Nuclear Futures and Fuel Cycles: The United States and China

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U.S.-China Clean Energy Cooperation
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The U.S. and China Will Drive Two Coupled Energy Markets

- Markets are driven by the major players
- Two markets are dominated by the U.S. and China
  - Liquid fuels (Largest energy source)
  - Nuclear fuel cycles
Liquid Fuels and Nuclear Energy
Oil Is the World’s Primary Energy Source

- French nuclear electricity program was driven by security concerns about Mideast oil
- The U.S. and China drive liquid fuel prices
  - High-price liquid fuels raise world natural gas prices
  - Example: Shell Pearl Project
    - $18 Billion natural gas to liquid fuel project in Qatar
    - Four-year financial payback at current oil prices
    - Abu Dhabi nuclear plant; a hedge against higher gas prices
  - High natural-gas prices push nuclear projects
- Nuclear energy can assist liquid fuels production
  - The wildcard option if oil gets too risky or expensive
  - Logical U.S./China area for cooperation
Unconventional Liquid Fuels Production Requires Energy

Energy Input May Become Second-Largest Energy User

<table>
<thead>
<tr>
<th>Oil Type</th>
<th>Heat Input as Fraction of Energy Content of Recovered Liquid Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Oil</td>
<td>25 to 40%</td>
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<tr>
<td>Oil Sands</td>
<td>Up to 20%</td>
</tr>
<tr>
<td>Oil Shale</td>
<td>~35%</td>
</tr>
<tr>
<td>Biomass</td>
<td>Currently ~40%</td>
</tr>
</tbody>
</table>

Global Situation is Similar: If Biofuels Are to Replace Oil in Transportation, Then We Need an External Energy Source for Biorefineries
Nuclear Energy and the Fuel Cycle

- In any technology, the country with the largest domestic market is most likely to drive technology developments
  - Renewables market transformation today by China
  - Time delay for more complex technologies
- China is likely to become a major exporter of reactors as it drives down the manufacturing cost curve
MIT Future of the Nuclear Fuel Cycle

Just released study (Yesterday)

Key conclusions

- Changing understandings of fuel cycles and new technologies are creating a wider set of options
- Near-term: LWR with once-through fuel cycle preferred
- Not known today if LWR SNF is a waste or resource
- Will take some time to sort out preferred options

The U.S. and China Do Not Have Large Existing Investments in Advanced Fuel Cycles

Both Thinking Through the Path Forward
Nuclear Energy Obstacles and Cooperation

Each brings something to the table
- Common liquid-fuels challenge
- China
  - AP-1000 lead plants are being built in China; lead plants for AP-1000s built in the U.S.
  - High temperature reactor program (Liquid fuels production)
  - Major test facilities built on short schedules
- United States
  - Operations and safety experience
  - Large scale modeling and simulation
  - Advanced reactor design (AP-1000 U.S. design)

Obstacles
- Commercial competition
- Neither side has really thought the path forward
Questions
Biography: Charles Forsberg

Dr. Charles Forsberg is the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.
Liquid Fuels

The Major Market for Nuclear Heat

Driven by U.S. and China Oil Demand
Oil and Gas Reserves Are Concentrated in the Persian Gulf
Reserves of Leading Oil and Gas Companies (2007)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Company</th>
<th>Total Oil/Gas Reserves: Oil Equivalent (10^9 Barrels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Saudi Arabian Oil Company</td>
<td>303</td>
</tr>
<tr>
<td>2</td>
<td>National Iranian Oil Company</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>Qatar General Petroleum Corp.</td>
<td>170</td>
</tr>
<tr>
<td>4</td>
<td>Iraq National Oil Company</td>
<td>134</td>
</tr>
<tr>
<td></td>
<td><strong>Non-Government Corporations</strong></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>ExxonMobil Corp.</td>
<td>13</td>
</tr>
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<td>19</td>
<td>BP Corp.</td>
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Price and Availability are Political Decisions
U.S. Sources of Greenhouse Gases

Need Nuclear Options That Address More Than Base-Load Electricity Production

Derived from a 2007 U.S. EPA report, this chart breaks down the annual U.S. emissions of greenhouse gases by source. Each of the 726 squares represents the equivalent of 10 million tons of CO₂.
Many Oil Alternatives Require Heat to Produce Liquid Fuels

Unconventional Oil
- Resources several times larger than conventional oil
- Resources not in the Mideast
- Two major classes
  - Heavy oil
  - Shale oil

Biofuels
- No Greenhouse gas emissions
- Limits on biomass availability
Unconventional Oil: Sources and Recovery Technologies

- Heavy oil (Venezuela, California) and oil sands (Canada)
  - Too thick to flow
  - Heat rock to lower oil viscosity until it flows to recovery wells
  - LWRs can often meet required temperatures

- Shale oil (U.S., Europe, etc.)
  - Contains no oil—but 2.8 to 3.3 trillion barrels of oil equivalent
  - Heat rock to thermally crack oil shale
    - Recover light oil and gases
    - Carbon residue remains sequestered underground
  - Need high-temperature reactor
Unconventional Oil Recovery Requires Heat

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Nuclear Benefits and Characteristics for Unconventional Oil Recovery

- Avoid burning oil and gas for oil and gas recovery
- Reduced greenhouse gases
- Geology determines peak temperature
  - LWRs for many applications
  - HTR for oil shales
Option for Co-Production of Heavy Oil and Peak Electricity

- Steam injection for oil recovery takes weeks to months
- Alternative production strategy
  - Reactor produces electricity when high electricity demand
  - Reactor produces heat for oil recovery when low electricity demand and price
- Phase II Option
  - Transition to nuclear-geothermal heat storage system
  - Enable fuller recovery of oil

Ongoing MIT California Case Study
Inputs For Liquid Fuels Production

**Carbon:**
- Fossil fuel \((CH_x)\)
- Biomass \((CHOH)\)
- Atmosphere \((CO_2)\)

**Energy:**
- Fossil fuel
- Biomass
- Nuclear

**Hydrogen**
- Fossil Fuel
- Biomass
- Nuclear \((Water)\)

**Products:**
- Ethanol
- Biofuels
- Diesel

Feedstock Conversion Process

Can Avoid Greenhouse Gas Releases to Atmosphere If Carbon, Energy, and Hydrogen from Non-Fossil Sources
Biomass Fuels: A Potentially Low-Greenhouse-Gas Liquid-Fuel Option

Energy

Fossil

Biomass

Nuclear

Biomass

Fuel Factory

Atmospheric Carbon Dioxide

Liquid Fuels

Cars, Trucks, and Planes

\[ C_xH_y + (X + \frac{y}{4})O_2 \rightarrow CO_2 + (\frac{y}{2})H_2O \]

Global Situation is Similar

If Biofuels to Replace Oil, Need an External Biorefinery Energy Source
Biomass: The Wet Soggy Feedstock: Use Heat for Three Purposes

- Remove water from feedstock
- Remove water from product (ethanol)
- Convert feedstock to hydrocarbon (high-temperature)
  - Pyrolysis
  - Gasification
Nuclear Biofuels Potential

- Biofuels have a limited role if feedstock and biorefinery energy source: Insufficient biomass
- Nuclear enables full use of biomass to make fuels
  - Biomass as carbon feedstock
  - Low-cost off-peak nuclear heat input to biorefinery
References


8. C. Forsberg, Nuclear Power: Energy to Produce Liquid Fuels and Chemical, Chemical Engineering Progress (July 2010)