The Road to Environmentally Responsible Energy Security

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The Road to Environmentally Responsible Energy Security

OUTLINE

1. The World Energy Situation
   - Need for more energy, dominance of fossil fuels, impact on the environment, energy-water nexus

2. Renewable Energy Sources
   - Solar, wind, geothermal, biomass, hydro, etc.

3. Nuclear Fission
   - Existing plants, and contribution to current world energy needs
   - Nuclear future outlook

4. Fusion
   - Incentives to fusion
   - Approaches to fusion and DEMO goal
   - Current Progress AND when can we have fusion?

5. Closing Remarks
World Energy Situation
Energy Situation

- The world uses a lot of energy
  - Average power consumption = 17.7 TW (2.5 KW per person)
  - World energy market ~ $3 trillion / yr (electricity ~ $1 trillion / yr)

- The world energy use is growing
  - To lift people out of poverty, to improve standard of living, and to meet population growth

- Climate change and debilitating pollution concerns are on the rise
  - 80% of energy is generated by fossil fuels
  - CO₂ emission is increasing at an alarming rate

- Oil supplies are uncertain
  - Special problem for transportation sector (need alternative fuel)
China energy use has been rising faster than anticipated

Source: Energy Information Administration, International Energy Outlook 2010
Energy Flows in the U.S. Economy, 2013

Estimated U.S. Energy Use in 2013: ~97.4 Quads

Quadrillions of Btus

Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant “heat rate.” The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-M1-410527

BTU Content of Common Energy Units

1 Quad = 1,000,000,000,000,000 Btu
1 cubic foot of natural gas = 1,028 Btu
1 barrel of crude oil = 5,800,000 Btu
1 short ton of coal = 20,169,000 Btu
1 gallon of gasoline = 124,000 Btu
1 kilowatthour of electricity = 3,412 Btu
Energy Use by Sector (2013)

Total Energy
- Commercial: 28%
- Industrial: 32%
- Residential: 19%
- Transportation: 21%

Electricity
- Commercial: 36%
- Residential: 38%
- Industrial: 26%

Source: US Energy Information Administration
Carbon dioxide levels over the last 60,000 years - we are provoking the atmosphere!

Source: University of Berne and US National Oceanic and Atmospheric Administration
Where we’re headed under BAU: by 2030, energy +60%, electricity +75%, continued fossil dominance

WEO 2007
What is problematic about this future?
The problem is not “running out” of energy

Some mid-range estimates of world energy resources. Units are terawatt-years (TWy). Current world energy use is ~17.7 TWy/year.

OIL & GAS, CONVENTIONAL 1,000
UNCONVENTIONAL OIL & GAS (excluding clathrates) 2,000
COAL 5,000
METHANE CLATHRATES 20,000
OIL SHALE 30,000

URANIUM in conventional reactors 2,000
...in breeder reactors 2,000,000

FUSION (if the technology succeeds) 250,000,000,000

RENEWABLE ENERGY (available energy per year)
Sunlight on land 30,000
Energy in the wind 2,000
Energy captured by photosynthesis 120

From J. Holdren, OSTP
Real problems: the economic, environmental, and security risks of fossil-fuel dependence

- Coal burning for electricity & industry and oil burning in vehicles are main sources of severe urban and regional air pollution – $\text{SO}_x$, $\text{NO}_x$, hydrocarbons, soot – with big impacts on public health, acid precipitation.

- Emissions of $\text{CO}_2$ from all fossil-fuel burning are largest driver of global climate disruption, already associated with increasing harm to human well-being and rapidly becoming more severe.

- Increasing dependence on imported oil & natural gas means economic vulnerability, as well as international tensions and potential for conflict over access & terms.
Real problems: Alternatives to conventional fossil fuels all have liabilities & limitations

- **Traditional biofuels** (fuelwood, charcoal, crop wastes, dung) create huge indoor air-pollution hazard
- **Industrial biofuels** (ethanol, biodiesel) can take land from forests & food production, increase food prices
- **Hydropower and wind** are limited by availability of suitable locations, conflicts over siting
- **Solar energy** is costly and intermittent
- **Nuclear fission** has large requirements for capital & highly trained personnel, currently lacks agreed solutions for radioactive waste & links to nuclear weaponry
- **Nuclear fusion** doesn’t work yet
- **Coal-to-gas and coal-to-liquids** to reduce oil & gas imports doubles CO₂ emissions per GJ of delivered fuel
- **Increasing end-use efficiency** needs consumer education
Solving the Energy Problem and Reducing Greenhouse Gas Emission Requires Pursuing a Diversified Portfolio Approach

- Improve energy efficiency
- Expand use of existing “clean” energy sources (e.g. nuclear and renewable sources – solar, wind, etc.)
- Develop technologies to reduce impact of fossil fuels use (e.g. carbon capture and sequestration)
- Develop major new (clean) energy sources (e.g. fusion)
- Develop alternate (synthetic) fuels and electrical energy storage for transportation
Potential for Increasing Energy Efficiency is Enormous
Potential Electricity Savings in Commercial and Residential Buildings in 2020 and 2030 (currently 73% of electricity used in US – space heating and cooling, water heating, and lighting)
Energy Intensity* (efficiency) of the U.S. Economy Relative to 1970 levels

*Energy consumed per dollar GDP (2000 constant dollars)

Source: Based on EIA, 2006
Renewable Energy (Solar, Wind, Geothermal, Biomass, hydropower)

- Other Speakers will cover Renewable Energy – will make only a few remarks
- Renewable energy technologies, a critical element of the low-carbon pillar of global energy supply, are rapidly gaining ground, helped by global subsidies amounting to $120 billion in 2013.
- Renewable energy sources – in power generation as well as transport – reached a record 3.0% of global energy consumption in 2014, up from 0.9% a decade ago. Renewables accounted for a record 6.0% of global power generation. The strong growth of renewables in many countries raises their expected share in global power generation to ~ 30% by 2040.
- Cost and efficient energy storage remain as issues requiring innovative solutions. For example, the high cost of solar plus being intermittent source is not helping solar in some countries such as the US.
- Renewables alone cannot meet the booming global population’s insatiable appetite for energy in the long term. The World needs Other Clean Energy Sources (e.g. nuclear fission and fusion) to meet growing energy demands and make the transition to a cleaner world by 2050.
Estimated Greenhouse Gas Emissions from Electricity Generation

Nuclear and Renewable Energy Sources are essential to addressing Climate Change
Nuclear Fission
Current Contributions and Future Outlook
Internationally, there are ongoing plans for nuclear energy expansion (Nuclear Renaissance)

- **Worldwide Currently Operating**: 436 fission power reactors totaling 392 GWe of capacity in 31 countries (11% of world’s electricity). Additionally, 67 more reactors with ~70 GWe currently under construction.
  - 357 of the 436 reactors are light-water reactors (LWRs). The rest are heavy-water reactors, gas cooled reactors, and graphite-moderated light-water reactors.

- **US** has currently 99 nuclear power plants. As of October 2015:
  - 5 under construction

- **China** has the most aggressive nuclear energy plan
  - Present: 23.1 GWe
  - 2020: 58 GWe
  - 2030: 150 GWe

  -- China’s fast reactor plans
  - Experimental: 20 MWe (2010)
  - Large: BN-800 (2018, suspended) and CDFR-1000 MWe (2023)

But managing nuclear materials and proliferation is becoming increasingly complex, requiring a modernized international approach.
Global Status of Nuclear Power Plants at the end of 2013

This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.
History of installed nuclear power capacity by key world region and future outlook based on IEA-WEO-2014 scenario
Impressive Improvements in Economics of Nuclear Power in Existing Fission Power Plants

- Incremental improvements enabled currently operating fission power plants to produce more energy than anticipated over their lifetimes. **The U.S. average plant capacity factor increased from 66% in 1990 to 91.7% in 2014.** Source: Nuclear Energy Institute

- From Australian National Affairs Article:

**The standout technology, from a cost perspective, is nuclear power.** From the eight nuclear cost studies we reviewed (all published in the past decade, and adjusted to 2009 dollars), the median cost of electricity from current technology nuclear plants was just above new coal plants with no carbon price. Having the lowest carbon emissions of all the fit-for-service technologies, **nuclear remains the cheapest solution at any carbon price. Importantly, it is the only fit-for-service baseload technology that can deliver the 2050 emission reduction targets.**

- Also, other improvements in safety and reduced generation of high level waste.
Nuclear Power Must Remain a KEY Part of Our Energy Portfolio

Nuclear is the third largest source of U.S. electricity
• 19 % of electricity generation
• 59 % of GHG emission-free electricity
• Nuclear electricity is 3 times more than Solar, Wind and Geothermal combined

Nuclear energy is the dominant non-fossil energy technology

US. Energy Information Administration, 2014
Nuclear power avoided the release of over 56 Gt of CO2 globally between 1971 and 2012. Cumulative global CO2 emissions avoided by nuclear power are projected to climb to 111 Gt in the period 1971-2040.

Figure shows Cumulative CO2 emissions AVOIDED by Nuclear Power in selected regions, 1971-2040 (IEA-WEO-2014 scenario)
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

Generation III+
- Near-Term Deployment
  - AP1000
  - PBMR
  - SWR-1000
  - ABWR-II

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

Current Nuclear Energy Research Objectives

- **Extend life of currently operating plants**
  - Goal is to extend currently operating LWRs plant life from design life (40 years) to beyond 60 years

- **Enable new builds for electricity and process heat production and improve the affordability of nuclear energy**
  - Develop and demonstrate next generation advanced plant concepts and technologies

- **Enable sustainable fuel cycles**
  - High burnup fuel
  - Develop optimized systems that maximize energy production while minimizing waste

- **Understand and minimize proliferation risks**
  - Goal is limiting proliferation and security threats by protecting materials, facilities, sensitive technologies and expertise

Enhancing SAFETY is a MAJOR PRIORITY (passive safety systems)
CREATING a Star on Earth
Fusion: The Ultimate Energy Source for Humanity
What is nuclear fusion?

- **Fusion powers the sun and stars:** Fusion is the energy-producing process taking place in the core of the sun and stars. Fusion research is akin to “creating a star on earth”
- **Two light nuclei combine to form a heavier nuclei, converting mass to energy** - the opposite of nuclear fission where heavy nuclei split
- **In nuclear (fission and fusion), mass is converted to energy**,
  Einstein’s famous Eq. \( E = mc^2 \)
  
  Small mass \( \rightarrow \) Huge energy

In contrast to fossil fuels (oil, gas, coal) where chemical energy is stored, and huge mass needed to “store” energy
A number of fusion reactions are possible based on the choice of the light nuclides

The World Program is focused on the Deuterium (D) - Tritium (T) Cycle

- D-T Cycle is the easiest to achieve: attainable at lower plasma temperature because it has the largest reaction rate and high Q value.

\[ E = mc^2 \]

17.6 MeV

80% of energy release (14.1 MeV)

Used to breed tritium and close the DT fuel cycle

\[ \text{Li} + n \rightarrow T + \text{He} \]

Li in some form must be used in the fusion system

20% of energy release (3.5 MeV)
Incentives for Developing Fusion

- Sustainable energy source
  (for DT cycle: provided that Breeding Blankets are successfully developed and tritium self-sufficiency conditions are satisfied)
- No emission of Greenhouse or other polluting gases
- No risk of a severe accident
- No long-lived radioactive waste

Fusion energy can be used to produce electricity and hydrogen, and for desalination.
The World Fusion Program has a Goal for a Demonstration Power Plant (DEMO) by ~2040(?)

Plans for DEMO are based on Tokamaks

- Cryostat
- Poloidal Ring Coil
- Coil Gap
- Rib Panel
- Blanket
- Vacuum Vessel
- Plasma
- Center Solenoid Coil
- Toroidal Coil
- Maint. Port

(Illustration is from JAEA DEMO Design)
The World has started construction of the next step in fusion development, a device called ITER.

ITER will demonstrate the scientific and technological feasibility of fusion energy.

ITER will produce 500 MW of fusion power.

Cost is ~16 billion dollars.

ITER is a collaborative effort among Europe, Japan, US, Russia, China, South Korea, and India. – represent half the world’s population

ITER construction site is Cadarache, France

ITER will begin operation in the early 2020’s

ITER will open the way for commercial reactors
ITER is a reactor-grade tokamak plasma physics experiment - a huge step toward fusion energy

- Will use D-T and produce neutrons
- 500MW fusion power, Q=10
- Burn times of 400s
- Reactor scale dimensions
- Actively cooled PFCs
- Superconducting magnets

By Comparison

JET
- ~10 MW
- ~1 sec
- Passively Cooled

~29 m

~15 m
Fusion Research is about to transition from Plasma Physics to Fusion Nuclear Science and Engineering

- **1950-2015**
  - The Physics of Plasmas

- **2015-2035**
  - The Physics of Fusion
  - Fusion Plasmas-heated and sustained
    - $Q = (E_f / E_{\text{input}}) \sim 10$
    - ITER (MFE) and NIF (inertial fusion)

- **ITER** is a major step forward for fusion research. It will demonstrate:
  1. Reactor-grade plasma
  2. Plasma-support systems (S.C. magnets, fueling, heating)

**But the most challenging phase of fusion development still lies ahead:**
The Development of Fusion Nuclear Science and Technology

The cost of R&D and the time to DEMO and commercialization of fusion energy will be determined largely by FNST.
**Fusion Nuclear Science & Technology (FNST)**

**FNST** is the **science, engineering, technology** and **materials**
for the fusion nuclear components that
**generate, control and utilize neutrons, energetic particles & tritium.**

**In-vessel Components (Core)**
- Divertor/PFC
- Blanket and Integral First Wall
- Vacuum Vessel and Shield

**Key Supporting Systems**
- Tritium Fuel Cycle
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems

Tritium Fuel Cycle pervades entire fusion system
A Key FNST Component is the Blanket
The primary functions of the blanket are to provide for:
Power Extraction & Tritium Breeding

Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant. He-cooled Li ceramics are also candidates.
Comparison of Heat Fluxes

Heat Flux (MW/m²)

- Plasma Disruptions
- Reentry Vehicles
- Rocket Nozzles
- Fusion Divertor
- Fusion 1st Wall
- Fission (fast breeder)
- Fission reactor (LWR)

Duration (s)

Sun surface
In fusion, the fusion process does not produce radioactive products. Long-term radioactivity and waste disposal issues can be minimized by careful selection of materials.

- This is in contrast to fission, where long term radioactivity and waste disposal issues are “intrinsic” because the products of fission are radioactive.
- Based on safety, waste disposal and performance considerations, the three leading candidates are:
  - RAFM and NFA steels
  - SiC composites
  - Tungsten alloys (for PFC)
Solid breeder blankets utilize immobile lithium ceramic breeder and Be multiplier

**Material Functions**

- **Beryllium** (pebble bed) for neutron multiplication
- **Ceramic breeder** (Li$_4$SiO$_4$, Li$_2$TiO$_3$, Li$_2$O, etc.) for tritium breeding
- **Helium purge** to remove tritium through the “interconnected porosity” in ceramic breeder
- **High pressure Helium cooling** in structure (advanced ferritic)

0.2 - 0.4 mm Li$_4$SiO$_4$ pebbles (FZK)  
0.6 – 0.8 mm Li$_2$TiO$_3$ pebbles (CEA)  
NGK Be-pebble
Flows of electrically conducting coolants will experience complicated **MHD** effects in the magnetic fusion environment. 3-component magnetic field and complex geometry

- Motion of a conductor in a magnetic field produces an EMF that can induce current in the liquid. This must be added to Ohm’s law:

\[ \mathbf{j} = \sigma (\mathbf{E} + \mathbf{V} \times \mathbf{B}) \]

- Any induced current in the liquid results in an additional body force in the liquid that usually opposes the motion. This body force must be included in the Navier-Stokes equation of motion:

\[ \frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{V} + \mathbf{g} + \frac{1}{\rho} \mathbf{j} \times \mathbf{B} \]

- For liquid metal coolant, this body force can have dramatic impact on the flow: e.g. enormous MHD drag, highly distorted velocity profiles, non-uniform flow distribution, modified or suppressed turbulent fluctuations.

**Dominant impact on LM design.**

**Challenging Numerical/Computational/Experimental Issues**
Pathway Toward Higher Temperature through Innovative Designs with Current Structural Material (Ferritic Steel): 

*Dual Coolant Lead-Lithium (DCLL) FW/Blanket Concept*

- First wall and ferritic steel structure cooled with helium
- Breeding zone is self-cooled
- Structure and Breeding zone are separated by SiCf/SiC composite flow channel inserts (FCIs) that:
  - Provide thermal insulation to decouple PbLi bulk flow temperature from ferritic steel wall
  - Provide electrical insulation to reduce MHD pressure drop in the flowing breeding zone

FCI does not serve structural function

**Pb-17Li exit temperature can be significantly higher than the operating temperature of the steel structure ⇒ High Efficiency**
The problem with fusion is that it is not being developed fast enough (taking too long!)
“The Time to Fusion seems to be always 40 years away”

The World Needs Fusion.
To accelerate the development of fusion energy requires a change in Governments Policies and in the Fusion Community strategy/focus:

- Need More Substantial Funding: Governments must invest in long-term solutions for the future
- Problems are challenging: Need More Ingenuity
- Fusion Community strategy/focus need to change: Need to Focus on the Major Remaining Challenge: Launch an aggressive FNST Program NOW

This is essential to realizing fusion by the middle of the 21st Century
Closing Remarks

• Energy plays a critical role in economic development, economic prosperity, national security, and environmental quality

• Solving the Energy Problem and Reducing Greenhouse Gas Emission Requires Pursuing a Diversified Portfolio Approach

• Key Major Transformations required:
  – Efficient use of energy, e.g., buildings (lighting, heating and cooling), cars and trucks, and industry.
  – New sources of energy for producing electricity that reduce emissions of CO$_2$—nuclear, fusion, coal with CO$_2$ removed and stored, solar, wind, and geothermal.
  – Transportation fuels that derive from alternatives to petroleum, e.g., liquids from biomass, coal and electricity.
Closing Remarks (cont’d)

• Fusion is the most promising long-term energy option
  – Renewable fuel, no emission of greenhouse gases, no long-term
    radioactive waste, inherent safety

• But the problem is that fusion is not being developed fast
  enough. “The Time to Fusion seems to be always 40
  years away”. Need more funding, more ingenuity, and
  focus on the most difficult remaining challenge:
  Fusion Nuclear Science and Technology (FNST)

Fusion research requires the talents of many scientists
and engineers in many technical disciplines. Need to
attract and train bright young students and researchers.
For References and Additional Reading:

1. Abdou’s presentations and publications on: (http://www.fusion.ucla.edu/abdou/)
2. UCLA Energy Center (http://cestar.seas.ucla.edu/)
3. CEREL (http://ncseonline.org/cerel/)
4. Additional Information on the America’s Energy Future Effort: (http://www.nationalacademies.org/energy)
5. John P. Holdren, Assistant to the (US) President for Science and Technology, OSTP: http://www.whitehouse.gov/administration/eop/ostp
Thank You!