FUSION BREEDERS TO FUEL FISSION BURNERS, A NEW (OLD) IDEA FOR FUSION DEVELOPMENT
OR
WHAT’S A FUSION TALK DOING IN A FISSION SYMPOSIUM?
(MY ANSWER: FISSION MIGHT NEED FUSION)

GCEP SYMPOSIUM NOV AT MIT, NOV 29, 2007
Wallace Manheimer
Retired from NRL
With lots of help from:
Tokomaks: Bill Tang, Mike Bell and Mike Zarnstoff (PPPL), Nat Fisch (PPPL), Ralph Moir (retired from LLNL), Jeff Freidberg (MIT)
World Development: Marty Hoffert (NYU), Doug Lightfoot,
Nuclear Science: Ralph Moir (retired LLNL), Dan Meneley (President of CNS), George Stanford (retired from ANL)
Editors: Steve Dean (JFE), George Miley (Fus. Tech.)
And Special thanks to Ralph Moir
What is fusion

- Two approaches:
  - Magnetic: Long series of tokomak experiments ultimately producing $\sim 10^{19}$ neutrons in a 1 second pulse for $Q \sim 0.5$ with a 30% efficient driver (neutral beams) \{TFTR, JET, JT60\}
  - Inertial: Not nearly as mature. $\sim 10^{13}$ neutrons for $Q \sim 10^{-3}$, but with a 1% efficient driver \{UR: LLE\}.
- Fusion has made great progress over the last 60 years but has a very long way to go, greatly testing the patience of sponsors.

Tritium must be bred from lithium and this is an ultimate limit to the resource.
Magnetic fusion energy (MFE)

• World effort centered on ITER – originally a $20B machine to produce ~1.6 GW of neutron power (~600 MWe).
• Reduced in scale to a $10B machine, 400 GWnd, (~150 GWe).
• ITER Will dominate world MFE effort for decades.
• Even conceding CW power for ITER (actually 1-2 10-20 minute shots/day), cost/n must be brought down at least one order of magnitude.
• No clear idea how to do this.
Inertial fusion (IFE)

- **NIF (LLNL)** indirect drive, glass laser, largest program, but has little application to energy. Hopes for ignition by 2011.
- **NIKE/ELECTRA/HAPL/FTF (NRL)**. Direct drive, KrF laser, energy application.
- **NIKE**: 3kJ laser for laser matter interaction studies
- **ELECTRA**: Rep rated KrF laser
- **HAPL**: Examines all areas necessary for energy production. No analogous MFE program.
- **FTF**: Proposed 100 MW (average power) neutron source, ~$3B, t<2020.

The uniform focal spot of the NIKE laser

FTF conceptual design
The fusion hybrid:
From Hans Bethe, Phys. Today, May 1979

Wall must contain Neutron multiplier so To breed both T and $^{233}\text{U}$

But each $^{233}\text{U}$ releases $\sim 200$ MeV when burned. Q is effectively raised by at least an order of magnitude

Fission is energy rich and neutron poor, while fusion is energy poor and neutron rich. A perfect match!
This is a very old idea

• Andrei Sakharov, Memoirs, p142: “An important proposal of mine (in 1951 or late 1950) was that neutrons from thermonuclear reactions be used for breeding purposes”.

• Hans Bethe, Physics Today, May, 1979: “It seems important to me to have an achievable goal in the not too distant future in order to encourage continued work, and continued progress toward the larger goal, in this case pure fusion”

• Others: R. Moir, J. Kelly, D. Jassby, J. Maniscalco, etc
Two approaches

- Fast Fusion (Stodiek, Rebut): Take a fusion reactor and clad it with uranium or thorium and burn it all at once.
- Rebut suggests cladding ITER and making the 400 MW fusion reactor into a 4 GW fission fusion plant.
- But: Fission and Fusion reactor must work seamlessly together (an accident waiting to happen [Ralph Moir]). Also 400 MW of fusion power means a total of 4GW, much too big for a prototype.
• Fission Suppressed (Ralph Moir and others)
  • Use a liquid or flowing blanket and reprocess the $^{233}\text{U}$ or $^{239}\text{P}$ on the fly and burn these in a reactor designed to do this and only this.
  • Proliferation considerations, $^{232}\text{Th}/^{233}\text{U}$ cycle
  • One calculation [Moir] shows that in a ‘engineered blanket’, one fusion neutron produces 1.1 triton, 0.73 $^{233}\text{U}$ and 35 MeV.
  • But the 0.73 $^{233}\text{U}$ when burned produce ~150MeV!
• Fusion is neutron rich and energy poor, fission is neutron poor and energy rich, a perfect marriage.
My own efforts concentrated on U(233) cycle

- Could be mixed with U(238) in a slightly enriched fuel with no greater a proliferation risk than today’s fuels for use in today’s reactors.
- In case of an accident, uranium is much less toxic than plutonium.
- In case of an accident, U(233), because of mix with U(232), which has a high energy gamma in its decay chain, is much easier to find, and much more dangerous for a terrorist user.
- Could export the fuel, even to countries we did not fully trust, as long as they sent the spent fuel back for treatment (more later).
- Why shouldn’t the USA, using our brains, be the world’s fuel supplier – the Saudi Arabia for the mid to late 21st century?
How have others reacted?

• The American fusion community has been mostly hostile, believing that one of the strongest selling points of fusion is that it is not only unlimited, but clean (but is actually limited by lithium supply).

• This is the first time I have presented this to the fission community. My perception is that they have been mostly preoccupied with overcoming public resistance to fission (the last fission plant in the USA was built in the 1970’s).
Today the world’s 6 B people use ~13 TW, 85% from fossil fuel. 10 B people in 2050 mean 20 TW. But not 15-20% of people use lion’s share. Not sustainable if 21st century to find a measure of peace. If USA cut its energy use in half, and rest of world brought to that level, 30 TW today and 50 TW by 2050. Clearly at ~10-30 TW of carbon free energy must be found. Conservation **AND** new sources important!
What are the world’s energy resources (with lots of qualifications, mostly from Hoffert 2002)

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy (TW-yrs)</th>
<th>Relative Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>5000</td>
<td>1.6</td>
</tr>
<tr>
<td>Oil</td>
<td>1200</td>
<td>1.3</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1200</td>
<td>1.0</td>
</tr>
<tr>
<td>Mined Uranium Burner*</td>
<td>300</td>
<td>0</td>
</tr>
<tr>
<td>Wind, Solar**</td>
<td>~20GW Average Today</td>
<td>0</td>
</tr>
<tr>
<td>Biofuel***</td>
<td>~0.5 TW today</td>
<td>0</td>
</tr>
</tbody>
</table>

* High grade ore – once through cycle. Nuclear appears very unimportant except there are many ways this number can be greatly increased, the fusion hybrid being one of them.

** Intermittent, will always be small players

*** Mostly from dung and bi products. Fuel to produce ethanol ~ what it gives from burning it

Upshot: Over the next decades the world will be building many coal fired and nuclear power plants, there is simply no avoiding this.
Once through Nuclear cycle

• Nuclear fuel is enriched to about 4% $^{235}$U and 96% $^{238}$U.
• Mostly the $^{235}$U is burned, but $^{238}$U generates $^{239}$Pu which is partially burned. (i.e. every burner is a little bit of a breeder too).
• A highly toxic waste is produced, mostly of intermediate Z elements which are highly radioactive, but also containing U, Pu and others. A 1 GWe plant yearly burns ~ 1000 kg $^{235}$U and produces ~750 kg highly radioactive, short lived material (half life ~30 yrs), 200 kg actinides, and 50 kg long lived radioactive waste (i.e. $^{99}$Tc 200,000 yr)
• The entire waste will be buried in a geological repository.
• Many people advocate this, but is the world so well endowed with energy that we can afford do discard 99% of this energy resource?
• 40 years of 400 GWe means 400 years of 4 TWe from depleted uranium alone (but I think there are much better ways to go).
• This gives an idea of the enormity of the uranium and thorium resource, much greater than the Li resource supporting DT fusion.
Two emails from Dan Meneley (head of Canadian nuclear society)

- I've nearly finished prepping my talk for the CNS on June 13th (2006) -- from what I can see now, we will need A LOT of fissile isotopes if we want to fill in the petroleum-energy deficit that is coming upon us. Breeders cannot do it -- your competition will be enrichment of expensive uranium, electro-breeding. Good luck.

- We (I'm on the Executive of the Environmental Sciences Division of ANS) held a "Sustainable Nuclear" double session at the ANS Annual in Reno a couple of weeks ago. I have copies of all the presentations. ............ The result was an interesting mixture of "we have lots", just put the price up and we'll deliver (we've heard the same from Saudi recently) and "better be sure you have a long-term fuel supply contract before you build a new thermal reactor".
# How can we increase uranium resource, at what cost?*

<table>
<thead>
<tr>
<th>Source</th>
<th>Fuel cost (cents/kwhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct mining high grade uranium ores</td>
<td>0.5</td>
</tr>
<tr>
<td>Direct mining lower grade ores**</td>
<td>1.0</td>
</tr>
<tr>
<td>Sea Water extraction</td>
<td>1.6</td>
</tr>
<tr>
<td>Breeder reactor***</td>
<td>1.8</td>
</tr>
<tr>
<td>Accelerator aided hybrid</td>
<td>2.0</td>
</tr>
<tr>
<td>Fusion hybrid (MIT-ARIES)</td>
<td>1.7</td>
</tr>
<tr>
<td>Fusion hybrid (Author est. ITER extrapolation)</td>
<td>2-2.5</td>
</tr>
<tr>
<td>Gasoline a $1/gallon</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*From MIT Study (Freidberg). All entries but first and last have large error bars.

** Author estimate. Assumes 3000 TWyrs available at 1/3 concentration. Half of cost from getting the uranium is tripled, process stays the same.

*** Breeders have largely been abandoned worldwide and will not be an important player before mid century. Superphenix experience indicates breeder power will be expensive.
But price does not tell the whole story

- **Price may include price of more energy than generated:** Consider accelerators. Electricity ($\eta \sim 30\%$) to accelerator ($\eta \sim 50\%$) 1Gev proton to 30 spallation neutrons to 30 $^{233}\text{U}$ each of which gives 200 MeV when burned. We have traded a joule of coal for a joule of $^{233}\text{U}$. Accelerators may make sense for producing fuel to start a breeder or to provide neutrons for a subcritical reactor, but certainly not to provide fuel for a burner.

- **Price on a small scale may obscure what is necessary on relevant scale:** Consider uranium from sea water. 1.8 MJ of $^{235}\text{U}/m^3$. Assume 100% extraction and we want 10 TW.

- **Using ocean flows:** Catch all $^{235}\text{U}$ in the flow of 5x the world’s rivers. Seems to mean putting a stationary, man made object in say the Gulf Stream to catch everything flowing by.

- **Mining the sea:** This means mining 150,000 km$^3$ of sea water every year. If every person in the world has 1000 m$^3$ in his home and work place (more than I have), this is 6000 km$^3$. Must process every year 25 times the volume of all the world’s buildings.
This led to the fusion-fission energy park
The Energy Park
More than a dream, certainly less than a careful plan

A. A Nuclear reactor, perhaps of today’s design. Each year takes in 1000 kg of $^{233}$U (mixed with 24,000 kg of $^{238}$U) and discharges, among other things, 200 kg of $^{239}$Pu, 750 kg of highly radioactive intermediate Z isotopes, and 50 kg of lower activity isotopes, e.g. $^{99}$Tc with 200,000 year half life.

B. Output electricity

C. Output hydrogen

D. Cooling pool where waste is taken and low Z highly radioactive isotopes cool for perhaps 300-500 years.

E. Low Security fence

F. High security fence
The energy Park, con’t

G. Separation plant where actinides (mostly plutonium), highly radioactive elements, and less active elements are separated. Highly radioactive elements go back to cooling pool, plutonium to a plutonium burner, and low active waste perhaps back to fusion reactor for transmutation.

H. Plutonium burner. Separated plutonium from all 5 reactors are burned here. Most likely to be a fast neutron reactor, but might be a thermal neutron reactor if the fertile material is $^{232}$Th, or if there is no fertile material.

I. The fusion reactor. Produces 1.5 GW of neutron power (like the large ITER), 3.5 GW thermal power and 15 GW of $^{233}$U, enough to feed the 5 thermal reactors. 5% of wall area might be used to transmute all the low activity elements produced in park if one neutron for 1 transmutation.
The energy Park, conclusion

- Produces 7 GWe
- No long time storage or long distance travel of material with proliferation potential.
- Treats all of its own wastes.
- Waste treated with a combination of fission, fusion and patience.
- Only $^{232}\text{Th}$ comes in, only electricity and hydrogen go out!
Symbiotic relation between fission and fusion breeding

- If breeders become viable and economical, there will still be a large legacy of burners by mid century.
- In steady state, with 5%/yr ‘speed limit’, 20 fission breeders are needed to fuel one of today’s reactors.
- Transporting the plutonium fuel may be the most dangerous aspect of fission breeders.
- Possibility is to have fission breeders fuel only themselves.
- Fusion breeders could then fuel existing stock of burners with a uranium fuel enriched to 4% U233.
Many components of the energy park can be built today, but research is needed to make the vision a reality:

**Fusion:**

**CHANGE PSYCHOLOGY!!!** FUSION SHOULD STOP LETTING PERFECT BE THE ENEMY OF GOOD ENOUGH AND AIM FOR LARGE SCALE CARBON FREE ENERGY PRODUCTION BY MID CENTURY. NEED IS THERE! HYBRID ONLY OPTION.

- Magnetic fusion
- Build a steady state, high duty factor DT tokomak to breed both $^{233}$U and T on small scale. At least two approaches:
  1. Steady state TFTR, Q~1, 40 MW average neutron power. R~3.5m, beam driven. Cost estimate based on extrapolation of ITER costs ~ $2.6B (R^2.5). Would take 70% of base program for 15 years.
  2. High field Ohmically heated tokomak based on Alcator scaling (Freidberg). Cost ~??

**Inertial fusion**

Less mature. Could add a task to HAPL to look into a hybrid configuration. [BUT I DO NOT SPEAK FOR NRL!]
Research needed to make the vision a reality: Fission

- Plutonium burner: Thermal neutron reactor? $^{239}$Pu absorbs and fissions with thermal neutrons. But more Pu is produced from the $^{238}$U so it is difficult to win. Can we used $^{232}$Th as the fertile material so no additional buildup of Pu, and ultimately we burn much more of it. Also we generate $^{233}$U as a fuel. If so we could start to burn Pu and produce and use a more long term viable fuel TODAY!

- Tritium production: Moir calculation - 1 fusion n to 1.1 T and 0.73 $^{233}$U. Blanket covers 95% of wall and we recover 95% of T. Then no solid blanket because in the year between recoveries, we lose an additional 3%. Can fission reactors help? TVA WATTS BARR reactor is beginning to breed T for our nuclear deterrent. They estimate 4 Moles $^{235}$U to 1 mole T. Some cost penalty but no performance penalty. Then fusion 1n to 1.25-1.3 T. Better safety margin and Energy Park becomes truly symbiotic between fission and fusion.

- Also ITER and FTF may soon be require tritium.
Research needed to make the vision a reality: Separation Technology

• Can we economically separate out the long lived radio nuclides to transmute with fusion neutrons (i.e. $^{99}$Tc with 200,000 yr half life) or should we just bury them and forget them?

• To minimize the number of cooling pools needed for the highly radioactive nuclides, can we separate out the inert material as it forms?
A role for GCEP?

• Question: “How can GCEP, with its objectives and relatively modest budgets, create additional options that would have a significant impact?”

• Possible Answer: MIT has expressed interest in the fusion hybrid concept and has put together a tentative consortium from both the fission and fusion areas to evaluate this. But it needs support. The dollars and time are the scale GCEP could consider (~$200-300k/yr for 2-3 years). After this period, GCEP could organize another workshop inviting the MIT group as well as other experts in fission and fusion. If the concept survives this scrutiny, and has the support of both MIT and Stanford, a proposal to DoE would have much greater chance of success.
The upshot:

• Without fission or fusion breeding, not only will we be unable to lift low countries up the curve, the high countries will begin to slide back down.

• This is the real threat to civilization.
Published papers, available from author, contact wallymanheimer@yahoo.com,

1. W. Manheimer, Back to the Future, the Historical, Scientific, Naval and Environmental Case for Fission Fusion, Fusion Tech. 36, 1, (1999);
2. W. Manheimer, Can a Return to the Fusion Hybrid Help both the Fission and Fusion Programs? Physics and Society, v29, #3, July 2000
6. W. Manheimer, Hybrid Fusion, Physics and Society, vol25, #2, April 2006
Backup viewgraphs

• Magnetic fusion
Can fusion deliver by mid century?

- Tokomaks have delivered 20 MW ($10^{19}$) neutrons in a 1 second pulse with $\sim 30\%$ efficient driver.

Figures of merit for recent tokamaks: (a) triple fusion product, (b) input power, and (c) D-T neutron production rate.
The graph of tokomak advance is comparable to Moore’s law.

(But chip makers produced something useful and profitable at every point on the curve.)
The ITER PROJECT

- WORLD WIDE EFFORT TO BUILD A TOKOMAK TO GENERATE ABOUT 400 MW OF NEUTRON POWER IN PULSES 300-1000 SECONDS LONG. IF ONE SHOT/DAY, POWER< 5MW
ITER: History and cost

• Original ITER (Large ITER) cost ~$20B, divided among construction costs (~50%), operating costs for 10 years (~45%) and decommission costs (~5%). Would generate ~1.6 GW of neutron power.

• When USA (temporarily) pulled out, new ITER (Small ITER) had half the price and would produce ~400 MW of neutron power for ~300-1000 sec.
ITER: History and cost, con’t

• Conventional power plant costs ~$1-2B for ~3GWt (1GWe) vs. >$5B for ITER.

• Take ITER construction costs, grant cw operation, add on operating costs but for 30 years, and add on decommissioning costs and figure 140MWe.

• This comes out to ~$0.6-0.7/kwhr

• My electric bill would go from ~$100/mo to over $1000/mo!
But what about ARIES studies?

- These show fusion power at ~$0.05-0.1/kwhr.
- **BUT**
  - These assume some sort of advanced plasma regime, higher B, higher density, transport barriers, etc.
  - ITER is what the world can very likely do today and for the next 30 years. To achieve these advanced regimes on an ITER scale device will almost certainly take additional decades.
ITER NEEDS **AT LEAST** AN ORDER OF MAGNITUDE HIGHER Q (OR REDUCTION COST PER NEUTRON) TO BE ECONOMICALLY Viable.

NO CLEAR IDEA WHERE THIS WILL COME FROM.

BY THEN FUSION WILL HAVE BEEN SUPPORTED FOR 80 YEARS WITH ECONOMIC PAYOFF STILL DECADES AWAY.

**IS ITER FOR PURE FUSION A ‘BRIDGE TO NOWHERE’?**
Backup viewgraphs

• An introduction to the NRL KrF direct drive laser fusion effort (pure or hybrid fusion)
Direct and indirect drive ICF

- Direct drive uses laser to illuminate the target. Target must be dropped in, followed and the lasers aimed properly. Cost per shot is only target and cleanup is of only target. Optimum configuration for energy application, but laser must have high average power capability.

- Indirect drive has lasers illuminate the walls of a ‘hohlraum’ by focusing the laser through small holes in it. The walls emit X rays which illuminate the target. The application at LLNL is not energy but stockpile stewardship. The laser used can get off at best a shot or two a day at full power. For energy one would have to not only follow the hohlraum, but keep it properly oriented. Cost per shot is target and hohlraum, and one must clean up the target and hohlraum between shots.
THE NRL KrF LASER FUSION PROGRAM

Three linked experimental programs

• NIKE: 3 kJ single shot laser: planar target studies and laser development (Google NRL NIKE laser)

• ELECTRA: A repled laser, 5Hz, 750 Joules, >50,000 shots so far (Google NRL Electra laser)

• HAPL (NRL Led/Multi institution): Development of the technologies needed for laser fusion. (Google NRL HAPL high average power laser)
Compared to MFE, plasma physics of IFE is relatively simple

- Plasma Physics complexities are mostly of a fluid nature, with other plasma effects less important: Symmetry, Rayleigh Taylor and Richtmeyer Meshkov instabilities. Much progress in understanding these and designing pellets resistant to them.
- Long mean free path electron transport.
- Laser Plasma Instabilities (2 omega p, Raman and Brillouin scatter).
- High density physics issues.
Goal: Development & Deployment of Fusion Energy
Using Repetitively Pulsed High-Energy Lasers

Fusion Test Facility
150 MW (thermal)
Operating by 2020
Google NRL FTF Fusion Test Facility

NRL is very serious about this effort, estimated cost << ITER
NIKE laser provides highly uniform target illumination (best by far in the business) & deepest UV
2D computer simulations predict gains > 160 if we use a laser pulse shape that suppresses hydro-instability.

Hydro-instability grows from laser and pellet imperfections.

But theory and codes still evolving, today’s winner could be tomorrow’s dud.

GAIN = 0.5 😞

GAIN = 160 😊
Nike is used to study laser-accelerated planar targets
The Electra KrF Laser
700 Joules, 5 Hz, 100,000 shots

“Large enough to be convincing
Small enough to be manageable”
John Sethian
The HAPL Program: Developing the science & technologies needed for laser fusion energy

Multi-institutional HAPL: High Average Power Laser program administered by NNSA
“You cannot solve your problem if you make the next guy’s problem impossible” John Sethian
Some recent accomplishments of HAPL

- Achieved 8000 shots continuous at 2.5 Hz with both sides firing (Laser energy > 250 J)

- Demonstrated room temperature operation of a fluidized bed that will be used to demonstrate mass produced smooth D2 ice layers on the target.

- Reported the first demonstration of a key component: a “glint” signal from a falling target was used to align and steer a laser beam with a fast steering mirror. Accuracy is within a factor of five of what is required.

- Experiments and modeling show Tungsten/steel armor on first wall should be sufficiently resistant to thermo-mechanical stresses, provided peak temperature is kept below 2400 deg C.
500 kJ is predicted to be sufficient for direct drive ignition and gains >50× with a KrF driver

Fusion Test Facility (FTF)
- Direct laser drive
- Sub-megajoule laser energy
- High-Rep operation (5Hz)
- Goal of ~150 MW fusion power
- High flux neutron source
- Lies on a development path to a power plant
Our three-stage plan for laser IFE:
Key elements are developed and implemented in progressively more capable IFE oriented facilities

**Stage I (≈6 years)**: Develop full size components
- Laser module (25 kJ 5 Hz KrF beam line)
- Target fabrication/injection/tracking
- Chamber
- Verify pellet physics

**Stage II (≈2014-2022)**: Fusion Test Facility (FTF)
- Demonstrate physics / technologies for a power plant
- Operating: ≈2019

**Stage III (≈2024 - 2032)**: Prototype Power plant(s)
- Electricity to the grid
- Significant participation by private industry
A LASER FUSION HYBRID
Radiation Damage Studies on the First Wall of a HYLIFE-II Type Fusion Breeder
*Sümer Sahin and Mustafa Übeyli*
Energy Conversion and Management 46 (2005) 3185-3201

Schematic for Laser Fusion Breeding

Fissile Breeding $^{233}\text{U}$ from $^{232}\text{Th}$
Comparison of magnetic and inertial fusion results

- Magnetic: $\sim 10^{19}$ DT neutrons with $\sim 30\%$ efficient driver. Focus on ignition, frequently to the exclusion of all else (e.g. FIRE or IGNITOR), no consensus on how to get order of magnitude improvement needed for reactor.

- Inertial: $\sim 10^{13}$ neutrons (cryogenic target implosions at UR LLE) with $\sim 1\%$ efficient driver. But real progress on a broad front in achieving average power capability with HAPL program, which has persisted and advanced for about a decade already. Goal is not an intermediate step like ITER, but a commercial power plant. “You cannot solve your problem if you make someone else’s problem impossible” (John Sethian)
Backup viewgraphs

The energy situation
Example of Mexico

Mexico Generates ~24 GWe for ~10^8 people.

USA Generates ~ 500 GWe for ~3x10^8 people.

I believe the difference in per capita energy use is main explanation for higher living standard in USA.
What about coal

- In the absence of carbon free sources, India and China, ignoring Kyoto, are mining and burning coal as fast as they can. They are building 750 coal fired power plants (and USA is building 100). 2007: China becomes largest CO$_2$ emitter. The world is beginning to recarbonize its energy and there is no stopping this. The poor parts of the world want to get rich too.
Oil. When will be (or was) the Hubbert’s peak. In USA ~ 1970

Clearly the oil resource is running, or soon will run short. Oil is also concentrated in parts of the world that may not be reliable or stable.
Renewables: Example of solar
(Mid latitude perspective)

• Solar energy is intermittent.
• No way to store power for nights or cloudy days.
• Maximum average solar power 40W/m² (200 W/m²@ η~20%).
• 1TW requires 2.4x10⁴ km² solar collectors.
• 3 km² delivered between 1982 and 1998.
Renewables, example of wind

Grid cannot accept more than 10% of capacity from such a sporadic source. More windmills, less fractional utilization. Depends on large subsidies.

Denmark has made largest commitment to wind power (24% of its power, 8% of Nordel grid) but was unable to decommission any thermal power plants and will be unable to meet its Kyoto treaty requirements.

No simple extrapolation of from where wind is now now to providing power on scale required for mid century.

From Eon-Netz, largest wind provider in Germany
Renewables: Example of Ethanol

- Total Brazilian production is 4 billion gallons, or 100 million barrels, equivalent to 60 million barrels of oil, or ~1% of US use!
- In USA, it takes about 1 joule of oil to produce 1.3 joules (i.e. Q =1.3 in fusion parlance) of ethanol (Argon study).
- Photosynthesis is very inefficient, more land required than for solar power or wind.
- Land can be used for other more productive uses, food, cotton, lumber etc.
An ITER based scheme for mid century

- Simple estimate gave power cost from ITER at $0.7/kwhr.
- Large ITER, twice the cost, more than 4 times the power, ~$0.3/KWhr.
- But as hybrid this translates to ~$0.025/KWhr as a fuel cost.
- Gasoline at $1/gallon is ~$0.025/KWhr.
- ITER is no longer a bridge to nowhere, but becomes a bridge to somewhere!
I believe fusion can deliver large amounts of energy by mid century with a focused program on the hybrid.