Role of Fusion Energy in the 21st Century

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Energy and Well Being

Most of the data is from IEA World Energy Outlook 2006
World uses a lot of energy!

- World Primary Energy consumption is 14 TW (2004)
  - Equivalent to ~0.5 EJ or 11.2 Billion Ton of Oil Equivalent pa
  - World energy [electricity] market ~ $4.5 trillion [$1.5 trillion] pa

- World energy use is expected to grow 50% by 2030.
  - Growth is necessary in developing countries to lift billions of people out of poverty

- 80% of world energy is from burning fossil fuels

- Use is very unevenly distributed (average 2.4 kW per person)
  
<table>
<thead>
<tr>
<th>Country</th>
<th>Average Watts</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>10,500</td>
</tr>
<tr>
<td>California</td>
<td>7,300</td>
</tr>
<tr>
<td>UK</td>
<td>5,200</td>
</tr>
<tr>
<td>China</td>
<td>1,650 (growing 10% pa)</td>
</tr>
<tr>
<td>India</td>
<td>700</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>210</td>
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With industrialization of emerging nations, energy use is expected to grow ~ 4 fold in this century (average 1.6% annual growth rate)
Quality of Life is strongly correlated to energy use.

**HDI:** (index reflecting life expectancy at birth + adult literacy & school enrolment + GNP (PPP) per capita)
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- Typical goals: HDI of 0.9 at 3 toe/cap for developing countries.
- For all developing countries to reach this point, world energy use would double with today’s population, or increase 2.6 fold with the 8.1 billion expected in 2030.
World Primary Energy Demand is expected to grow substantially.

- Data from IAE World Energy Outlook 2006 Reference (Red) and Alternative (Blue) scenarios.
- World population is projected to grow from 6.4B (2004) to 8.1B (2030)
Energy supply will be dominated by fossil fuels for the foreseeable future

Source: IEA World Energy Outlook 2006 Reference Case (Business as Usual)
Conclusions on Energy Need

- Large increase in energy use expected, and needed to lift billions of people out of poverty

- Seems (IEA World Energy Outlook) that it will require increased use of fossil fuels
  - Pollution and global warming*
  - Will run out sooner or later

- There is a need to curb the growth of primary energy use, and seek cleaner ways of producing energy on a large scale
  - IEA: “Achieving a truly sustainable energy system will call for radical breakthroughs that alter how we produce and use energy”

*Ambitious goal for 2050 - limit CO$_2$ to twice pre-industrial level. To do this while meeting expected growth in power consumption would need 50% more CO$_2$-free power than today’s total power
Many sources contribute to the emission of greenhouse gases. It is more important to consider Emissions instead of Energy end-use.

Energy emissions are mostly CO₂ (some non-CO₂ in industry and other energy related). Non-energy emissions are CO₂ (land use) and non-CO₂ (agriculture and waste).
Technical means to meet the energy need and their issues

(Seeking a significant fraction of world’s 14 TW consumption)
Meeting the Challenge: No silver bullet exists!

- **Improved efficiency and Conservation**
  - Huge scope but demand has always risen faster due to long turn-over time.

- **Renewables**
  - Intermittency, cost, environmental impact.

- **Carbon sequestration**
  - Requires handling large amounts of C (Emissions to 2050 =2000Gt CO₂)

- **Nuclear (Fission)**
  - fuel cycle and waste disposal

- **Fusion**
  - Probably a large contributor in the 2nd half of the century
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
Potential of Renewables

- **Solar** - 85,000 TW reaches earth’s surface → 25,000 TW on land, if capture [PV] 0.5% at 15% efficiency ⇒ 19 TW ~ 1.35x current total use
  - but: cost, location, intermitency → storage? [note: lose (conversion efficiency)^2]

- **Wind** - 200 TW input ⇒ no more than a few TW available (bottom of atmosphere) Issues are similar to solar.

- **Biomass** - 40 TW from all current growth (farms + forests etc) absorbing CO₂ [average solar → biomass efficiency ~ 0.2%]

- **Hydro** – 1.5 TWₑ max, 1 TWₑ useful, 0.3 TWₑ already in use

- **Geothermal** - total flux out of earth ~ 10 TW → maximum useful 0.1 TW (well exploited where sensible: 10 GW installed) ; more available by ‘mining’ up to 100 GW?

- **Waves** - 1 TW available in principle on continental shelves, 0.1 TW in shallow water
Energy Challenge: A Summary

- Large increases in energy use is expected.
- IEA world Energy Outlook indicates that it will require increased use of fossil fuels
  - Air pollution & Climate Change
  - Will run out sooner or later
- Limiting CO$_2$ to 550ppm by 2050 is an ambitious goal.
  - To do this while meeting expected growth in power consumption would need 50% more CO$_2$-free power than today’s total power
- Public funding of energy research is down 50% since 1980 (in real term). World energy R&D expenditure is 0.25% of energy market of $4.5 trillion.
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
Politics of Energy Challenge

- Energy debate is dominated by activists and lobbyists.
  - Left: “Energy challenge can be readily met by conservation and renewables alone.”
  - Right: “Limiting greenhouse emissions are so costly that it will wreck the economy.” or “Uncertainty in the CO₂ impact justifies inaction.”

- Energy scientists and engineers are NOT involved in the debate
  - Most proposals by activist and hyped by popular media either violate physical laws, or are beyond current technology, or would not make any sizeable impact.

- No carbon-neutral commercial energy technology is available today.
  - Solution CANNOT be legislated.
  - Subsidies do not work! Energy market is huge (T$ annual sale)
  - Time-scale for developing and fielding energy technologies are long!

- **We need to launch an aggressive Energy R&D program**
  - 5% tax on energy sale = $50 B per year!
Status of Fusion Research
Fusion is one of very few non-carbon based energy options

- Practically no resource limit ($10^{11}$ TWy D; $10^4$ ($10^8$) TWy $^6$Li)
- 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, i.e., 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.

\[ \text{D + T} \rightarrow ^4\text{He} (3.5 \text{ MeV}) + n (14 \text{ MeV}) \]
\[ n + ^6\text{Li} \rightarrow ^4\text{He} (2 \text{ MeV}) + T (2.7 \text{ MeV}) \]
\[ \text{D + } ^6\text{Li} \rightarrow 2 \ ^4\text{He} + 3.5 \text{ MeV (Plasma)} + 17 \text{ MeV (Blanket)} \]
Fusion Energy Requirements:

- Confining the plasma so that alpha particles sustain fusion burn
  - Lawson Criteria: $n \tau_E \sim 10^{21} \text{ s/m}^3$

- Heating the plasma for fusion reactions to occur
  - to 100 Million Celsius (routinely done in present experiments)

- Optimizing plasma confinement device to minimize the cost
  - Smaller devices
  - Cheaper systems, e.g., lower-field magnets (MFE) or lower-power lasers (IFE)

- Extracting the fusion power and breeding tritium
  - Developing power extraction technology that can operate in fusion environment
  - Co-existence of a hot plasma with material interface
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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 per second with large gain (fusion power/input power).
National Ignition Facility is expected to demonstrate inertial fusion ignition in 2010.
Two Approaches to Fusion Power –
2) Magnetic Fusion

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

- Pressure balance (equilibrium) does not guarantee stability.
  - Example: Interchange stability

Impossible to design a “toroidal magnetic bottle” with good curvatures everywhere.
Fortunately, because of high speed of particles, an “averaged” good curvature is sufficient.
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)
T3 Tokamak achieved the first high temperature (10 M °C) plasma
JET is currently the largest tokamak in the world

ITER Burning plasma experiment (under construction)
Progress in plasma confinement has been impressive.

ITER Burning plasma experiment

500 MW of fusion Power for 300s
Construction will be started shortly in France
Large amount of fusion power has also been produced
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We have made tremendous progress in optimizing 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.
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Managing the plasma material interface is challenging

- Alpha power and alpha ash has to eventually leave the plasma
  - Particle and energy flux on the material surrounding the plasma
- Modern tokomaks use divertors:
  - Closed flux surfaces containing hot core plasma
  - Open flux surfaces containing cold plasma diverted away from the first wall.
  - Particle flux on the first wall is reduced, heat flux on the first wall is mainly due to radiation (bremsstrahlung, synchrotron, etc.)
  - Alpha ash is pumped out in the divertor region
  - High heat and particle fluxes on the divertor plates.
DT Fusion requires a T breeding blanket

- **Requirement:** Plasma should be surrounded by a blanket containing Li
  
  \[ D + T \rightarrow He + n \]
  
  \[ n + 6Li \rightarrow T + He \]

- Through careful design, only a small fraction of neutrons are absorbed in structure and induce radioactivity:
  - Rad-waste depends on the choice of material: Low-activation material
  - Rad-waste generated in DT fusion is similar to advanced fuels (D-3He)
  - For liquid coolant/breeders (e.g., Li, LiPb), most of fusion energy (carried by neutrons) is directly deposited in the coolant simplifying energy recovery

- **Issue:** Large flux of neutrons through the first wall and blanket:
  - Need to develop radiation-resistant, low-activation material:
  - Different from fission material because the high energy fusion neutron generates H and He in addition to displacement damage.
New structural material should be developed for fusion application

- **Fe-9Cr steels**: builds upon 9Cr-1Mo industrial experience and materials database
- **(9-12 Cr ODS steels are a higher temperature future option)**
- **V-4Cr-4Ti**: Higher temperature capability, targeted for Li self-cooled blanket designs
- **SiC/SiC**: High risk, high performance option (early in its development path)
- **W alloys**: High performance option for PFCs (early in its development path)
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.
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
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.
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) is huge. Solutions should fit this size market
  - 100 Nuclear plants = 20% of 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
- Large synergy between fusion nuclear technology R&D and Gen-IV.
Thank you!
Any Questions?