Where in the World Can We Find Clean, Safe, Long Lasting, and Economical Energy Sources for the 21st Century and Beyond?

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UCLA
November 6, 2007
Outline of Presentation

• Where we have been?--(History)
• Where we are now?--(Fact)
• Where are we going in the next ≈20-30 years?--(Projection)
• Where will we be in 100 years?--(Speculation)
The Total Energy Use in the World Has Increased by Over a Factor of 5 Since World War II

Fossil Fuels Still Account for Over 85% of the Primary Energy Consumed in the World

The Worldwide Emissions of Carbon from the Burning of Fossil Fuels is Now Over 1 Tonne per Person per Year

The World Energy Demand is the Product of Two Simple Numbers

Population \times \text{Energy Use per Person}
Annual World Energy Use Per Capita Has Started to Rise Again After Having Been Essentially Constant Since the 1973 Oil Crisis

The U. S. Continues to Use a Large Amount of Energy Per Capita

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• Where are we going in the next 20-30 years?--(Projection)
• Where will we be in 100 years?--(Speculation)
Currently, Fossil Fuels Provide 87% of the World’s Primary Energy
The World Can Be Broken Up into 6 Major Regions to Analyze World Energy Consumption
In 2005 the OECD Nations Comprised Less Than 18% of the World's Population But Consumed 50% of the World's Energy.
China’s GDP Has Reached 20.9 Trillion Yuan RMB by the End of 2006 While GDP Per Capita Exceeds 2,000 USD

Dr. Xu Kuangdi, President of Chinese Academy of Engineering-Oct., 2007
The Current Energy Use per Person in the U.S. is Much Larger Than in the Rest of the World

United States

0.3 Billion x 60 BOE/person = 18 Billion BOE/year

Rest of the World

6.3 Billion x 10.2 BOE/person = 64 Billion BOE/year
Outline of Presentation

- Where we have been?--(History)
- Where we are now?--(Fact)
- Where are we going in $\approx 20$-$30$ years?--(Projection)
- Where will we be in $100$ years?--(Speculation)
Over the Next 25 Years the Rate of Increase in Energy Consumption of the Non-OECD Asian Nations is Projected to be 5-6 Times that of the OECD Nations

Growth of World Energy Use Per Capita

Barrels of Oil (Equivalent) per Capita per Year

Year

Historical  Projected

1960 1980 2000 2020 2040 2060 2080 2100

(???)
Annual World Energy Needs

Present

- 6.6 Billion people
- 12.4 barrels/capita
- 82 Billion BOE/year

Future

- 10 Billion people
- 15 barrels/capita
- 150 Billion BOE/year
Over 10 trillion boe in energy is needed in this century.

**World Energy Consumption and Resources for the 21st Century**

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Required</th>
<th>Annual Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2020</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2040</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2060</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>2080</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>2100</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>2120</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

CUMULATIVE NEEDS

Over 10 trillion boe in energy is needed in this century.
The World is Already Increasing its Oil Consumption Faster Than it is Discovering New Reserves

After Hirsch-2005
The worldwide production of oil is predicted by Campbell et. al., (Scientific American, March 1998) to peak about now!
RECENT PROJECTIONS OF WORLD OIL PRODUCTION PEAKING

<table>
<thead>
<tr>
<th>Projection</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006-2007</td>
<td>Bakhitari, A.M.S.</td>
</tr>
<tr>
<td>2007-2009</td>
<td>Simmons, M.R.</td>
</tr>
<tr>
<td>After 2007</td>
<td>Skrebowski, C.</td>
</tr>
<tr>
<td>Before 2009</td>
<td>Deffeyes, K.S.</td>
</tr>
<tr>
<td>Before 2010</td>
<td>Goodstein, D.</td>
</tr>
<tr>
<td>Around 2010</td>
<td>Campbell, C.J.</td>
</tr>
<tr>
<td>After 2010</td>
<td>World Energy Council</td>
</tr>
<tr>
<td>2010-2020</td>
<td>Laherrere, J.</td>
</tr>
<tr>
<td>2016</td>
<td>EIA nominal case</td>
</tr>
<tr>
<td>After 2020</td>
<td>CERA</td>
</tr>
<tr>
<td>2025 or later</td>
<td>Shell</td>
</tr>
<tr>
<td>No visible peak</td>
<td>Lynch, M.C.</td>
</tr>
</tbody>
</table>

SAIC / MISI
The World Reserves of Fossil Fuel are Dominated by Coal (January 1, 2006)

There is 5 Times as Much Energy in the World's Reserves of Uranium Used in Breeder Reactors Than in All the Fossil Fuel Reserves in the World

Source: OECD/NEA-IAEA “Red Book”-2006
World Energy Consumption and Resources for the Future

CUMULATIVE NEEDS

NUCLEAR ENERGY (Fission, Fusion)

RECOVERABLE FOSSIL FUEL (Oil, Gas, Coal)

Year

TOTAL ENERGY

Trillion Barrels of Oil Equivalent
## Technical Maximum Potential of Renewable Resources

<table>
<thead>
<tr>
<th>Resource</th>
<th>Annual Energy Potential (billion boe/y)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>30</td>
<td>Requires cultivation of a large fraction the productive land in the world</td>
</tr>
<tr>
<td>Hydro power</td>
<td>15</td>
<td>Includes minor contribution from glaciers</td>
</tr>
<tr>
<td>Wind</td>
<td>15</td>
<td>High quality but utilization must deal with energy storage</td>
</tr>
<tr>
<td>Geothermal</td>
<td>10</td>
<td>Technology not available for large scale heat “mining”.</td>
</tr>
<tr>
<td>OTEC</td>
<td>5</td>
<td>Potential is great if ocean heat can be diverted on a large scale</td>
</tr>
<tr>
<td>Tidal</td>
<td>0.2</td>
<td>Very localized</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>≈ 75</strong></td>
<td></td>
</tr>
</tbody>
</table>

Source: W. Hafele, ENERGY IN A FINITE WORLD-A Global Systems Analysis
Technical Potential of Solar Energy Used Collected on the Earth

1.) Solar energy has the same level of potential to provide essentially inexhaustible long-term energy source for society as does the LMFBR.

2.) A global solar option would exhibit enormous heterogeneity

3.) No more than 5-10 billion boe/y should be expected before 2030.

4.) Solar Power Satellites are a potential solution for >2050

5.) Large scale storage capacity will probably turn out to be the key barrier

6.) Environmental effects are not entirely benign (risks in material intensive industries, GaAs, etc.)

7.) High capital costs are the immediate barrier to commercialization

After: W. Hafele, ENERGY IN A FINITE WORLD-A Global Systems Analysis
Outline of Presentation

• Where we have been?--(History)
• Where we are now?--(Fact)
• Where are we going in ≈ 20-30 years?--(Projection)
• Where will we be in 100 years?--(Speculation)
Framework

• Look out 100 years from now (≈ 2100)
• Assumptions
  – China, India, and other developing countries continue economic growth
  – No major catastrophes of the several billion people scale
How Much Energy Will be Needed to Get Through the Next 100 Years?

• Assume energy use between 2000-2050 rises from 80 to an “equilibrium” of 150 billion boe/y

• Assume “equilibrium” energy use between 2050-2100 is 150 billion boe/y

• Energy Consumption between 2000 and 2050 is 5,500 billion boe.

• Energy needed between 2050 and 2100 is 7,500 billion boe.
What Will the Status of Energy Sources be in 2100?

- Oil - Essentially gone for use as a major energy source, used only for special applications.
- Natural Gas - Essentially gone for use as a major energy source, used only for special applications.
- Coal - Approaching the end of economically retrievable resources
What Will the Status of Energy Sources be in 2100? (cont.)

- **Renewables**: If developed to 50% of their potential, they could provide 25% of required energy (<40 billion boe/y, or < half of world energy demand today)
What Will the Status of Energy Sources be in 2100? (cont.)

• Fission—Could satisfy total demand if the present fleet of \( \approx 450 \text{ Gw}_e \) in LWR’s is increased by 30 times in Breeder Reactors (\( \approx 13,500 \text{ GW}_e \))

• Fusion—Could be competitive with fission if the fusion reactors produce \( \ll \) less long half life radioactivity per kW\(_e\)h than current DT designs and show reasonable economics.
The Evolution of Nuclear Power

**Generation I**
- Early Prototype Reactors
  - Shippingport
  - Dresden, Fermi I
  - Magnox

**Generation II**
- Commercial Power Reactors
  - LWR-PWR, BWR
  - CANDU
  - VVER/RBMK

**Generation III**
- Advanced LWRs
  - ABWR
  - System 80+
  - AP600
  - EPR

**Near-Term Deployment**
- Generation I-III Evolutionary Designs Offering Improved Economics

**Generation IV**
- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

Timeline:
- Gen I: 1950-1960
- Gen II: 1970-1980
- Gen III: 1990-2000
- Gen III+: 2010-2020
- Gen-IV: 2030
Required Attributes of Major Energy Sources in the Latter Half of the 21st Century and Beyond

- Satisfy the needs of ≈10 billion people
  - Energy equivalent to 7.5 trillion barrels of oil @ >150 bboe/y from 2050-2100
- Have minimal impact on environment
  - Greenhouse gases, nuclear waste, etc
- Produce energy safely without side effects and international conflicts
  - i.e., proliferation of weapons grade material
- Be affordable
The Public Developed a Resistance to Nuclear Fission Power in the Late 20th Century

The resistance seems to be largely based on:

1) Fear of radioactivity releases
2) Uneasiness with long-term nuclear waste storage
3) Fear of proliferation of nuclear weapons grade material

All of the above problems stem from the nuclear reaction:

1) Radioactive fuel
2) Radioactive reaction products
3) Neutrons
The Use of Fusion Fuels May Evolve in the Future to Address the Radioactive Waste Problem

<table>
<thead>
<tr>
<th>Generation</th>
<th>Reaction</th>
<th>Products</th>
<th>Energies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Generation</td>
<td>D + T $\rightarrow$ n (14.07 MeV) + $^4$He (3.52 MeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D + D $\rightarrow$ n (2.45 MeV) + $^3$He (0.82 MeV)</td>
<td>$\rightarrow$ p (3.02 MeV) + T (1.01 MeV)</td>
<td>{50%}</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd Generation</td>
<td>D + $^3$He $\rightarrow$ p (14.68 MeV) + $^4$He (3.67 MeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Generation</td>
<td>$^3$He + $^3$He $\rightarrow$ 2p + $^4$He</td>
<td></td>
<td>(12.9 MeV)</td>
</tr>
</tbody>
</table>
Advanced Fusion Fuels are More Difficult to “Burn”
The 20th Century Approach to Fusion Only Partly Alleviates Public Concerns About Nuclear Fission Power

<table>
<thead>
<tr>
<th>Public Concern</th>
<th>How DT Fusion Addresses Concern</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radioactive Releases</strong></td>
<td>Avoid runaway reactions and &quot;meltdown&quot; scenarios</td>
</tr>
<tr>
<td></td>
<td>However, still have gigacuries in reactor in the event of an accident</td>
</tr>
<tr>
<td><strong>Long Term Radioactive Waste Storage</strong></td>
<td>Choice of fuel and structural material can reduce effective half life to &lt; 100's years</td>
</tr>
<tr>
<td></td>
<td>However, radiation damage and replacement of components can produce large volumes of radioactive waste</td>
</tr>
<tr>
<td><strong>Proliferation</strong></td>
<td>Fusion Reactor does not require fissile or fertile material</td>
</tr>
<tr>
<td></td>
<td>However, excess neutrons can be used to breed fissile fuel</td>
</tr>
</tbody>
</table>
How Do Fission and Fusion Stack Up Against Our Criteria For 21st Century Energy Sources?

• Satisfy the needs of 6-10 billion people (Energy equivalent to 13 trillion barrels of oil over 100 years)
  – Land resources of U contain more than 35 trillion boe (LMFBR)
  – Current DT is limited by Li (more >15 trillion boe of Li resources)
  – D is essentially unlimited (longer than the sun will last)
  – $1.5 \times 10^5$ tonnes of $^3$He used in fusion contain $\approx 15$ trillion boe

• Have minimal impact on environment (Greenhouse gases, nuclear waste, etc)
  – Both fission and fusion have low GHG emissions during operation
  – Advanced fusion fuels can greatly reduce or even eliminate nuclear wastes
How Do Fission and Fusion Stack Up Against Our Criteria For 21st Century Energy Sources? (cont)

• Produce energy safely without side effects and international conflicts (i.e., proliferation of weapons grade material)
  - Fission inherently produces material that can be used for weapons
  - Today’s fusion (DT) can also produce weapons grade material
  - $^3$He fuels cannot be used to produce fissile material

• Be affordable (Consume no more than 10% of the World GNP)
  - Fission is already the most economical way to produce electricity in many countries
  - Fusion ??? (@ $1 billion dollar a tonne, $^3$He increases the COE by 1¢/kWh)
Why Are We Interested in the Advanced Fusion Fuel Cycles if DT Fusion is Easier?
The Number of Neutrons Generated by Helium-3 Fusion Fuels is Very Small

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Rel. n/MeV Released in</th>
<th>Fusion Fuels</th>
<th>*burn half of T bred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission</td>
<td>1</td>
<td>DT</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DD</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D³He</td>
<td>0.04–0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>³He-³He</td>
<td>0</td>
</tr>
</tbody>
</table>

The number of neutrons generated by Helium-3 fusion fuels is very small, with DT producing significantly more neutrons (11) compared to other fuels.
Characteristics of D\(^3\) He Fusion Power Plants

- No Greenhouse or Acid Gas Emissions During Operation
- Very High Efficiencies (>70%)
- Greatly Reduced Radiological Hazard Potential Compared to Fission Reactors (<1/10,000)
- Low Level Waste Disposal After 30 y
- No Possible Offsite Nuclear Fatalities in the Event of Worst Possible Accident
Characteristics of $^3\text{He}^3\text{He}$ Fusion Power Plants

- No Greenhouse or Acid Gas Emissions During Operation
- Very High Efficiencies Possible (>70%)
- No Residual Radioactivity After 30 Years of Operation (No Radioactive Waste or Nuclear Safety Hazard).

*Nuclear Energy Without Nuclear Waste !!*
## Major Societal and Technical Concerns of Nuclear Energy Options

<table>
<thead>
<tr>
<th>Fission</th>
<th>Fusion Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
</tr>
<tr>
<td></td>
<td>DT</td>
</tr>
<tr>
<td></td>
<td>³He/³He</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Concern</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proliferation</td>
<td>⬤</td>
<td>⬤</td>
<td>none</td>
</tr>
<tr>
<td>Nuclear Waste</td>
<td>⬤</td>
<td>⬤</td>
<td>none</td>
</tr>
<tr>
<td>Radiological Hazard</td>
<td>⬤</td>
<td>⬤</td>
<td>none</td>
</tr>
<tr>
<td>Physics Req't.</td>
<td>none</td>
<td>⬤</td>
<td>⬤</td>
</tr>
</tbody>
</table>

- Proliferation
- Nuclear Waste
- Radiological Hazard
- Physics Req't.

### Difficulty Scale
- Hardest
- Easiest
- Major Problem
- Minor Problem
If Helium-3 Fusion is So Great, Why Has it Not Been Developed by Now?

• Need a demonstration of $^3$He fusion physics
• Need a source of $^3$He
The ITER DT Facility is Presently (2008) Under Construction in France

Cost
10-20 $B

2 meter Worker

First Plasma
2016
Full Power
500 MW
≈2022
How Can We make the Advanced Fusion Fuel Cycles “Burn” More Efficiently?
To Avoid the Limitations of Maxwellian Plasmas, Farnsworth Invented the Inertial Electrostatic Concept

1. Positive ions are created from the fuel gas near the outer grid, and are accelerated towards the negativity charged inner grid.

2. The ions can oscillate through the inner grid several times, creating a concentration of high temperature ions.

3. The ions can collide, creating a fusion reaction.

4. The ions can also undergo a charge exchange, creating a fast neutral.

5. Fast neutrals can collide with the neutral gas, also creating fusion reactions.

6. High energy fusion products, such as protons and neutrons, are created and can be used in many different applications.
Using the IEC concept, accelerating ions to 100 keV makes much more efficient use of the input energy.
Steady State Helium-3 Fusion has Already Been Produced in Different Chambers at the University of Wisconsin
The Steady State D-\(^3\)He Fusion Reaction is Routinely Produced in the UW IEC Device
\(^{3}\text{He}(^{3}\text{He},2p)^{4}\text{He}\) Fusion Reactions Have Been Measured in a Fusion Device at UW-Madison

\(^{3}\text{He}-^{3}\text{He}\) Fusion
Where Can We Find a Large Source of $^3$He?

There are only a few 100 kilograms of Helium-3 on the Earth (from nuclear weapons programs)
The Solar Wind has been "blowing" on the planets (and Moons) of our solar system for some 4.5 billion years.

The Solar wind is ionized and therefore is deflected by the Earth's magnetic field.
Solar Wind

96% H⁺
4% He⁺⁺

Solar Wind is deflected by any body that has a magnetic field or absorbed in an atmosphere around a planet.

Total $^3$He to hit the Moon is about 500 million tonnes over 4.5 billion years.
Lunar Helium-3 Is Well Documented

- Helium-3 concentration ($\approx 20 \text{ ppb}$) verified from Apollo 11, 12, 14, 15, 16, 17 and U.S.S.R. Luna 16, 20, and 24 samples.

- Current analyses indicate that there are at least 1,000,000 tonnes of helium-3 imbedded in the lunar soil (3m depth).
The regolith in those regions is made up of very fine grains which has been “gardened” by meteorites over billions of years (NASA Photo).
When Lunar Regolith is Heated the Helium-3 is Released

Pepin and Co-Workers, University of Minnesota, 1970
Significance of Lunar Helium-3

• 1 tonne of Helium-3 can produce enough electricity to fulfill the needs of 10 million Americans for a whole year.

• 40 tonnes of Helium-3 will provide all the electricity used in the United States in 2007.
At today’s spot coal prices ($3/million BTU or $66/tonne) the energy in one tonne of Helium-3 would be worth $1.8 billion
At today’s natural gas prices ($9/million BTU) the energy in one tonne of Helium-3 would be worth $5.4 billion
At today’s oil prices ($13/million BTU or $80/barrel) the energy in one tonne of Helium-3 would be worth $8 billion.

One of today’s U. S. shuttles could return a “payload” worth over $150 billion.
There is 10 Times More Energy in the Helium-3 on the Moon Than in All of Today’s Economically Recoverable Coal, Oil, and Natural Gas on the Earth
The Moon May be the Major Source of New Energy Supplies in the 21st Century.

This would make the investment in the Space program one of the largest payoffs in history.
NASA’s Exploration Roadmap

- **Initial CEV Capability**
- **1st Human CEV Flight**
- **Lunar Outpost Buildup**
- **Lunar Robotic Missions**
- **Science Robotic Missions**
- **Commercial Crew/Cargo for ISS**
- **Space Shuttle Ops**
- **CEV Development**
- **Crew Launch Development**
- **CEV Production and Operations**
- **Lunar Lander Development**
- **Lunar Heavy Launch Development**
- **Earth Departure Stage Development**
- **Surface Systems Development**
- **7th Human Lunar Landing**
- **Mars Expedition Design**
Conclusions

• We have an energy problem that requires immediate attention and new sources must be made available by 2050.
• Nuclear sources appear to be the only worldwide solution for the long run.
• Fusion has many advantages over fission.
• Advanced fusion fuels using $^3$He have significant advantages over the DT cycle.
Conclusions (cont.)

- There are 2 main remaining issues before a $^3$He based fusion economy can be realized:
  - Successful demonstration of breakeven and net energy gain
  - A resource base of > 10,000 tonnes of economically accessible $^3$He
- The $^3$He resources on the Moon ($\approx 1,000,000$ tonnes) can satisfy the world electricity demand for more than a 1,000 years.
- For fusion reactors based on the $^3$He fuel cycle to be available by the 2040-2050 time frame, a significant worldwide effort in research is needed now.
"Man will not fly for fifty years."
– Wilbur Wright, 1901

"Heavier-than-air flying machines are impossible."
– Lord Kelvin, president, Royal Society, 1895

"There is not the slightest indication that [nuclear energy] will ever be obtainable. It would mean that the atom would have to be shattered at will."
– Albert Einstein, 1932

"Anyone who looks for a source of power in the transformation of the [nucleus of the] atom is talking moonshine."
– Ernest Rutherford, 1933

"Airplanes are interesting toys but of no military value."
– Marshall Foch, future WWI French commander-in-chief, 1911

"Space travel is utter bilge."
– Dr. Richard Wooley, Astronomer Royal, space advisor to the British government, 1956
Where in the World Can We Find Clean, Safe, Long Lasting, and Economical Energy Sources for the 21st Century and Beyond?

Possibly Here!
Questions?