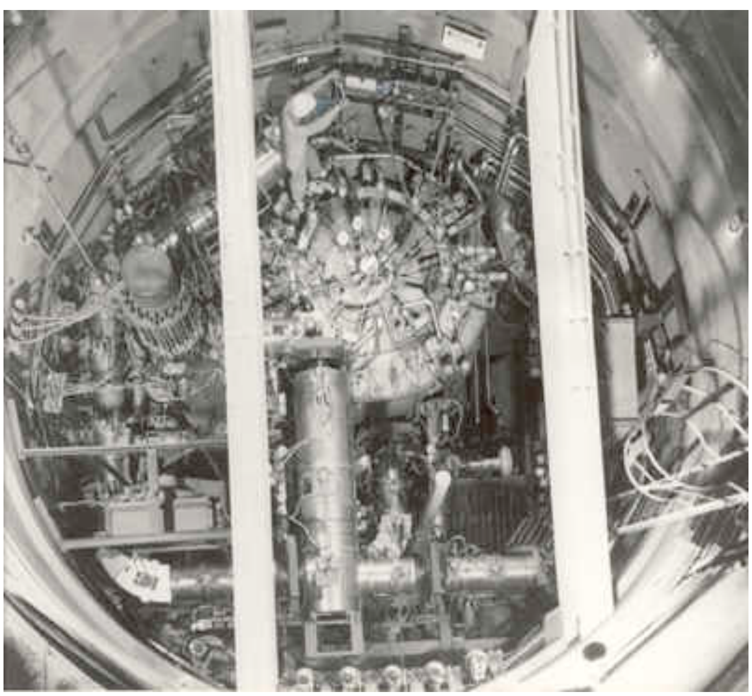
Figure 22. The energy mix of Taiwan through the decades



History of the MSR

According to the opinions of many reactor experts, the molten salt reactor was a wonderful invention. Why then did the USA cancel this project in 1972 after a small experimental power reactor (MSRE, Fig. 23) had been built, but before a full-scale power reactor was attempted? The reflections of Alvin Weinberg, the Director of ORNL during the development of the MSR, and of H. G. MacPherson, the Principal Investigator of the MSRE project, are illuminating.

Figure 23. The MSRE as built and operated by the ORNL in Tennessee



Writing in his memoirs, Weinberg states that the Atomic Energy Commission did not understand the MSR because it had "too much chemistry." In 1973, Congress summoned Weinberg to explain why he thought that LWRs, as then designed, were not sufficiently safe. He was told that if he felt safety to be a major concern for nuclear reactors, then maybe he should step down as Director of the ORNL. Fired from his job, he was vindicated in his judgment six years later when the TMI accident occurred. Almost too late, the nuclear power industry began a program of retrofitting their reactors with passive safety devices. However, the large improvements in safety occasioned by such actions received a devastating blow when the former USSR failed to heed similar warnings, and allowed the disastrous Chernobyl accident to occur in 1986. The subsequent cover-up by the government may have hastened the dissolution of the USSR.

MacPherson has a somewhat different interpretation why the MSR project was eventually cancelled. He writes in a published reminiscence that the MSR encountered too much opposition from entrenched groups. He actually used more polite language, but the meaning is the same. In any case, we are left to speculate what groups MacPherson regarded as the entrenched opposition. Did the US military prefer the rival concept, the liquid-sodium fast breeder, because it represented technology that could produce Pu-239 quickly and efficiently, which the military wanted for atomic bombs? Did they have little use for a design, the MSR coupled with the Th-232/U-233 cycle, that would only consume Pu-239, and produce none in return? Did the nuclear power industry not want a reactor, the MSR, that did not involve solid-fuel fabrication? Had they already stumbled on the business model (perfected later by Hewlett-Packard) of earning profits, not by selling the customer the reactor (printer), but by charging a premium for the disposable fuel rods (disposable ink cartridges)? Or did the vast array of researchers working on the liquid-sodium fast breeder not want competition from the MSR, and thereby torpedoed the latter through the scientific review process?

MacPherson attributes "the stigma of abandonment of the MSR by the country of its origin" to why there is no funding for its development anywhere in the world. But trying to assess blame may not be constructive. The decisions made thirty-five years ago occurred in a very different environment. The bright early promise of "electricity too cheap to meter" has bogged down in the marsh of the "plutonium economy." To find a way out of the mire, we may have to abandon the concepts of plutonium as a nuclear fuel, of solid-fuel fabrication as a way of business, and of the once-through fuel cycle as part of a throwaway mentality. This paradigm shift should be acceptable to Taiwan because it has no vested interest in any of the three older ways of thinking. Perhaps potential international collaborators can be persuaded to agree.

Judging Risk: The Realistic Choice Before Us

Given the realities of renewable energy resources, the death knell of carbon capture and sequestration, and the economic aspirations of yet-to-be-born billions of humans, the realistic choice before us is not renewables versus nuclear power, but nuclear power and renewable *in moderation* versus coal burning. In Figure 24, we compare the relatively

Figure 24. Nuclear versus Coal

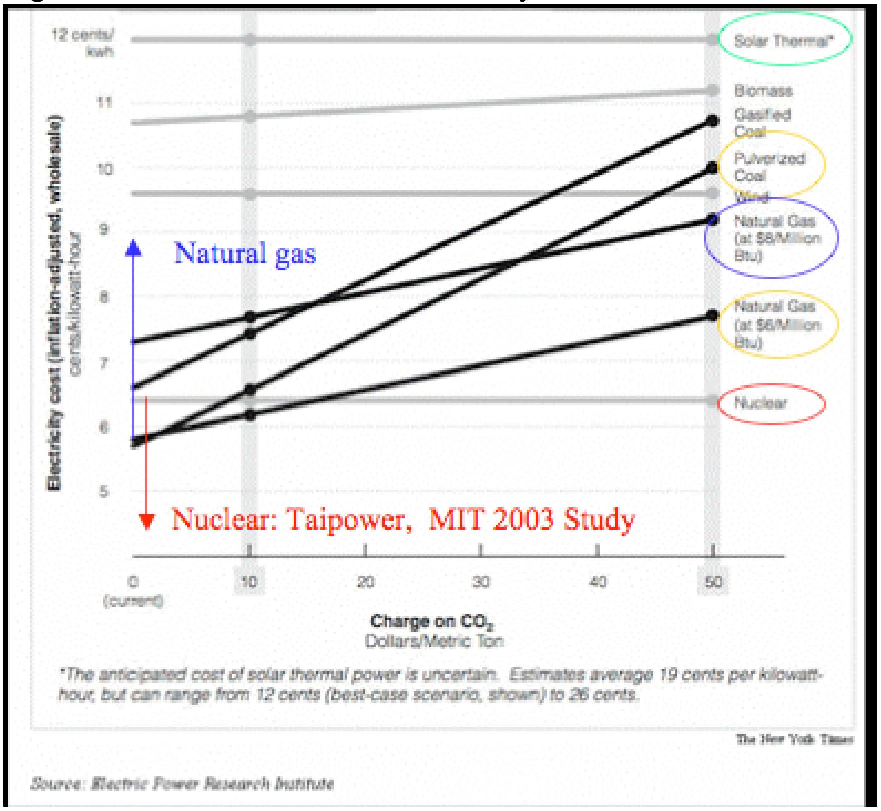
small physical footprint of nuclear power plant 3 in Kenting with the relatively large profile of the Tunghsiao coal-fired plant near Miaoli. The visual choice seems clear as to which has a less deleterious impact on the surrounding environs for the same generation of electric power. The reader who prefers the windmills of the first photograph ought to consider the situation if the number of windmills were ten thousand rather than three.

However, the visuals are the least part of the actual impact. Far more important is what one does not see from the photographs of Figure 24. The meaningful nuclear waste (if reprocessing were available) generated per day by nuclear power plant 3 is 6 kg of fission products. The meaningful waste generated per day by Tunghsiao coal-fired plant is 60,000,000 kg of CO_2. Because the former is a small but visible piece of radioactive solid, and the latter is a colorless, odorless, almost invisible gas (except for accompanying pollutants), we obsess over the former beyond its true threat, while we turn a blind eye to the dangers of the latter by spewing it into an atmosphere that we have mistreated for centuries as a garbage dump. We ignore at our peril the fact that 6 kg per day of even a radioactive solid is easy for modern chemical treatment, whereas 60,000,000 kg per day of a robust, heat-retaining, toxic gas is difficult to capture and sequester once the demon has been let out of the bottle.

Monetary Incentive

Al Gore, the man who should have been President of the United States, but settled instead for a Nobel Peace Prize, announced in 2008 an energy policy that attracted worldwide attention. The centerpiece of his policy that would wean the USA from fossil fuels forever was a carbon tax on CO_2 emission. Many economists view such a tax as the missing monetary incentive. Without it, generating electricity by burning coal or natural gas is regarded as appreciably cheaper than any alternative, including nuclear (data on left-hand border of Fig. 25).

Figure 25. The Economics of Electricity Generation



With a tax of 50 USD per tonne of CO_2 emission, Figure 25 shows that generating electricity by burning pulverized coal or natural gas exceeds or approaches the cost engendered by wind. This analysis ignores the fact that wind-generated electricity is not highly useful without an energy storage system, which involves additional costs. Adding heated molten-salt storage to solar thermal about doubles its plotted price. In any case, such a tax would make nuclear the most economical method to generate electricity.

However, there is a political cost to making energy more expensive. Moreover, China and India have already announced that they will not participate in such a plan. Their cooperation is essential if we are realistically to address the problem of global warming.

Fortunately, the recent run-up in oil price has already had a salutary effect on natural gas prices – they have risen too, roughly to the level indicated by the blue arrow. The effect is the same on that commodity as if the indicated tax on CO_2 emission had been enacted. However, the issue of coal is more complex, as the worldwide price of coal is no deterrent to any country that is intent on using its large domestic reserves of coal. China and America both occupy such a position. Fortunately, here too, economic events have changed the landscape. The experience of Taipower is that the longer a nuclear power plant is in service, the cheaper does it become to operate and to pay off one's initial investment. The real cost of nuclear power in Taiwan has, in fact, already dropped to the level indicated by the red arrow. Nuclear power is already more economical than burning coal for generating electricity.

A study in 2003 by MIT on the future of nuclear energy indicates two effective directions whereby we can push down even farther the lifetime costs of generating electricity by nuclear power. First, we should trim the licensing time of new reactors by placing them on the same sites as existing nuclear power plants. By this method, it should be possible to achieve the construction time of four years for a new plant that is routinely accomplished in Japan and France. Second, we should use modern mass-manufacturing techniques to drive the unit cost down for new reactors. Such a strategy is especially appropriate for Taiwan (and Asia in general), which has perfected the art of cost-down manufacturing. Finally, vastly expanding nuclear capacity should prove an economically attractive option since the investment is capital-intensive and produces numerous good jobs, while the real costs of the fuel is minuscule. Thus, money spent on nuclear reactors, especially on any MSRs that Taiwan builds for itself, will stay at home, and not be shipped abroad as now happens with fossil fuels.

Two Cultures: Dominate Nature or Intrude as Little as Possible

There is a cultural reason why the time is opportune for Asia to take a leadership position in the development of nuclear energy. My father once pointed out to me a key difference in the cultures of West and East. He said that in Western Art, nature often takes a back seat to humans, with the landscape being very small and the person being very large (Fig. 26a). In Asian Art, on the other hand, the landscape is often depicted as being very large, and the humans are very small (Fig. 26b). In Western landscape painting, there are usually no humans. Western culture sees humans as being "Apart from Nature;" Asian culture, as "A part of Nature." So it is with nuclear energy, which has the smallest environmental footprint of all the alternatives to fossil fuels. Nuclear energy generation is entirely compatible with Asian values of intruding on nature as little as possible.

Figure 26a,b. Examples of Western and Asian Art

We All Inhabit This Small Planet

Saving the Earth requires good will, honesty, and everyone's cooperation. Good will is needed to see past the labels of "good guys, bad guys." Everyone wants to solve the problem, so it is counter-productive to call each other names. Honesty is also needed so that all presentations will include both the pros and the cons. Balance is essential if we are not to fool ourselves as to what is possible, and what is not. And the cooperation of everyone is needed because the overall problem is too large for any individual, or even a small group of individuals, to tackle alone.

Figure 27a,b. JFK and the Apollo Mission to the Moon

On this theme, we should recall what John Fitzgerald Kennedy said and did (Fig. 27a,b). JFK was, of course, the second youngest president of the United States. His children were quite small when he entered the White House. After JFK assumed office in 1961, he announced the goal that before the decade was done, the United States would land astronauts on the Moon. During Christmas 1968, the Apollo 8 astronauts orbited the Moon without landing. But from their spacecraft, for the first time in human history, they took a picture of Earthrise. Its broadcast lifted the conscience of humanity: our home is a small planet – very small, but also very beautiful – not like the desolate wasteland that is the Moon. The picture came to symbolize the global environmental movement.

In June 1963, JFK gave a commencement speech at American University on the topic of peace with the USSR. Five months later he was assassinated. Thus, JFK did not live to see his children grow up. He did not live to see the photograph taken by the Apollo 8 astronauts. Yet, he must have seen these things in his heart, because in his commencement speech he spoke the following words:

"So, let us not be blind to our differences – but let us also direct attention to our common interests and to the means by which those differences can be resolved. And if we cannot end now our differences, at least we can help make the world safe for diversity. For, in the final analysis, our most basic common link is that we all inhabit this small planet. We all breathe the same air. We all cherish our children's future. And we are all mortal."

Commencement means a new beginning. So let us make a new beginning. Let us honor JFK's words. Let us rally our spirits for the sake of the future by setting aside our differences and uniting in a common cause to save the world.

Appendix: Limitations of Renewable Energy Sources

In this appendix, we provide numerical estimates to support our conclusions concerning the limitations of renewable energy sources. We begin with the solar energy flux *f*. The Sun's luminosity is $L_\odot = 3.9 \times 10^{26}$ watts, and it lies at a mean distance from the Earth $r = 1.50 \times 10^{11}$ m. Thus, the solar energy flux incident on the Earth is $f = L_\odot / 4\pi r^2$. The Earth has a radius $R_E = 6.37 \times 10^6$ m, and 80% of the solar energy flux incident on it is absorbed on average by the oceans or the ground, the rest being scattered back to space by ice and clouds. Since roughly ¼ of the surface area of the Earth is in continents occupied by humans, the usable solar power that can be harnessed by humans is, when averaged over day and night, latitude, and seasons,

$$0.8 \frac{1}{4} f \pi R_E^2 = 0.05 \left(\frac{R_E}{r} \right)^2 L_\odot = 3.5 \times 10^{16} \text{ watts} = 35{,}000 \text{ TW}.$$

This is a very large number compared to 25 TW, which is what gives primary solar resources their outstanding potential.

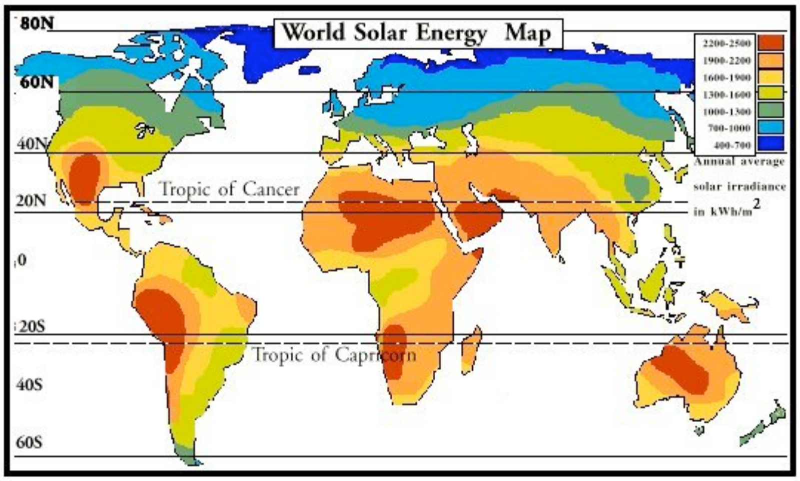
Biofuels

The net efficiency of obtaining ethanol from sunlight using land plants like corn is estimated to be about 0.1%. (Some analysts even claim the number is negative.) Thus, the maximum harvestable power via growing such land plants is 0.1% of 35,000 TW, or 35 TW of ethanol. To obtain 3 TW for t, t, b, j requires the cultivation of corn on about 8% of all the land on Earth. Given that a truck consumes about 100 times the carbon that its driver does, it is better to use the corn to feed the driver and all his relatives.

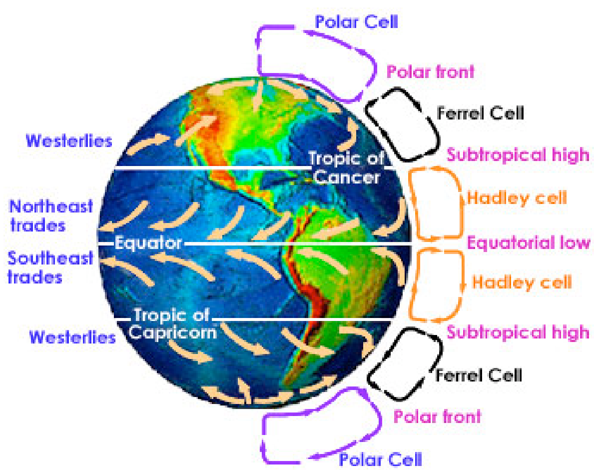
Scientists hope that the production of cellulosic ethanol from switchgrass will be 5 times more efficient than corn., i.e., 8%/5 = 1.6% of all land would have to be devoted to biofuel production to power trucks, trains, boats, and jets. This estimate allows for future improvements and is somewhat more optimistic than expert baselines of 1.12 kg ethanol production per m^2 per yr of land use = 0.89 W m^{-2}. At present technological levels, to obtain 3 TW would require $3.4 \times 10^{12} \text{ m}^2$ or 2.6% of all land.

Photovoltaics

Without pre-concentration (which adds cost), the efficiency of the best solar cells to convert sunlight into electric power is about 20%. Thus, the sunlight falling on land could potentially yield 0.2 times 35,000 TW or 7,000 TWe. To obtain 25 TWe would only require 0.36% of the land area of Earth. In fact, we should avoid very northerly or southerly latitudes (where the Sun can disappear for months), so in the text, we rounded the number down to 0.3%.



Wind



The power of wind is derived from uneven solar heating, with the meridional circulation of Hadley cells deflected by Coriolis forces associated with the Earth's spin to easterlies and westerlies at sea level. The maximum efficiency for a heat engine of this type is given from the second law of thermodynamics by Carnot's formula:

$$\varepsilon = \frac{T_g - T_E}{T_g} = 0.14$$

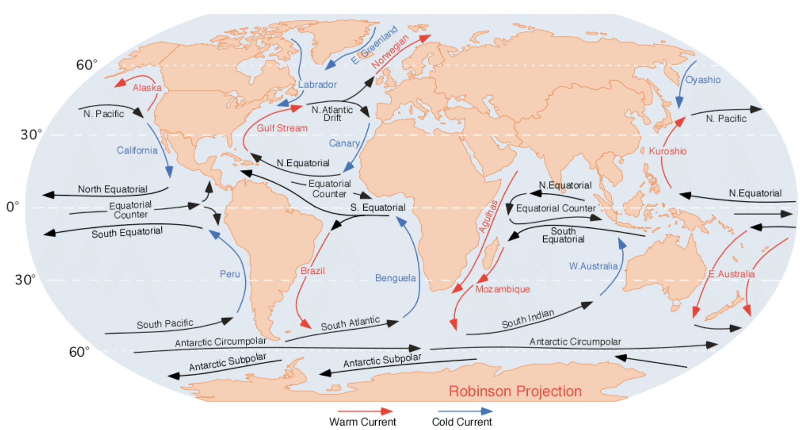
if we model the heat input as coming at a ground temperature $T_g = 290$ K and the heat output as occurring at an effective temperature $T_E = 250$ K. Thus, the maximum wind power over land is 0.14 times 35,000 TW or 4900 TW. This wind power is distributed over 8 km of atmosphere (or an air mass of 1.3×10^{18} kg over land), and if we assume that it is renewed against frictional losses every 24 hr = 86400 s, we obtain a mean wind speed for this air mass equal to

$$\sqrt{2\frac{(4.9\times10^{15}\ \text{w})(86400\ \text{s})}{1.3\times10^{18}\ \text{kg}}} = 26\ \text{m s}^{-1}.$$

At the hub height of a good location for windmills with arms of diameter D = 80 m, the mean wind speed might be 7 m/s (e.g., at the Horns Rev site in the North Sea). Since kinetic energy varies as the square of the speed, and since we are only tapping 80 m out of 8000 m of atmosphere, we get a fraction $(80/8000)\times(7/26)^2 = 0.00073$ of 4900 TW, or 3.6 TW in the kinetic energy of wind. If we assume a conversion efficiency of 50% into electricity, the second law of thermodynamics yields the maximum extractable electricity generation from wind as 1.8 TWe, which we rounded up to 2 TWe in the text.

Note that the above number is much less than the 72 TWe from a 2005 Stanford study that assumed $4D\times7D$ spacings at the best 13% of wind locations in the world. Such a relatively dense packing of windmills, however, will introduce "shadowing" and "drag" if applied on a global scale, violating a basic assumption of the study, which is that each windmill acts as an independent entity. (In effect, the whole array of the Stanford study is using the same wind energy multiple times.) We believe that our method gives a more realistic estimate of the maximum extractable electric power from wind.

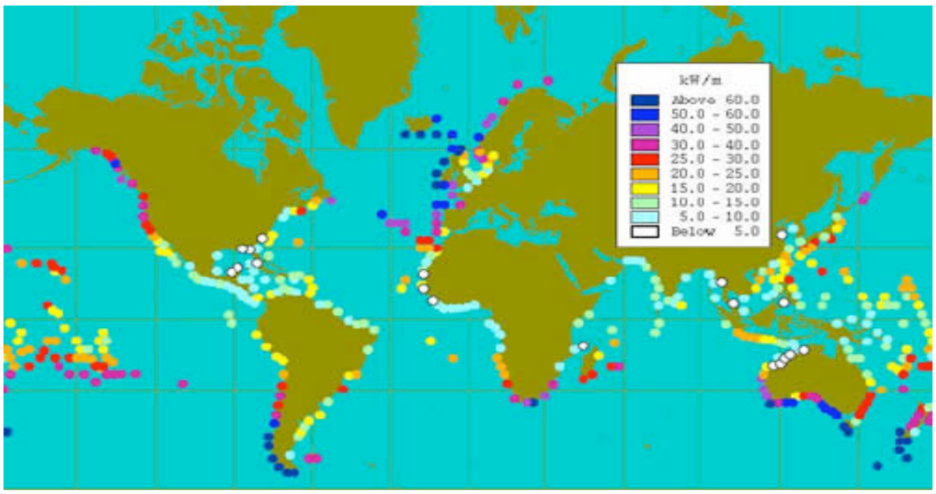
Ocean Currents



A glance at a map of ocean circulation shows that ocean currents (like winds) mostly flow east-west and not north-south until they are driven against the shores of continents. This suggests that the major role in establishing the steady pattern of ocean circulation is played by wind (Ekman) drag over the ocean's surface (as pointed out by the oceanographer Walter Munk). The Kuroshio current has a mean speed v ~ 1 m/s and a cross-sectional area (depth times width) of $A \sim 1$ km x 200 km = $2\times10^8\ \text{m}^2$. With a density of water $\rho = 10^3\ \text{kg m}^{-3}$, the Kuroshio current has a power $\rho v^3 A/2 \sim 100$ GW. Assuming an efficiency of 50% for conversion to electricity, we get a maximum extractable power of ~ 50 GWe from the Kuroshio current. Taiwan can tap only a small fraction of this maximum without affecting the climate and marine environment of Japan.

Ocean Waves

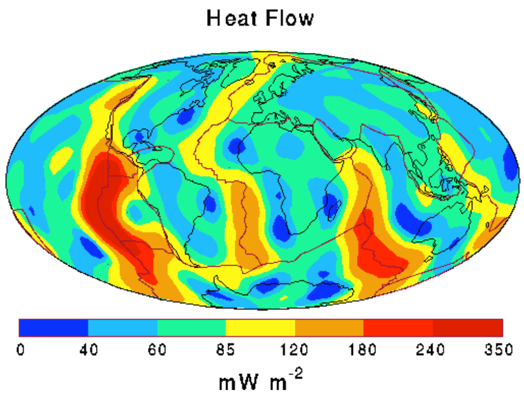
Ocean waves are created by instabilities when wind blows over the water of the sea. Thus, the power in ocean waves must be less than in wind. However, because water is 800 times denser than air, it might be easier to tap this power. We can tap the power only if we make use of the motion of the bobbing of the waves relative to the bottom of the sea. This implies that we can do it within only a limited distance from the shores of Earth.



If we look at a map of the wave power available near the shores of Earth, we get an average of 30 kW per m of usable energy impingent on shorelines. The regions of strong wave power are, not surprisingly, where strong east-west winds drive against the north-south shorelines of the continents. Since the world has roughly 4 such north-south shorelines, each with a total pole-to-pole length of $\pi R_{\text{E}} = 2\times 10^{7}\,\text{m}$, the maximum extractable power from ocean waves is $(30\ \text{kW/m})\times 4\times(2\times 10^{7}\ \text{m}) = 2.4\ \text{TW}$. EPRI of the DOE of the United States cites a workable fractional coverage of 20% for power generating buoys, each with an efficiency of 50% of converting the wave power into electricity. Adopting these estimates, we get a maximum of 0.24 TWe if we use the wave energy impingent on all the shorelines of Earth to generate electricity.

Geothermal

From the law of Dulong and Petit, we estimate the reservoir of heat energy E in the Earth's interior to be $3NkT$, where N is the total number of atoms inside the partly solid, partly molten Earth, $3k$ is the classical heat capacity of an atom in a solid, with $k = 1.38\times 10^{-23}$ joule K^{-1} being the Boltzmann constant, and T is the mean interior temperature of the Earth. The mass of the Earth is 6.0×10^{24} kg, composed of rock where oxygen (A = 16), silicon (A = 28), magnesium (A = 24), and iron (A = 56) are the most common atoms. If we take the mean atomic weight to be 24, with the atomic mass

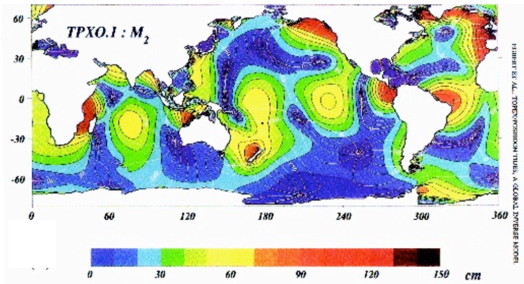


unit being 1.67×10^{-27} kg, then the Earth has $N = 1.5 \times 10^{50}$ atoms. If we further estimate T to be roughly 1000 K, we obtain $E = 6 \times 10^{30}$ joule. This heat is left over from the energy of the formation of the Earth plus radioactive decay. The time scale for heat leakage out of the Earth must exceed the age of the Earth, 4.6 Gyr = 1.5×10^{17} s, since the Earth's interior is still hot. With a time scale of flow to the surface $t_{flow} \sim 1.5 \times 10^{17}$ s, we obtain the heat flow to the surface to be $E / t_{flow} \sim 40$ TW. A global heat flow map shows that the part on land has about $(0.07 \text{ W m}^{-2})(1.3 \times 10^{14} \text{ m}^2)$ = 9 TW, roughly ¼ our global estimate. However, the temperature of the ground is empirically only $\Delta T_g \sim 1$ K warmer than the air above it at night because of this extra heat flow. The maximum thermodynamic efficiency for using this temperature difference is $\Delta T_g / T_g \sim 3 \times 10^{-3}$, yielding 30 GWe extractable from the dilute mean flow to land.

A more realistic geothermal strategy goes after the hot spots where ΔT_g is much larger. Famous for it hot spas, Iceland generates 0.5 GWe this way. An MIT study has looked into enhancing the output by drilling boreholes to the hot rock that lies everywhere if one goes deep enough (say, 10 km). This study estimates a worldwide extractable energy store of 2×10^{24} joules, which is much less than the $3NkT$ we computed for the whole Earth, but much greater than the 3×10^{22} joules in known coal reserves. Nevertheless, mining for heat is harder than mining for coal, and the MIT study cited a plausible rate of heat extraction for the US of 0.1 TW. Given the lesser capabilities of the world in general, it is difficult to imagine getting more than 4 times this value (multiple of total energy usage) for the whole world, or 0.4 TWe.

Tidal

The differential gravity of the moon relative to the near and far sides of the Earth lifts the ocean's surface relative to the surrounding land by an average of 0.5 m every 12.5 hours = 45,000 s. Since the ocean has a surface area of 3.8×10^{14} m^2 and the density of water is 10^3 kg m^{-3}, the total mass of water involved is $(0.5 \text{ m})(3.8 \times 10^{14} \text{ m}^2)(10^3 \text{ kg m}^{-3})$ = 1.7×10^7 kg, with each mass element displaced by 0.25 m relative to its mean position every 45,000 s against the gravitational field of the Earth, $g = 9.8 \text{ m s}^{-2}$. The total ocean power associated with tides is then $(1.7 \times 10^{17} \text{ kg})(9.8 \text{ m s}^{-2})(0.25 \text{ m})/45000 \text{ s} = 9.2$ TW.



Most of the energy of relative displacement is out in the deep ocean where it is difficult to tap. Assume that we can access only a band of 2 km width along the 4 north-south shores of length 20,000 km associated with the major continents, resulting in a surface area of 1.6×10^5 km^2. Compared to the total surface area of the Earth = $4\pi R_E^2 = 5.1 \times 10^8$ km^2, we then have access to only a fraction 3.1×10^{-4} of 9.2 TW, or roughly 3 GW, as cited in the text. The efficiencies are high, around 80%, for generating electricity only in bays where funneling leads to high tides in excess of 5 m. One can then trap the water behind dams, letting it flow out at low tide past marine turbines to generate electricity. This process only concentrates the tidal energy; it does not increase the total. It has been estimated that the Bay of Fundy between Nova Scotia and New Brunswick could generate as much as 1 GWe by such a process.

Hydroelectric

Taiwan has lots of rain and mountain valleys. How much hydroelectric power can be generated as a consequence? The average rainfall has a height of 2 m every year. Taiwan has a total land area of 3.6×10^{10} m^2. With a water density equal to 10^3 kg m^{-3}, the annual mass of rainfall is the product of these three numbers, or 7.2×10^{13} kg. After collection into streams and rivers, if this water falls 100 m through the gravitational field of the Earth, it will release a potential energy of $(7.2 \times 10^{13} \text{ kg})(9.8 \text{ m s}^{-2})(100 \text{ m})$ = 7.1×10^{16} joule. (It is hard to build wide dams much taller than 100 km because of the pressure on the concrete at the base of the dam.) This release occurs over the course of a year = 3.15×10^7 s, giving an average electric power generation when multiplied by an efficiency of 90% equal to 2 GWe. Taiwan's installed capacity is about 1 GWe, meaning that hydroelectric power is saturated at 50% of the maximum amount. If one performs a similar calculation for the world, one obtains that 3 TWe is the maximum that can be extracted from hydroelectric generation if one were to dam all the rivers of Earth.