Nuclear Power in the World's Energy Future

by
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Felice Ippolito Lecture
Rome, Italy
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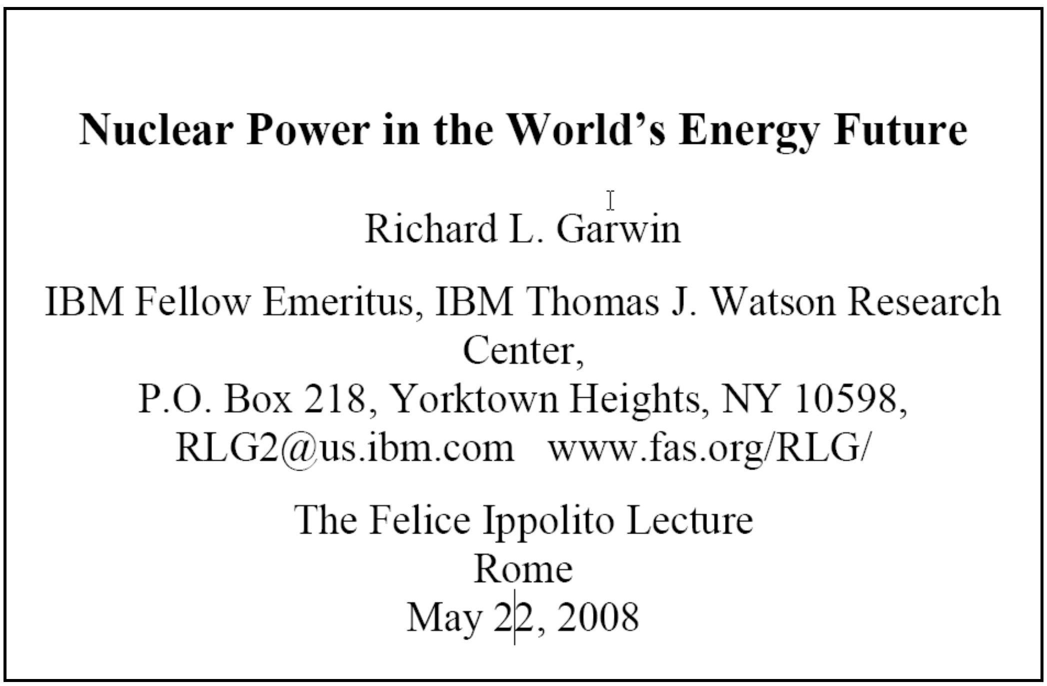
Nuclear power is still a miracle of nature, science, and technology. In this talk I want to indicate where we are and where we might be in the use of nuclear power to supply energy to society, taking into account other sources of energy and the requirements of safety, economy, environmental protection, and the availability of an adequate fuel supply. *Slide 1 is the title of the Ippolito Lecture, as presented.*



All here know that Enrico Fermi and his colleagues "I ragazzi di Via Panisperna" in 1934 found a bewildering array of radioactivity when they turned to investigate uranium with their marvelous new tool of slow neutron capture. Not until 1938 was it realized that they had caused fission of uranium, breaking the heavy nucleus into two, typically one less than and the other considerably more than half its mass, with the emission of an amount of energy enormous on the nuclear scale—some 30 times that of the ordinary radioactive decay. Soon after the recognition of fission, in 1939, it was established that each fission in uranium caused by the absorption of a neutron led to the emission of several neutrons, and the dream of Leo Szilard of 1932 was in sight. Now it could be imagined that one could have a neutron chain reaction, which for the production of power would have an almost unimaginable number of neutrons each second reproducing themselves on the average, accompanied by the destruction of a modest mass of uranium and the corresponding production of heat to be turned by normal engineering methods into electricity. Some examples of nuclear power plants in France and Japan are shown in Slide 2 and the fission reaction is pictured in Slide 3.

Outline of Talk

Nuclear power is still a miracle of nature, science, and technology.

Where we are. Where we might be to make a difference in the world.

The world's energy future.

Energy use, where. Energy use, how.

Current production not easy to maintain—production vs. resource.

Current production is not enough—Population; development and increasing living standards are even more important.

Energy field highly noncompetitive—e.g., OPEC, ENRON.

Not running out of energy. To quote John Holdren, Running out of: cheap energy; environment; societal will; time.

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Four nuclear reactors at the Cattenom nuclear power plant in France

Three-reactor NPP at Itaka, Japan

NUCLEAR POWER IS A MIRACLE, ANALOGOUS TO FIRE

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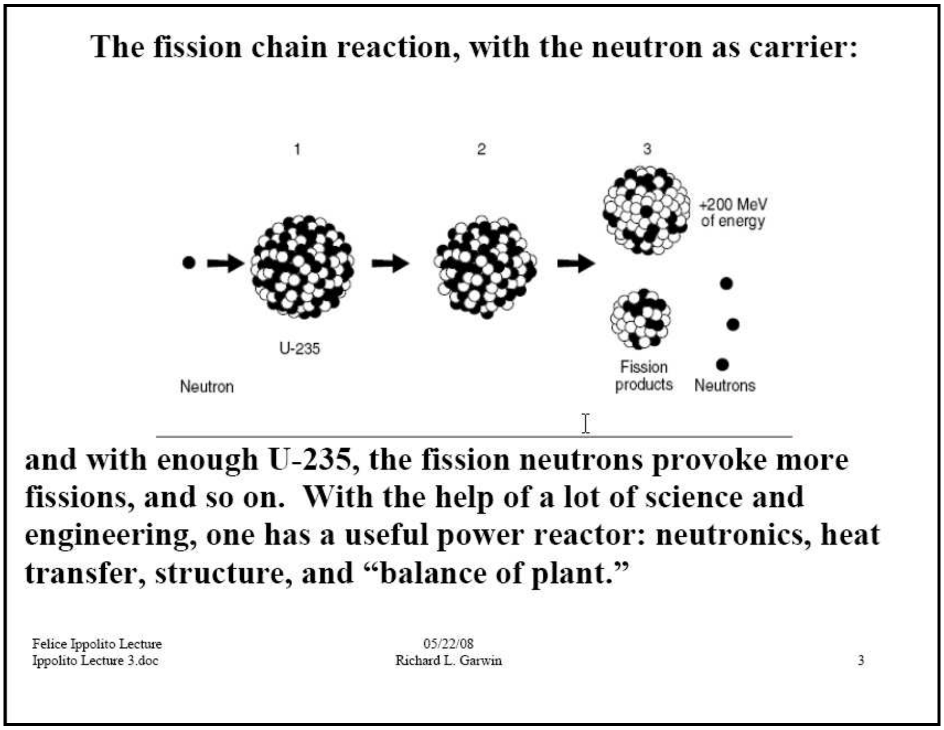


Of course, the first application of nuclear fission was the goal of a substantial mass of fissionable material, especially uranium-235, which was achieved in 1945 with some tens of kilograms brought together in a time of a few milliseconds in an ordinary artillery gun. A few neutrons injected by an ingenious polonium-beryllium initiator—caused double that number to be produced and ten nanoseconds later four neutrons, followed by eight after a further ten nanoseconds, and so on, until in less than one microsecond energy was liberated comparable to that produced by the explosion of 13,000 tonnes of high explosive. In the process, almost a kilogram of uranium had been transformed into highly radioactive materials with multiple beta and gamma decays that contributed an enormous blast of radiation from the exploding bomb and would continue to provide significant energy release for years as the debris rose to the stratosphere and fell to Earth over the next years.

Our purpose here is not to discuss nuclear weapons but nuclear power; in a nuclear power plant, rather than the rapidly expanding population of neutrons and the growing rate of release of energy, the ideal is to have a perfectly steady rate of fissions. The Hiroshima bomb fissioned a kilogram of uranium in less than a microsecond. A normal large-scale million-kilowatt nuclear plant fissions about 1 ton of uranium per year—about 1000 Hiroshima bombs.

In my discussion, I will standardize on the plant typical of the 300 full-size nuclear power reactors operating in the world today—generating each a million-kilowatts of electricity. These plants now operate at very good "capacity factor", delivering the rated electrical output about 90% of the time, with most of the downtime being intervals for annual refueling or for planned maintenance.

The world's 400+ power reactors contribute now almost 16% of the energy in the world. I can't show you a picture of a nuclear power plant in Italy to compare with those in France or Japan. In the United States, 103 reactors produce some 20% of the electrical power. The plant itself is normally innocuous, but is obviously connected to power transmission lines for delivering its valuable product and periodically must receive nuclear fuel, typically about 25 tons each year of uranium containing 4.4% U-235, in contrast with the 0.7% U-235 in natural uranium.

The usual power reactor is a very concentrated source of power, producing electricity to sustain about a million people. This can readily be seen from the numbers I provided—100+ reactors provide 20% of electrical power for a United States of 300 million people; 500 reactor-equivalents would provide ALL of the power for 300 million people, so a single reactor would empower about 0.6 million U.S. residents.

In our discussion of world energy futures, we'll note the enormous disparity between the developed world and the less developed world, even India and China. But now I want to characterize the reactor as a node in a system of supply of fuel, delivery of electricity, and creation of "spent nuclear fuel."

The 25-ton annual reload of uranium fuel to a power reactor could, conceptually, fit easily in a single railway freight car. Similarly the spent fuel from the reactor which is 1 kg lighter according to Einstein, because of the mass that has been absolutely converted not only into electrical energy of a million kilowatts for 8000 hours, but also into the heat that constitutes twice as much energy and is dissipated typically to cooling water in a neighboring lake or river.

Following this a bit farther, though, the 25 tons of uranium at 4.4% U-235 is derived from about eight times that much (200 tons) of natural uranium, that, itself, with a uranium ore concentration of 0.1%, corresponds to about 200,000 tons of ore mined in Australia, Canada, Russia, or one of the other sources of crude uranium, an article of commerce known as "yellow cake".

In contrast, a coal-fired plant requires about 3 million tons of coal to be delivered each year to the power plant, and results in almost 10 million tons of carbon dioxide—CO2—ejected into the atmosphere each year. It is clear that the transport of nuclear fuel is far less a burden than the transport of coal, as was evidenced by the impact of unusual snowstorms in China on the transport of coal to fuel the electrical generating and industrial plants of China in January 2008.

Indeed the disposition of ash from conventional coal-fired plants is also a problem, constituting as much as 10% of the 3 million-ton annual feed (at this point, we resort to a more compact notation in which a million is represented as "M" so that 3 million tons is 3 MT) and the ash requires perhaps 0.3 MT of transport capacity annually.

No matter what is done with the ash (much of it made into concrete) it does require transport of enormous magnitude compared with the transport of fresh or spent nuclear fuel.

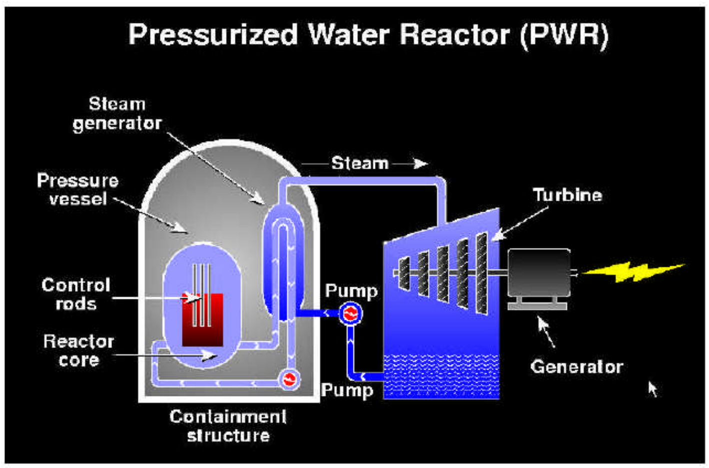
But the ash from a coal-fired plant is inert; once having cooled from the fiery temperature of the boiler to room temperature, it is like any other material, although it may contain toxic elements to some extent. The "ash" from a nuclear plant has nothing in common with that. At 25 tons per year it is perhaps 10,000 times less massive or voluminous than the ash from a coal-fired plant, but the comparison stops there.

Fresh fuel for a normal reactor consists of thin-walled metal tubes filled with small pellets of uranium oxide ceramic containing about 4% fissile U-235 and 96% U-238. Spent fuel, removed after 4 years in the reactor has about 4% fission products 0.9% residual U-235, 1% plutonium (about 65% fissile Pu-239 and Pu-241) and about 0.1% non-Pu transuranic elements. Pu-239 is formed by non-fission capture of neutrons on U-238. The U-235 in spent fuel would seem to be valuable, present in larger concentration than in natural uranium (0.7%), but in fact uranium from spent fuel sells for a lower price than does natural uranium, in view of the U-236 that is present, and a relatively small amount of U-234. The major problems though with the spent nuclear fuel are in the fission products which are highly radioactive, with the longest-life dominant components Sr-90 and Cs-137, each, coincidentally, of half-life about 30 years. The Sr-90 is a "pure beta" emitter, so requires very little shielding to be transported, but Cs-137 has an intense gamma ray and a tiny fraction of the annual production is used as an artificial source of very high energy "X rays" for medical diagnosis or treatment. Together with the other fission products, these 30-year half-life elements produce heat, and as a result a fuel element downloaded from a nuclear reactor, even after two years of 'cooling" in a deep pool at the reactor, if lifted into the air by a hoist or crane glows red hot within minutes because of the heat produced by the continuing decay of the fission products. About 10% of the mass of fission products have radioactive lifetimes exceeding a million years.

Despite the self-heating from radioactive decay, the spent fuel, after two or five years of cooling at the reactor (in the French model) can safely be transported in heavy-walled casks for ultimate deposition in a mined underground repository, or, in the case of France and soon-to-be Japan, to a reprocessing plant where the uranium, plutonium, and residual components of the spent fuel are separated. Being less valuable than natural uranium, the recovered uranium is often simply stored, with little radioactivity involved. The plutonium is separated in order to be recycled into mixed-oxide fuel (MOX) in which typically 5% Pu is diluted with uranium left over from the enrichment process ("depleted uranium") to form fuel elements that are essentially equivalent to the enriched uranium elements used in reactors (sometimes called UOX).

The fission products, intensely radioactive and containing as presently practiced the "transuranics" beyond plutonium, are vitrified with an appropriate glass-forming material and cast into stainless-steel containers, welded closed and cleaned. These are then stored with airflow to cool them, until they can be deposited into a mined-geological repository—MGR. Although this process is advertised in France and Japan as essential because these nations are without fossil fuel resources or native supplies of uranium, the maximum saving of fresh uranium is 20%, and the saving is achieved at a cost equivalent to $700 or so per kg of natural uranium. Traditionally uranium has been available at a cost of $30/kg, although it has spiked to $100/kg recently.

The present reactor fleet consists primarily of so-called light-water reactors with a small component of heavy-water reactors and graphite-water reactors. Slide 4 sketches a light-water reactor—LWR--in which uranium is fissioned in a thick pressure vessel containing about 100 tons of LEU, producing 3000 MW of heat, converted at about 33% efficiency by a turbine into 1000 MW of electrical output.



Schematic of the PWR, the most common power reactor

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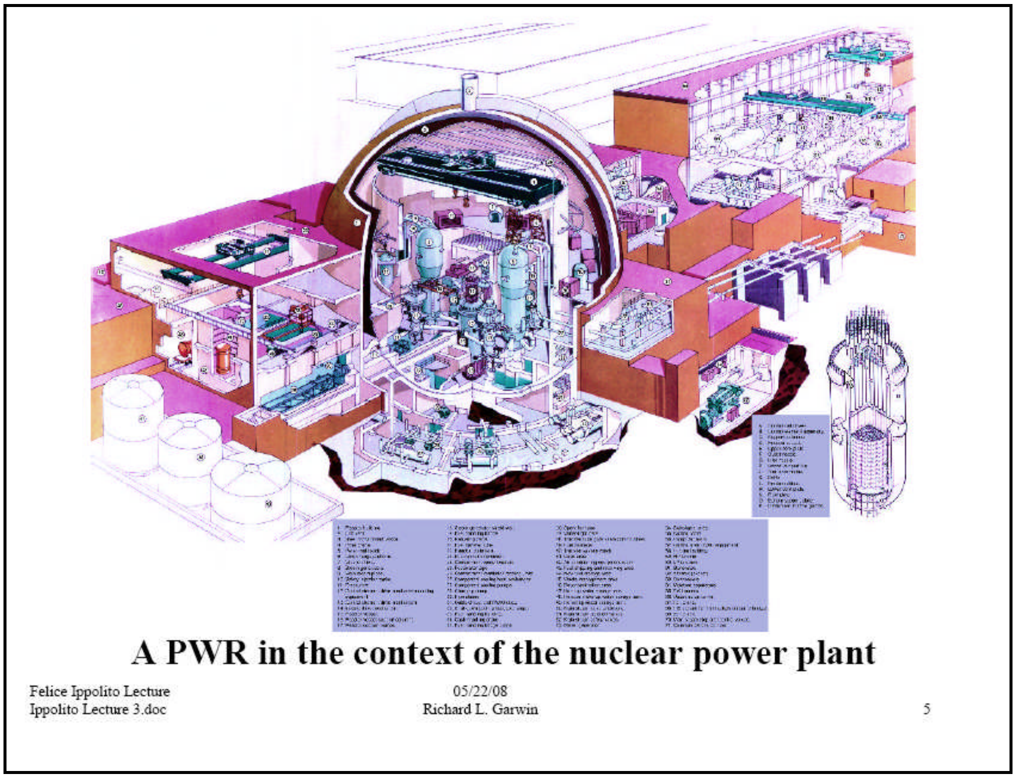
I want to consider expanding the present 20% of electrical power from nuclear energy to essentially all of electrical power, and to satisfy half of the remaining energy needs, leaving aside only remote locations and transport. In an expanding population and with, as we all hope, an improving standard of living, the power requirements of the world will increase rapidly. About 2000 reactors would, in principle, provide all the electrical power now used in the world, and 6000 would satisfy all current energy needs. So 9000 current-generation reactors would provide a substantial portion of the energy needs of the world of 2050. Slide 5 shows accurately the complexity of a real nuclear power plant, which dwarfs the nuclear reactor itself—a PWR—shown at the right. Such a plant is estimated to cost some $3 billion, but actual bids in the United States are reputed to be in the range of $6-10 B, perhaps linked to (to my mind unnecessary and undesirable) government loan guarantees.



A nuclear reactor in operation produces no CO_2, and, in fact, the steel and concrete used in construction of the plant contributes negligible carbon dioxide to the Earth's atmosphere—an important consideration in countering warming due to greenhouse gases.

But with a requirement of 200 tons per year of natural uranium per reactor, 9,000 reactors would require almost 2 MT of raw uranium per year, and the world reserve of uranium is estimated as 4 MT, which is absurd—two years supply for plants that take much longer than that to build and that will operate for 60 years.

However, experience teaches us that minerals are available in far greater quantities as the concentration demanded is reduced, and the "Generation-IV" analysis for cost vs. supply of uranium indicates that there would be 170 million tons of terrestrial uranium at a price of $260/kg. Beyond that, one of the greater failures of governments in the last decades has been the failure to determine a cost for obtaining uranium from seawater, where there are 4500 MT--enough for powering the 10,000-reactor world for 2000 years.

Should nuclear power become such an essential element of energy supply, long before we deployed 9000 light-water-reactors, we would probably have built a growing population of breeder reactors, envisioned since the very beginning of the nuclear era. In the breeder reactor, neutron-absorbing water is replaced by a heat-transfer fluid (commonly called a "coolant") that absorbs few neutrons—molten sodium, or lead, or lead-bismuth alloy—so that not only is there a neutron left over from the fission of U-235 or Pu-239 to provide the next generation of fissions and so to maintain the thermal power output of the reactor, but there is an additional neutron to be captured in a "fertile" element such as thorium or U-238, in order replace the fissioned material.

A plutonium-uranium breeder reactor, on balance, could be fed with natural uranium or even depleted uranium. The plutonium from its fuel would be recycled, so that the greater amount of plutonium from its fuel would provide the next load of fresh fuel for the breeder, while the small amount of excess plutonium would contribute to fueling an additional breeder reactor.

In fact, the French system was originally created with the expectation that the reprocessed plutonium would be loaded into breeder reactors. The net result, for our purposes, is that almost all of the raw uranium is ultimately fissioned in the breeder reactor, compared with about 0.5% in the light-water reactor, and even terrestrial uranium would be enough for many centuries of operation of a breeder economy. It is important to determine soon whether costly seawater uranium for once-through reactors is cheaper than costly breeder reactors with minimal uranium demands.

The spent fuel from the breeder would contain fission products, plutonium (to be recycled) and transuranics, but in a fast breeder reactor, the transuranics can efficiently be burned up, and in fact contribute to the power output. The intermediate case, though, as we find it in France, in which LWRs are fed by recycled Pu, presents a difficult problem in that the transuranics are not burned in the LWR and pose a very substantial problem of high toxicity, large amounts of spontaneous neutron generation, and the like. In fact, plutonium recycle as practiced in France if the spent fuel from the MOX is to be disposed of in the mined geological repository, requires just about as much repository volume as does the once-through process without recycle, which is, in addition, cheaper at present. Slide 6 shows an NPP site in the United States, with spent fuel in its interim storage casks. In contrast, Slide 7 shows the spent-fuel processing plant at Cap La Hague with capacity of 1600 tonnes of LWR fuel per year; it handles fuel from all 58 power reactors in France and has reprocessed also German and Japanese LWR fuel.

One approach to the treatment of spent fuel before disposition in a mined geological repository

Figure 9. Dry cask storage of spent fuel. Two casks typically contain the equivalent of a year's spent fuel discharges from a 1000 MWe nuclear power plant. Comparison of the simplicity of interim spent fuel storage with the complexity of the huge reprocessing complex shown in Figure 6 makes it easier to understand the relatively low cost of interim storage.[87]

Dry-cask storage of spent fuel (Yankee site)

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Another approach to the treatment of spent fuel before disposition in a mined geological repository

Figure 6. France's spent-fuel reprocessing complex on La Hague in northern France. Its plutonium fuel fabrication facility is in southern France, requiring regular long-distance truck shipments of separated plutonium.[49]

France's spent-fuel reprocessing complex at La Hague

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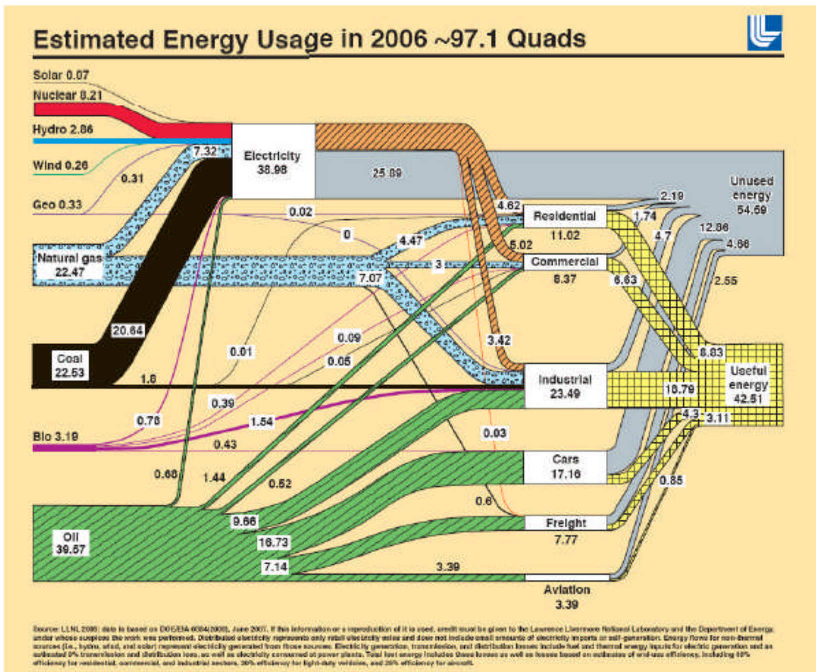
Other reactor types are possible and are under development, including those in which the fuel itself is microencapsulated and the tiny spherules (about 0.5 mm diameter) are housed in graphite spheres or blocks. Operating probably at somewhat less output power than the current reactors, these microencapsulated-fuel reactors promise improved safety in that they can be passively cooled by airflow or radiation, rather than requiring emergency core cooling water.

Now we turn to the world energy problem and the world energy future, in which nuclear power, in my opinion, should play a role.

Slide 8 shows the data-rich nature of the world energy problem. This indicates the estimated U.S. energy usage in 2006, totaling about 100 quadrillion BTU or about 100 EJ—exajoule.



U.S. energy usage in 2006 (1 quad = 1.055 exajoule)

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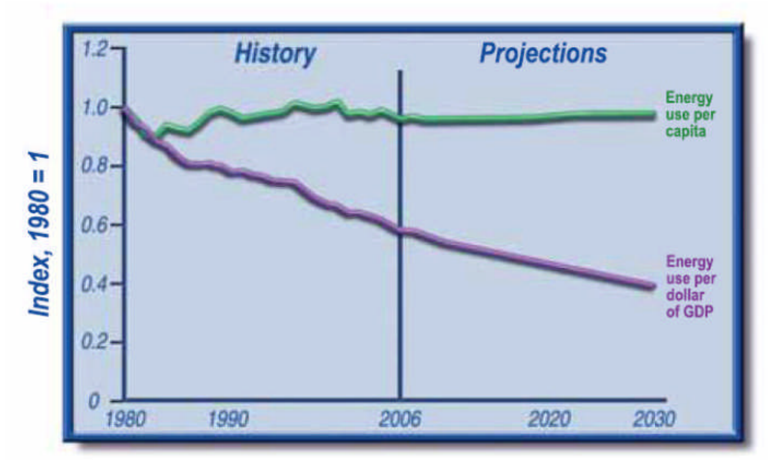
On the left are the primary energy sources for the U.S. in that year, dominated clearly by Oil, Coal, Natural gas, and Nuclear. On the right is a gross categorization of Unused Energy and Useful Energy, although much of the Useful Energy is degraded into heat, as is the case of the Unused Energy. In the middle are aggregations of various sectors, Electricity, Residential, Industrial, Cars, Freight, and Aviation. Note that almost no oil is used in the United States to make electricity, and only oil feeds transport—cars, freight, and aviation.

Slide 9 is much simpler, indicating the trend in U.S. energy use per capita and per dollar of gross domestic product—GDP—for a period of 50 years. Energy use per dollar is increasingly driven by the higher cost of energy, but, as we shall see, efficient use of energy can sometimes be achieved with savings in investment in addition to savings in energy cost.



U.S. energy use per capita and per dollar of GDP from 1980 to 2030

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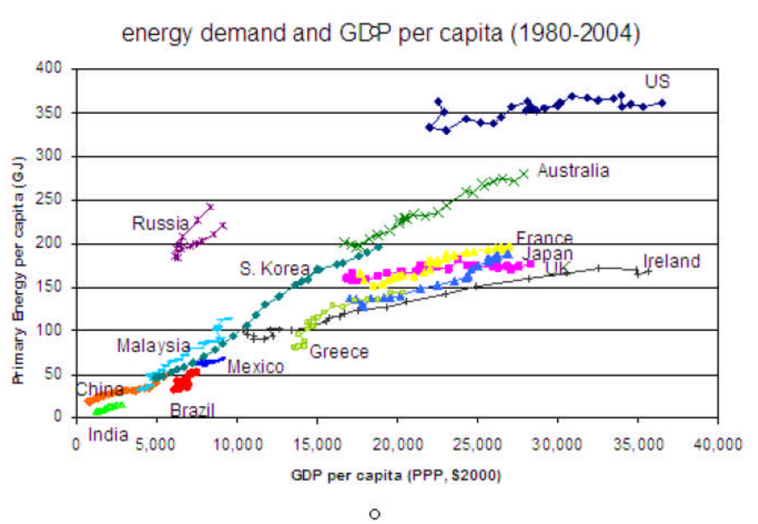
Slide 10 broadens this to show primary energy per capita plotted against GDP per capita for various nations, with the United States using far more energy per capita than any other nation. The evolution over 24 years is indicated. Note the astonishing increase in GDP per capita for Ireland over the last ten years.



Source: UN and DOE EIA
Russia data 1992-2004 only

(Courtesy of Dr. Steve Koonin, BP)

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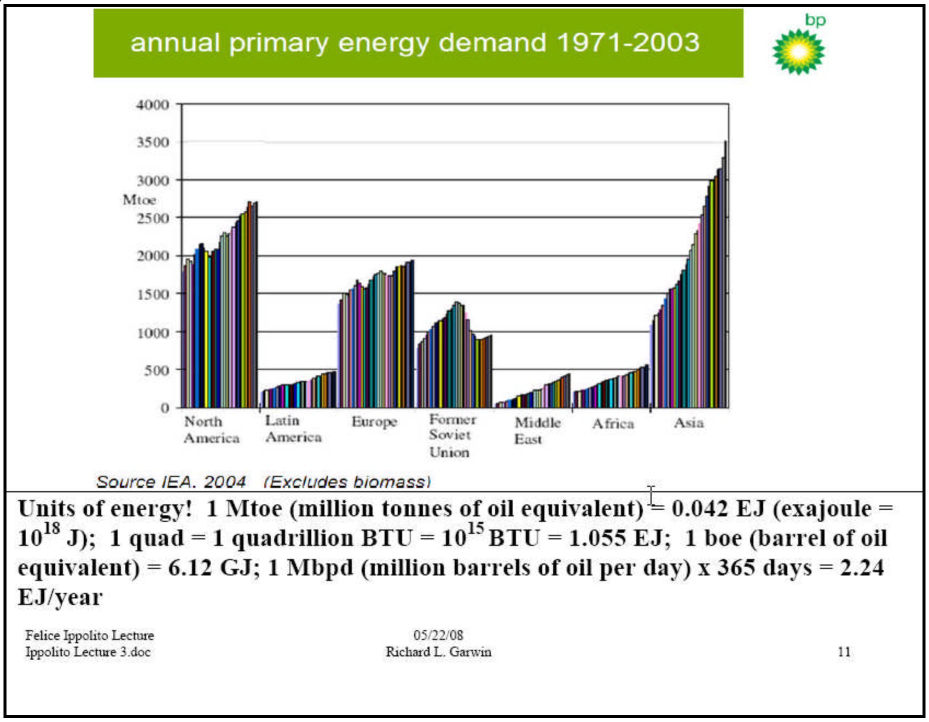
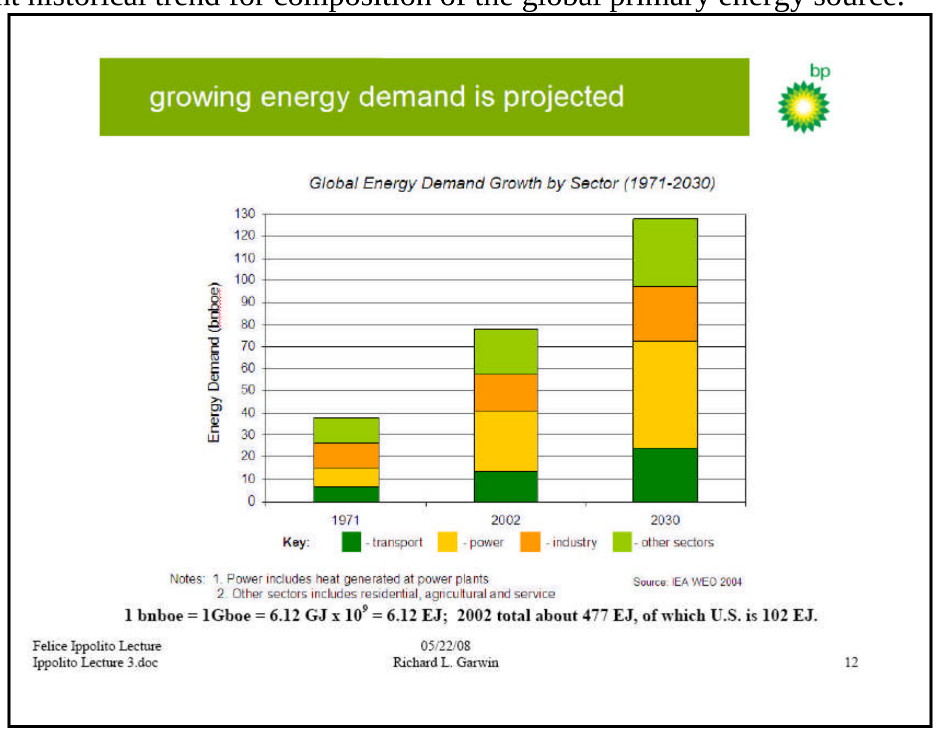
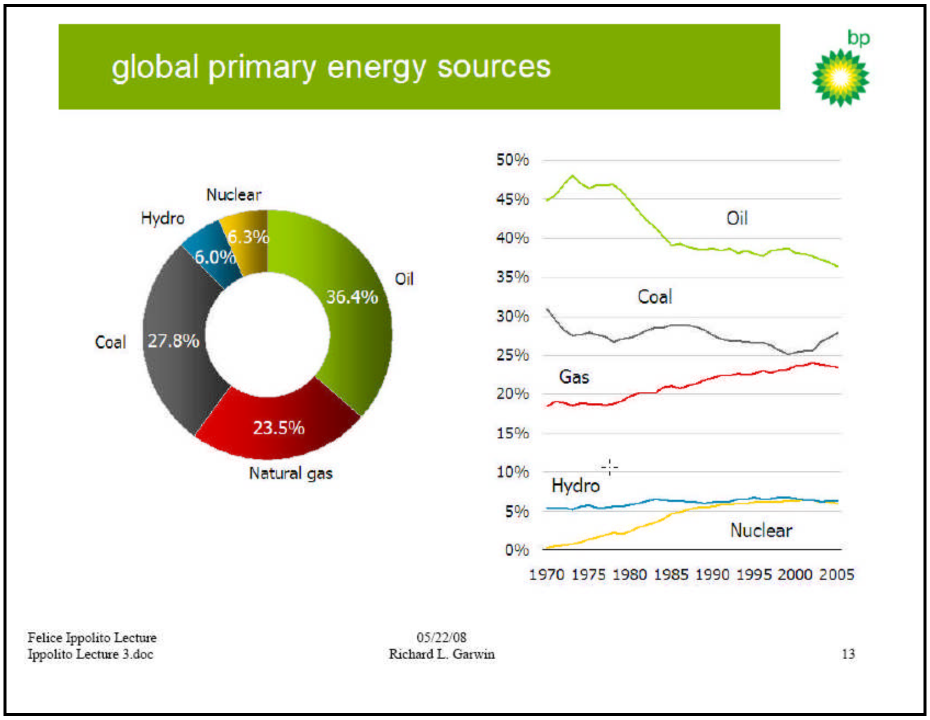
Slide 11 shows 23 years of energy demand by region, with the year redundantly coded in color and position. Just concentrate on the line-like nature of the top of each stack. The million tonnes of oil equivalent is a unit equal to 0.042 EJ, and at the foot of the slide the barrel of oil equivalent is defined as 6.12 GJ, and one million barrels per day as 2.24 EJ/year.

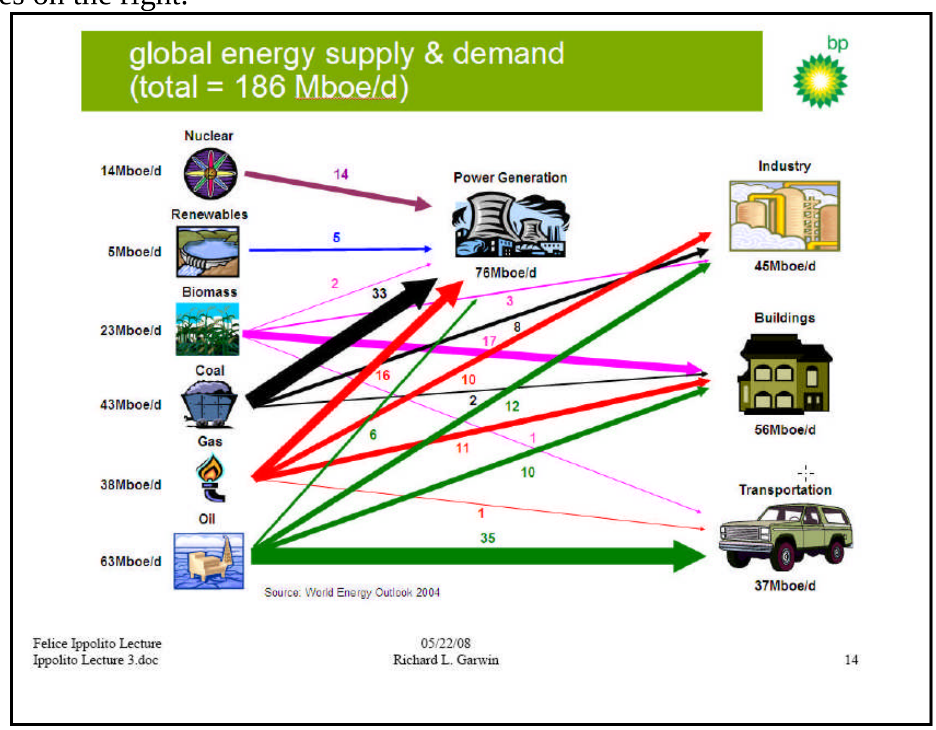


Slide 12 shows the projection of growing world energy demand by sector, and Slide 13 the recent historical trend for composition of the global primary energy source.

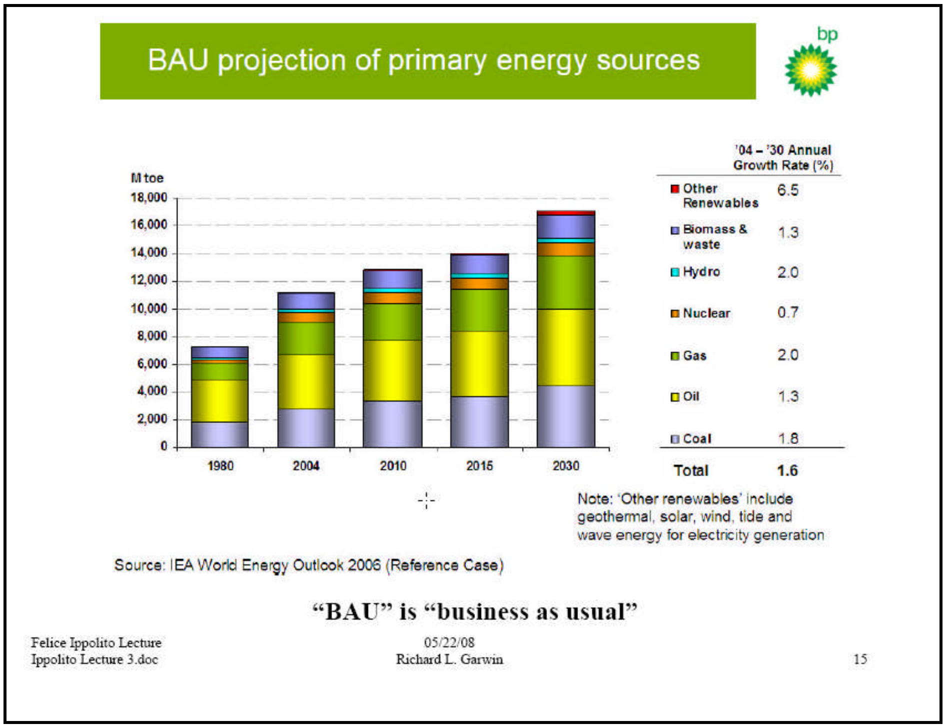




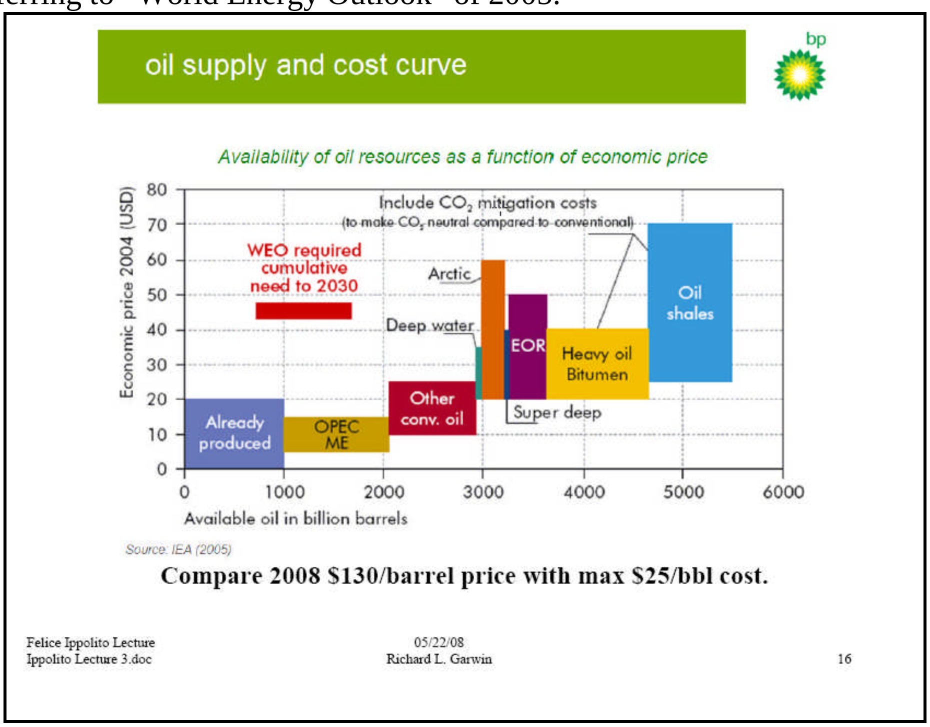
Slide 14 is a pale version for the world of primary energy sources on the left and end-use categories on the right.



On Slide 15 we meet "BAU", which means "business as usual." The composition of the primary sources is shown in the stacked graph in the bar graphs on the left, and the annual growth rate, largest for "Other Renewables" such as wind and solar power dominates the growth rate, although even in 2030 it will amount to only a couple percent of the total.

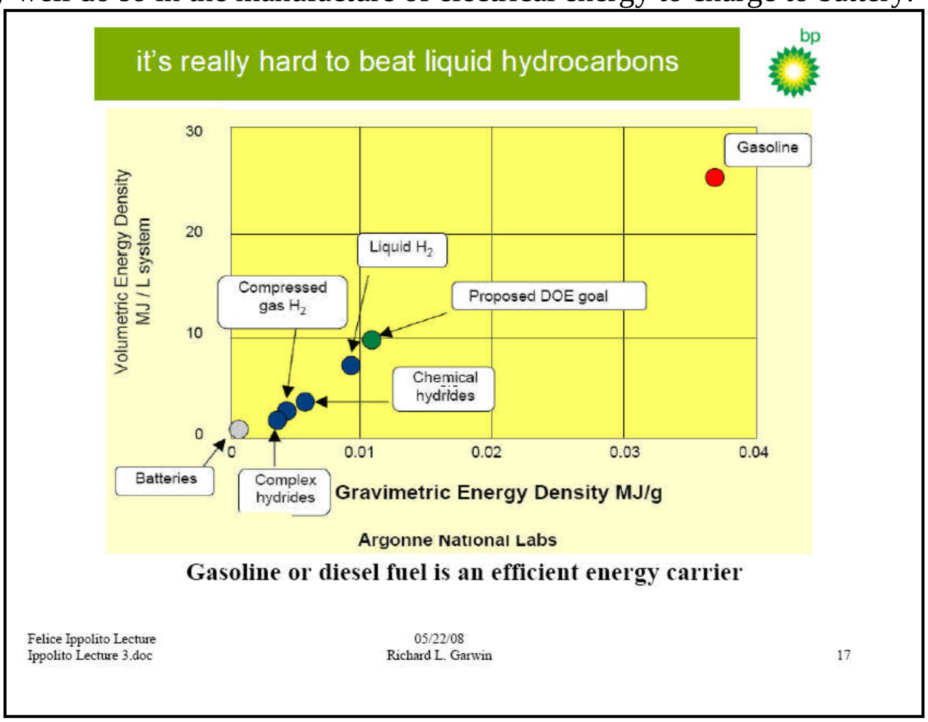


The "oil supply and cost curve" of Slide 16 shows a major part of the world energy problem. Here we have the economic price in U.S. dollars of 2004, plotted vs. available oil in billions of barrels. This is a "supply curve" for oil, and the amount of cumulative supply needed by 2030 and its uncertainty is shown in the "WEO-required" band, with WEO referring to "World Energy Outlook" of 2005.

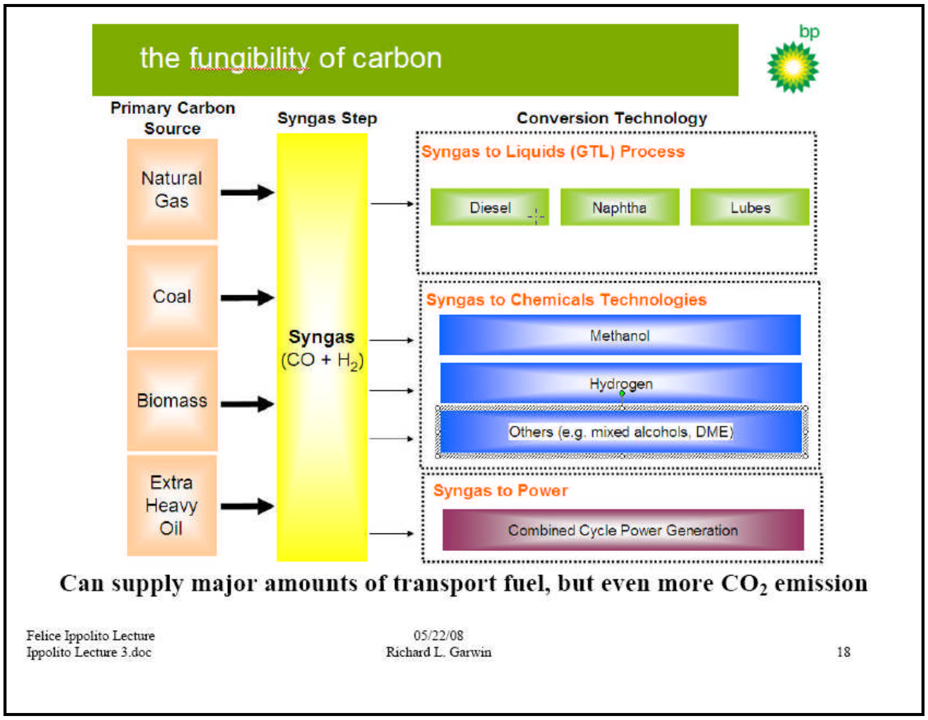


Note that in principle all this demand could be satisfied by OPEC and Middle Eastern oil at a cost of $15 per barrel, or other conventional oil such as that in the United States, the North Sea, and Russia, at a price of $25/bbl. Even enhanced oil recovery—EOR—or tar sands or oil shales would presumably be feasible at a cost below $70/bbl. And yet the world is paying a global price exceeding $120/bbl at present, with talk of $200/bbl or more in the future.

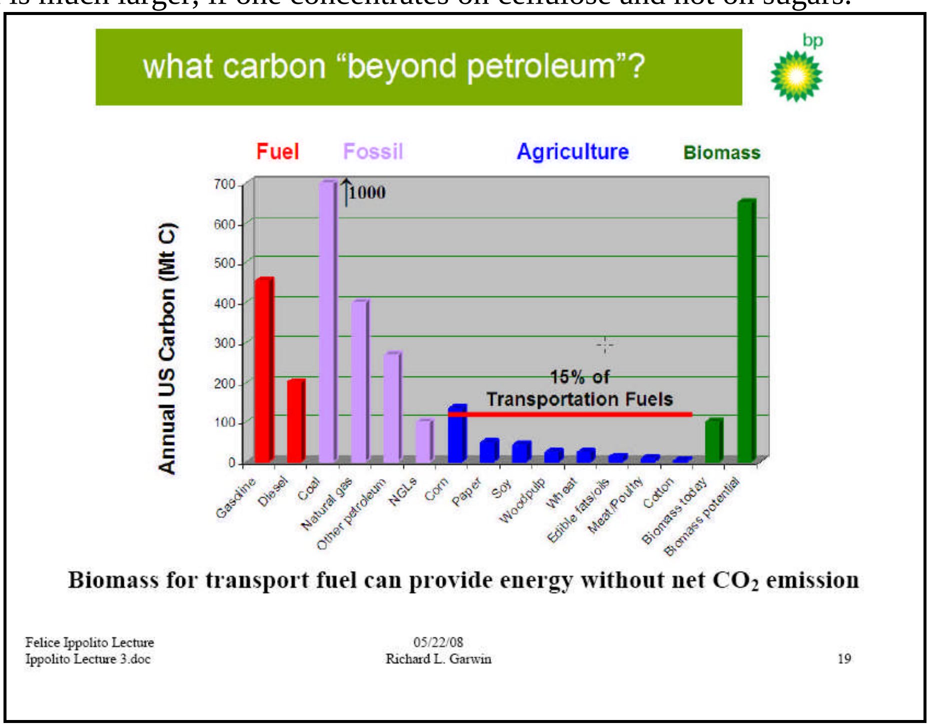
Slide 17 shows how difficult it is to replace gasoline or diesel for road transport. These fluids are just superb storage means for energy, in part because one stores only the carbon and hydrogen, and draws the combustion partner, oxygen, from the atmosphere. The petroleum products put carbon into the atmosphere, which is the principal reason to try to displace them as energy carriers. But hydrogen as an intermediary is a factor 3 less energy per unit volume, and a factor 4 less energy per unit mass, because of the mass of the pressure container, chemical linking, or the like. Batteries are far inferior, although they, like hydrogen, do not put CO_2 into the atmosphere from the vehicle, although they may very well do so in the manufacture of electrical energy to charge to battery.



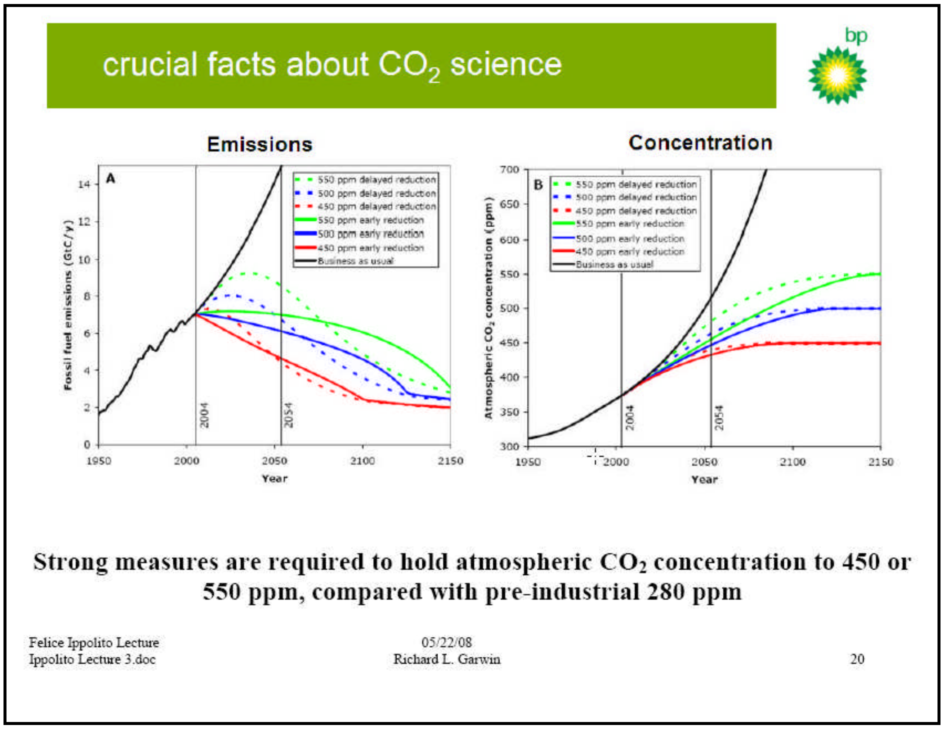
Slide 18 shows how relatively simple it is to provide liquid fuels for transport from any of the primary energy sources on the left. And on the right one can provide gasoline, diesel, methanol or other alcohols, or hydrogen. Note that the CO_2 into the atmosphere from bioliquids has been withdrawn from the atmosphere in the previous growing season, as indicated by the Keeling curve.



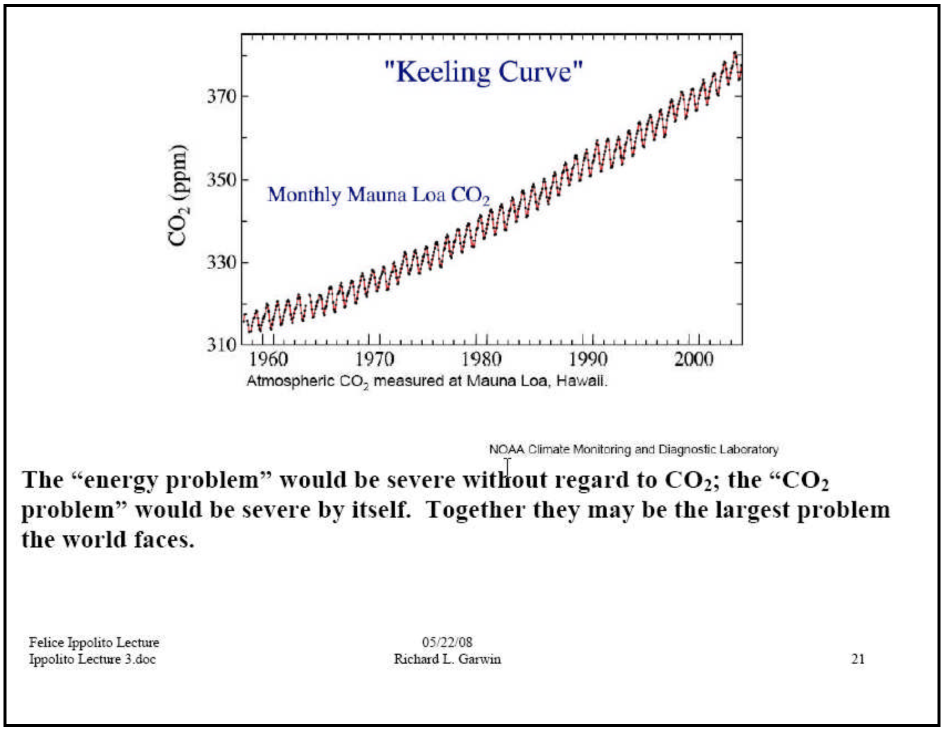
From Slide 19, the magnitude of fuel used in the U.S., for instance, is enormous compared with the mass of carbon produced annually from agriculture. But the biomass potential is much larger, if one concentrates on cellulose and not on sugars.



Slide 20 indicates on the left the course of emissions reductions from the steeply rising BAU curve, showing the strict measures that must be taken, and soon, to hold atmospheric CO_2 below 450 ppm, in contrast with the current 380 ppm. On the right are trajectories of concentration vs. time.



Slide 21 shows the very large transfer of CO_2 to and from the atmosphere from the agricultural sector, as CO_2 is extracted during the gross growing season (primarily in the northern hemisphere) to be embodied in wood, straw, sugars, and the like. The secular growth is largely due to CO_2 in to the atmosphere from fossil fuels, but also from deforestation.



The “energy problem” would be severe without regard to CO_2; the “CO_2 problem” would be severe without an energy crisis. Together they may be the largest problem the world faces.

Slide 22, from John Holdren, allows one to calculate from assumptions as to population, economic activity per person, energy intensity or content of the economic activity, and the carbon intensity of the energy supply the emissions at any future time, based on assumptions of these four factors. As an example, in the year 2000 the world figures work out to 6.4 GT of C per year.

Emissions from energy are 65% of the problem, above all CO_2 from fossil-fuel combustion

The emissions arise from a 4-fold product…

$$C = P \times GDP / P \times E / GDP \times C / E$$

where C = carbon content of emitted CO_2 (kilograms), and the four contributing factors are

P = population, persons

GDP / P = economic activity per person, $/pers

E / GDP = energy intensity of economic activity, GJ/$

C / E = carbon intensity of energy supply, kg/GJ

For example, in the year 2000, the world figures were…

6.1×10^9 pers x $7400/pers x 0.01 GJ/$ x 14 kgC/GJ

= 6.4×10^{12} kgC = 6.4 billion tonnes C

[From John Holdren]

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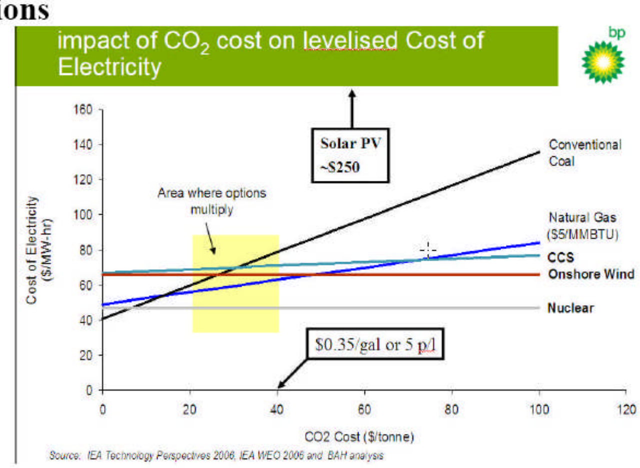
Slide 23 indicates that the market can help to resolve the greenhouse gas problem, but only if there are clear price signals in regard to carbon emissions to the atmosphere. The top curve is that for Conventional Coal, with the Cost of Electricity about $40/MWh or $0.04/kWh. With the addition of a carbon tax of $100/tonne (equivalent to $27/tonne of CO_2) the cost of electricity from coal would rise to about $140/MWh.

Near-term tools

- **A carbon tax to move toward low-carbon or no-carbon solutions**



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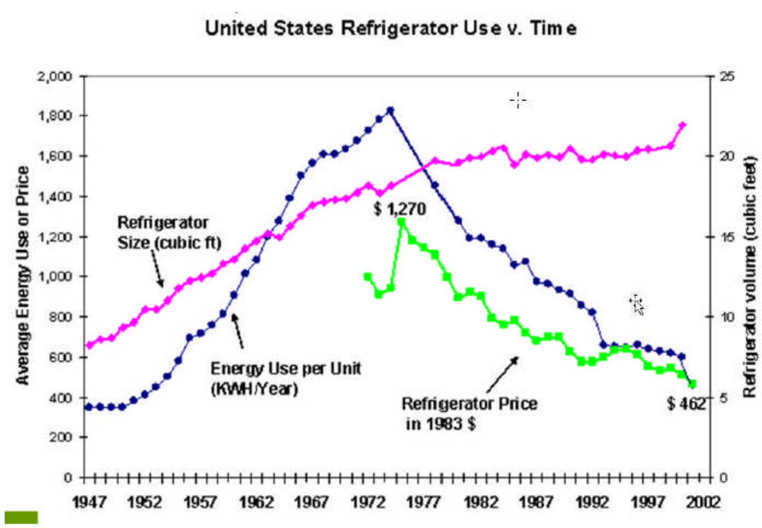
At that price, natural gas, with less carbon per unit energy would be considerably cheaper, as would wind energy and nuclear, all assumed more expensive than coal with no tax on carbon. Solar photovoltaic energy with currently high capital cost and a small duty cycle would still be twice as expensive as highly taxed coal. The relatively flat curve, CCS or "carbon capture and storage"—also known as carbon sequestration—shows the influence of the very important technique of capturing carbon as carbon dioxide from the combustion process and disposing of it other than into the atmosphere. Without a carbon tax, coal with CCS is considerably more costly than the normal use of coal, because additional energy is required to separate the CO_2 and to transport it to the disposal site and to dispose of it. But CCS would allow coal for electricity without contributing carbon to the atmosphere. The cost of CCS can be reduced by the use of oxygen instead of air to burn coal for power plants, or by gasifying the goal before combustion.

It is often argued that any of these benefits of reduced energy use or reduced carbon emissions come at a very high cost, but that is not necessarily the case. An important counter-example is illustrated in Slide 24. After the first "energy shock" of 1972, the U.S. government initiated a program to provide an award for a highly efficient kitchen refrigerator. Several manufacturers competed and these refrigerators went onto the market almost immediately with the spectacular results shown in the graph. Refrigerator size increased unabated, whereas the energy use per refrigerator dropped precipitously, AS DID THE PRICE. So in 2001 it was possible to buy a refrigerator for about 40% of the price of 1974, and it was 20% bigger and used a factor 4 less electrical energy per year.



Spectacular results in response to a government prize/incentive program

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On Slide 25, I show some near-term tools for solving the world energy problem. Right at the top is the more efficient use of energy as, for instance, in U.S. refrigerators. Add to that, of course, hybrid vehicles, automatic control of temperature, air conditioning, and lighting, to use no more energy than is required.

Near-term tools

- **More efficient use of energy, e.g., U.S. refrigerators.**
- **Major push for at-scale demonstration of "carbon capture and storage". A single coal-fired 1000 MWe plant burns 2 million tonnes of carbon per year, generating 2 x 44/12 = 7.3 MT CO_2 per year. Dispose in aquifers, deep-sea pools, sea-bed sediment.**
- **Develop and deploy cellulose-to-ethanol plants for transport fuel, using waste plant material for zero-C fuel.**
- **Low-cost exploration to determine availability and cost of extraction of uranium for nuclear power—the "supply curve" of uranium.**
- **Explore the production of clathrate methane from ocean margins, and define the resource (perhaps 2000 Gt of carbon, but a dilute, non-flowing resource)**

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The replacement of incandescent lights by fluorescent light saves a factor 3-4 in energy, and a further large factor would come from the use of solid-state lighting, such as light-emitting diodes—LED—or organic LEDs—OLED. But remember that the first factor of 2 saves as much as would the further total elimination of energy use.

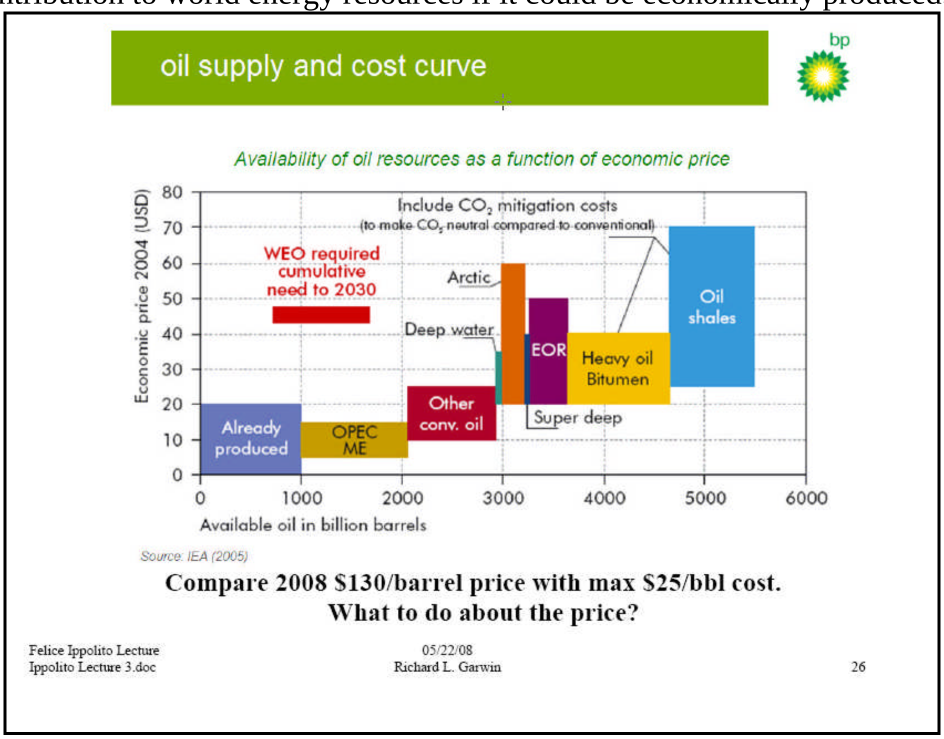
A major push for at-scale demonstration of "carbon capture and storage" is required. A single coal-fired 1000 MWe plant burns 2 million tonnes of carbon per year, generating 2 x 44/12 = 7.3 MT CO_2 per year, which can be sequestered in aquifers, deep-sea pools, seabed sediment. There are exciting technical problems in this field.

The potential contribution of CCS to the solution of the world energy problem is enormous. In fact, with a sufficiently high carbon tax, biomass can be used as a potent source of negative-carbon energy, simply by burning it for fuel and using CCS is dispose of the carbon rather than emitting it into the atmosphere. Since the carbon for the biomass is taken from the atmosphere, and no carbon is rejected to the atmosphere in the production of electrical or industrial energy in this way, CCS would be a potent tool. CCS is also highly desirable in diversifying sources of energy, although coal-to-liquid plants are capital intensive, and their creation will not happen automatically without, for instance, a guaranteed purchase in the long-term future.

Develop and deploy cellulose-to-ethanol plants for transport fuel, using waste plant material for zero-carbon fuel. Biodiesel is another option, but one should distinguish between the initial industrial facilities that use waste cellulose from the production of food and fiber, and the growth of energy crops such as miscanthus grass, which would then compete with agriculture for arable land.

Low-cost exploration is long overdue to determine availability and cost of extraction of uranium for nuclear power—the "supply curve" of uranium—to provide a rational basis for the introduction of breeder reactors. France now recycles plutonium from its light-water reactor fuel, and if the cost of this activity is assumed to be devoted to the saving of uranium consumption, that comes at a cost of about $700/kg of raw uranium—very much more than historical prices over the years that France has been doing this and much more than current prices for uranium.

Explore the production of methane hydrate from ocean margins, and define the resource (perhaps 2000 Gt of carbon, but a dilute, non-flowing resource). There is another large resource of fuel, widely distributed on the margins of the oceans—methane held in the form of hydrate in a so-called clathrate or "claw" structure. At suitable ocean depth on the order of 1 km, methane is believed to fill a few percent of the pore space of the sediment, amounting to perhaps 2000 gigatonnes of carbon but in the form of a dilute, non-flowing resource. Looking again at Slide 16, now Slide 26, this would be a very large contribution to world energy resources if it could be economically produced.



As for nuclear power, my recommendation is to deploy plants of current design, such as the evolutionary power reactor for which the prototype is being built in Finland and in France, not without delays and difficulties. In principle, other reactors could be even safer such as those involving micro-encapsulated fuel, in carbide spheres of the order of 0.5 mm diameter, consolidated into tennis-ball-sized "pebbles" or into prismatic blocks. Such reactors ought to be developed and tested and deployed if economical. Ultimately, either when a breeder reactor is as inexpensive as an LWR or the actual cost of uranium has risen to make a more expensive breeder economical, the world could make the transition to a breeder economy, with necessary reprocessing and recycle of fuel, to use essentially 100% of the raw uranium rather than the 0.5% used in current-generation reactors which can fission only the U-235 and not the U-238, of 99.3% abundance in natural uranium.

The crisis nature of the world energy problem arises first from the urgency to reduce greatly the carbon emissions to the atmosphere and from the economic distortions introduced by the great excess of energy price over the cost of production. This is a sickness of modern society, with markets run amok in my opinion. It was seen in pure form in the Enron scandal in the United States, in which Enron employees frankly manipulated the cost of electrical energy in the California market with the great leverage afforded by "marginal pricing". If energy supply was inelastic because the consumers did not know how much they were paying at the moment and had no easy way of reducing energy demand for less urgent needs at that time, the manipulation consisted of keeping some electrical energy generation capacity offline for repair, for instance, so that a high-cost producer would be called on as supply contracts were awarded in order of increasing price. Even the producer was not limited to its cost of production plus normal profit, but was part of a bidding mechanism, and if the bid were very high, then *all* of the electricity transferred at that time would be sold at the very high price.

In fact, under such circumstances the price is not in any way determined by the availability of electricity but by the demand curve. The state of California has now become a leader in allowing the control of demand.

The similar marginal pricing situation holds with the globalization of energy supply markets, especially in oil and to some extent in coal, and to a growing extent in natural gas.

Solutions are long-term contracts such as that used to good effect by Southwest Airlines in the United States, which has bought its fuel several years in advance and is thus paying less than half what other airlines are currently paying for fuel. But I am neither a regulator nor an economist, and I don't have the expertise or the time here to prescribe for the energy future. It will take concerted action on the part of the world's energy users to have a system in which energy producers will be properly rewarded for costs and risks, and energy consumers can count on a reliable supply of energy at a fair price.

The energy field is not alone in such pricing. In recent years, some pharmaceuticals in the United States have suddenly increased in price by a factor 10 or even 100—not because of increased cost of production and certainly not because of "expenditures on research and development" which was long since done, but because a single company manufactured the pharmaceutical, and they were bought up by others who had no scruples about charging the consumer for the drug absolutely necessary to keep them alive. "Your money or your life," the mantra of the highwayman has made its way into the pharmaceutical market. And into the energy market.

*
I have shown the “supply curve” for oil—which I should now title “fundamental supply curve”—the cost as a function of cumulative demand. Here it is again (Slide 16/26). The classic supply curve of the college course in economics shows increasing cost of production as the cumulative demand increases—after all, why not buy and consume the low-cost commodity first? But oil was produced in the United States domestically and elsewhere and sold at a profit over the cost of production, before global oil companies discovered and produced oil in Saudi Arabia at less than $2/bbl.

It took years to establish a global market and transport system for oil, and then the world was faced in the 1970s with the formation of OPEC and the nationalization of oil resources and facilities owned and built by these international companies.

We are now faced with the classic confrontation of suppliers who wish to charge more for a unit of their commodity (barrel of crude oil) and consumers who wish to pay less. But the consumers in many cases are not the ultimate consumers but intermediaries—some of whom, like the US refiners, are subsidiaries of the US domestic producers of oil. The US domestic production is still 5 million bbl/day, of a total consumption of 21 MBpd, and the US producers/refiners have no incentive to demand lower prices. As shown by Slide 16/26 their own production is at a cost of some $25/bbl, and the profit made by being able to sell at the marginal price of $120 bbl/day so far exceeds any benefit they might achieve by increasing production that their interest—in the service of their stockholders—is clearly in maintaining tight markets and restricted supply.
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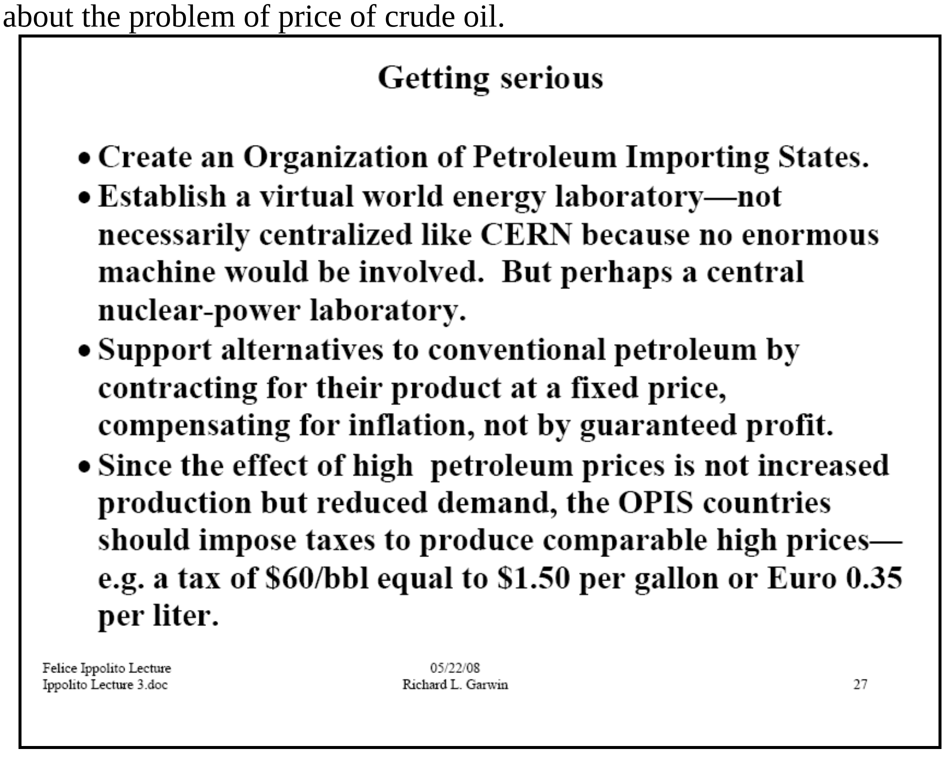
Slide 27 suggests what would be needed if the petroleum consuming states were to get serious about the problem of price of crude oil.



They would create an Organization of Petroleum Importing States, of which the United States, with its large domestic production, would not be a leader.

They would establish a virtual World Energy Laboratory, with elements modeled on the Energy and Resources Group at the University of California, Berkeley, and the Center for Building Science at the Lawrence Berkeley laboratory, established by Arthur Rosenfeld that has shown the way to hundreds of billions of dollars in energy savings. A central Nuclear Energy Laboratory might be the exception to the virtual organization.

Alternatives to conventional petroleum should be supported by a long-term contract for their product—not a guarantee of profit—in order to guard against collapse of petroleum price and to mobilize private initiative to reduce costs below the fixed selling price.

Finally, in recognition of the fact that the enormous jump in crude oil prices of the last two years has not brought increased production but only a moderation of demand, the OPIS nations should institute a large consumption tax on the order of $60/bbl or $1.50/gallon (about Euro 0.35 per liter) on all uses of petroleum in order to reduce demand without the enormous transfer of wealth to the petroleum producers. The problem will be to maintain discipline among the consuming states.