Energy Challenge

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Scope of the Challenge
World Primary Energy Demand is expected to grow substantially.

- Data from IAE World Energy Outlook 2006 Reference (Red) and Alternative (Blue) scenarios.
- Mtoe: Million Metric tonne oil equivalent. World average power use is 17 TW!
Energy supply will be dominated by fossil fuels for the foreseeable future.

Source: IEA World Energy Outlook 2006 (Reference Case), Business as Usual (BAU) case.
IEA study indicates that we are not running out of fossil fuels in the short term.

Short term issue is the distribution of fossil fuels, i.e., Energy Security. Long term issue is availability of liquid fuels for transportation.
Energy Security- World-wide Oil Flow
California and Baja California becoming major importer of LNG
Fossil Fuels & Global Warming

- The earth absorbs anthropogenic CO₂ at a limited rate
  - The lifetime of CO₂ in the atmosphere is ~ 1000 years
  - The atmosphere will accumulate emissions during the 21st Century

- Impact of higher CO₂ concentrations is uncertain
  - ~ 2X pre-industrial is a widely discussed stabilization target (550 ppm)
  - Reached by 2050 under IEA Reference Scenario shown.

- To stabilize CO₂ concentration at 550 ppm, emissions would have to drop to about half of their current value by the end of this century
  - This in the face of a five fold increase of energy demand in the next 100 years (1.6% per year emissions growth)
  - Modest emissions reductions only delay the growth of concentration (20% emissions reduction buys 15 years).

- Reducing emissions is an enormous, complex challenge; technology development must play the central role.
But, many sources contribute to the emission of greenhouse gases.

It is more important to consider Emissions instead of Energy end-use.
Energy Efficiency

- **Production:** e.g. world average power plant efficiency ~ 30% → 45% (state of the art) would save 4% of anthropic carbon dioxide
  - use of flared gas in Africa could produce 20 GW (= half Africa’s current electricity)

- **Distribution:** typically 10% of electricity lost (→ 50% due to ‘non-technical losses’ in some countries: need better metering)

- **Use:** e.g., better insulated homes, more efficient transport
  - Huge scope but demand is rising faster due to long turn-over time.

- Energy Efficiency and Conservation should not be confused
Buildings

- Consumes ~ 50% of energy (Constructing, maintaining, occupying buildings)
- Improvements in design could have a big impact (e.g. could cut energy used to heat homes by up to factor of three)
- **Issue:** turn over of housing stock ~ 100 years
- **Tools:** better information, regulation, financial instruments

Source: Foster and Partners. Swiss Re Tower uses 50% less energy than a conventional office building (natural ventilation & lighting…)
Transportation

- Road transport is growing rapidly e.g. IEA estimates 700 million light vehicles today → 1,400 million in 2030 (China: 9m → 100m; India: 6.5 m → 56m)
- (For the world’s per capita petrol consumption to equal that in the USA, total petrol consumption would have to increase almost ten fold)
- Huge scope for more efficient cars
- There have been huge improvements in efficiency – but they have been used to provide heavier cars.
- After the end of oil? Biofuels), coal & gas → oil, hydrogen, electric…
Hydrogen

- Excites public and politicians (no CO₂ at point of use)
- Has to be produces (e.g., by electrolysis, or ‘thermo [high temperature] - chemical cracking’ of water)
- Hydrogen would helpful only if no CO₂ at point of production, e.g.
  - capture and store carbon at point of production
  - produced from renewables (reduced problem of intermittency)
  - produced from fission or fusion
- Excellent energy/mass ratio but energy/volume terrible
- Need to compress or liquefy (uses ~ 30% of energy, and adds to weight), or absorb in light metals (big chemical challenge)
Most of public energy expenditures is in the form of subsidies.

Energy Subsidies (€28B) and R&D (€2B) in the EU

- Coal 44.5%
- Oil and gas 30%
- Renewables 18%
- Fission 6%
- Fusion 1.5%


Slide from C. Llewellyn Smith, UKAEA
UCSD Scientists Perform Leading-edge research in New Energy technologies

Some Examples
Resource Center for Alcohol Fuels: $3M from U.C. Discovery and West Biofuels

- Public / private partnership funded by U.C. Discovery Grant
- Providing research and development opportunity for students and industry
- Fusion of biochemistry, fuels chemistry, chemical processing, and process control faculty
- Led by Prof. Bob Cattolica

- Building a pilot scale plant for alcohol fuels from cellulosic feedstocks.
The Ultimate Power Play
Fusion Research at UCSD

**PISCES:** What is Effect Of Plasma on Reactor Walls?

Inertial Confinement Fusion Science and Technology

**ARIES:** What a fusion power plant look like (UCSD leads a National ARIES Team).

Edge Plasma & Plasma-Wall Interactions in NSTX & DIII-D Tokamaks
ECE Groups Increase Photovoltaic Efficiency through Novel Materials and Design

- In a conventional solar cell, full spectrum of light not exploited:
  - Photons (light) with energy below semiconductor band gap not absorbed
  - Photon energy in excess of band gap dissipated as heat
- Increase absorption efficiency
  - Current technology: multijunction (more expensive 3 solar cells in tandem)
- UCSD ECE developments: single junction with novel materials and/or design
  - Quantum-well solar cell: additional absorption through QWs (Ed Yu, Paul Yu, ECE)
  - Nanoparticles scattering into QW waveguides: enhanced absorption (Ed Yu, ECE)
  - Nanowire vertical arrays: improved collection efficiency (Deli Wang, ECE)
  - Multi-bandgap material: three absorption bands in one material (Charles Tu, ECE)
UCSD Photonic Systems Integration Laboratory Aims to Improve PV cell designs

- ECE Prof. Joe Ford’s group explores design concepts
- Interleaved design uses dichroic mirror, space-efficient beam path and molded lenslet bars

- Both Si and III-IV cells are interleaved and mounted on same PCB board, back plane of board available for heat dissipation
- 10x concentration with no dead space between rows
**Key Technical Strengths in Control Applications**

- **Control of Propulsion and Energy Systems**
  - Gas turbines and aeroengines
  - Automotive engines
  - Fusion control
  - Maglev control
  - Flow, thermal, and plasma control

- **Control of Structures and Noise**
  - Aerospace structures
  - Seismic shakers
  - Noise control

- **Sensor Networks and Unmanned Systems**
  - UAVs and underwater vehicles
  - Command and control with deceptive information
  - Coordinated motion control and sensor networks
  - Control of communication systems

- **Control of Positioning Systems**
  - Disk drives
  - Semiconductor manufacturing
  - Atomic force microscopes
Control of HCCI Engines

HCCI = Homogeneous Charge Compression Ignition

- Low NOx emissions like spark-ignition engines
- High efficiency like Diesel engines
- BUT: requires active control for trigger of combustion
- More promising in near term than hydrogen

Valve controls intake temp.
Real-Time Controller
PC running Labview

Maximization of efficiency and minimization of emissions in real time

Cylinder Pressure
Crank Angle Position

Miroslav Krstic, PI

Research and Advanced Engineering
Fusion Energy
Fusion is one of very few non-carbon based energy options

- DT fusion has the largest cross section and lowest temperature (~100M °C). But, it is still a high-temperature plasma!
- Plasma should be surrounded by a Li-containing blanket to generate T. Or, DT fusion turns its waste (neutrons) into fuel!
- Through careful design, only a small fraction of neutrons are absorbed in structure and induce radioactivity.
- For liquid coolant/breeders (e.g., Li, LiPb), most of fusion energy is directly deposited in the coolant simplifying energy recovery.
- Practically no resource limit (10^{11} TWy D; 10^{4} (10^{8}) TWy ^{6}Li)

\[
\begin{align*}
D + T & \rightarrow ^4\text{He} (3.5 \text{ MeV}) + n (14 \text{ MeV}) \\
\text{n} + ^6\text{Li} & \rightarrow ^4\text{He} (2 \text{ MeV}) + \text{T} (2.7 \text{ MeV}) \\
D + ^6\text{Li} & \rightarrow 2 ^4\text{He} + 3.5 \text{ MeV (Plasma)} + 17 \text{ MeV (Blanket)}
\end{align*}
\]
Two Approaches to Fusion Power –
1) Inertial Fusion

- Inertial Fusion Energy (IFE)
  - Fast implosion of high-density DT capsules by laser or particle beams (~30 fold radial convergence, heating to fusion temperature).
  - A DT burn front is generated, fusing ~1/3 of fuel (to be demonstrated in National Ignition Facility in Lawrence Livermore National Lab).
  - Several ~300 MJ explosions with large gain (fusion power/input power).
Two Approaches to Fusion Power –
2) Magnetic Fusion

Magnetic Fusion Energy (MFE)

- Strong magnetic pressure (100’s atm) to confine a low density but high pressure (10’s atm) plasma.
- Particles confined within a “toroidal magnetic bottle” for 10’s km and 100’s of collisions per fusion event.
- At sufficient plasma pressure and “confinement time”, the $^4\text{He}$ power deposited in the plasma sustains fusion condition.

Rest of the Talk is focused on MFE
Tokamak is the most successful concept for plasma confinement

DIII-D, General Atomics
Largest US tokamak

Many other configurations possible depending on the value and profile of “q” and how it is generated (internally or externally)
JET is currently the largest tokamak in the world

4 MA
Plasma Current
Fusion Energy Requirements:

- Heating the plasma for fusion reactions to occur
  - to 100 Million Celsius (routinely done in present experiments)
- Confining the plasma so that alpha particles sustain fusion burn
  - Energy Replacement time of about 1 s
  - Plasma density of $10^{21} \text{ /m}^3$ (Air Density is $3 \times 10^{25} \text{ /m}^3$)
  - Progress in confinement is measured by “Fusion Triple Product” $= (\text{plasma temperature}) \times (\text{energy replacement time}) \times (\text{plasma density})$
- Extracting the fusion power and breeding tritium
  - Co-existence of a hot plasma with material interface
  - Developing power extraction technology that can operate in fusion environment
Progress in plasma confinement has been impressive.

500 MW of fusion Power for 300s
Construction will be started shortly in France.
Large amount of fusion power has also been produced.
We have made tremendous progress in understanding fusion plasmas

- Substantial improvement in plasma performance though optimization of plasma shape, profiles, and feedback.
  - Achieving plasma stability at high plasma pressure.
  - Achieving improved plasma confinement through suppression of plasma turbulence, the “transport barrier.”
  - Progress toward steady-state operation through minimization of power needed to maintain plasma current through profile control.
  - Controlling the boundary layer between plasma and vessel wall to avoid localized particle and heat loads.
Fusion: Looking into the future
ITER will demonstrate the technical feasibility of fusion energy

- Power-plant scale device.
  Baseline design:
  - 500 MW of fusion power for 300s
  - Does not include breeding blanket or power recovery systems.
- ITER agreement was signed in Nov. 2006 by 7 international partners (US, EU, Japan, Russia, China, Korea, and India)
- Construction will begin in 2008.
ARIES-AT is an attractive vision for fusion with a reasonable extrapolation in physics & technology

- Competitive cost of electricity (5c/kWh);
- Steady-state operation;
- Low level waste;
- Public & worker safety;
- High availability.
Advances in fusion science & technology has dramatically improved our vision of fusion power plants.

**Major radius (m)**

<table>
<thead>
<tr>
<th>Mid 80's Pulsar</th>
<th>Early 90's ARIES-I</th>
<th>Late 90's ARIES-RS</th>
<th>2000 ARIES-AT</th>
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</thead>
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**Estimated Cost of Electricity (c/kWh)**

<table>
<thead>
<tr>
<th>Mid 80's Physics</th>
<th>Early 90's Physics</th>
<th>Late 90's Physics</th>
<th>Advanced Technology</th>
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Radioactivity levels in fusion power plants are very low and decay rapidly after shutdown.

- SiC composites lead to a very low activation and afterheat.
- All components of ARIES-AT qualify for Class-C disposal under NRC and Fetter Limits. 90% of components qualify for Class-A waste.

After 100 years, only 10,000 Curies of radioactivity remain in the 585 tonne ARIES-RS fusion core.

Level in Coal Ash

Level in Coal Ash
Waste volume is not large

- 1270 m³ of Waste is generated after 40 full-power year (FPY) of operation.
  - Coolant is reused in other power plants
  - 29 m³ every 4 years (component replacement), 993 m³ at end of service
- Equivalent to ~ 30 m³ of waste per FPY
  - Effective annual waste can be reduced by increasing plant service life.

- 90% of waste qualifies for Class A disposal
Modular sector maintenance enables high availability

- Full sectors removed horizontally on rails
- Transport through maintenance corridors to hot cells
- Estimated maintenance time < 4 weeks
Fusion: Why is taking so long?
There has been no urgency in developing new sources of energy

- Proposed fusion development plan in 1976 aimed at fielding a fusion Demo by 2000.
- Recent DOE Fusion Development Plan (2003) aimed at fielding a fusion Demo by 2030.
- The required funding to implement the plans were not approved.
- Proposals for fielding a burning plasma experiments since mid 1980s.
- Fusion program was restructured in mid 1990s, focusing on developing fusion sciences (with 1/3 reduction in US funding).
  - Fielding a fusion Demo is NOT the official goal of DOE at present
- Large interest and R&D investment in Europe and Japan (and China, India, Korea)
Development of fusion has been constrained by funding!

~ 1 week of world energy sale
In Summary, ...
In a CO$_2$ constrained world uncertainty abounds

- No carbon-neutral commercial energy technology is available today.
  - Carbon sequestration is the determining factor for fossil fuel electric generation.
  - A large investment in energy R&D is needed.
  - A shift to a hydrogen economy or carbon-neutral syn-fuels is also needed to allow continued use of liquid fuels for transportation.

- Problem cannot be solved by legislation or subsidy. We need technical solutions.
  - Technical Communities should be involved or considerable public resources would be wasted.

- The size of energy market ($1T annual sale, TW of power in US) is huge. Solutions should fit this size market.
  - 100 Nuclear plants = 20% of US electricity production
  - $50B annual R&D represents 5% of energy sale
Status of fusion power

- Over 15 MW of fusion power is generated (JET, 1997) establishing “scientific feasibility” of fusion power
  - Although fusion power < input power.
- ITER will demonstrate “technical feasibility” of fusion power by generating copious amount of fusion power (500MW for 300s) with fusion power > 10 input power.
- Tremendous progress in understanding plasmas has helped optimize plasma performance considerably. Vision of attractive fusion power plants exists.
- Transformation of fusion into a power plant requires considerable R&D in material and fusion nuclear technologies (largely ignored or under-funded to date).
  - This step, however, can be done in parallel with ITER