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

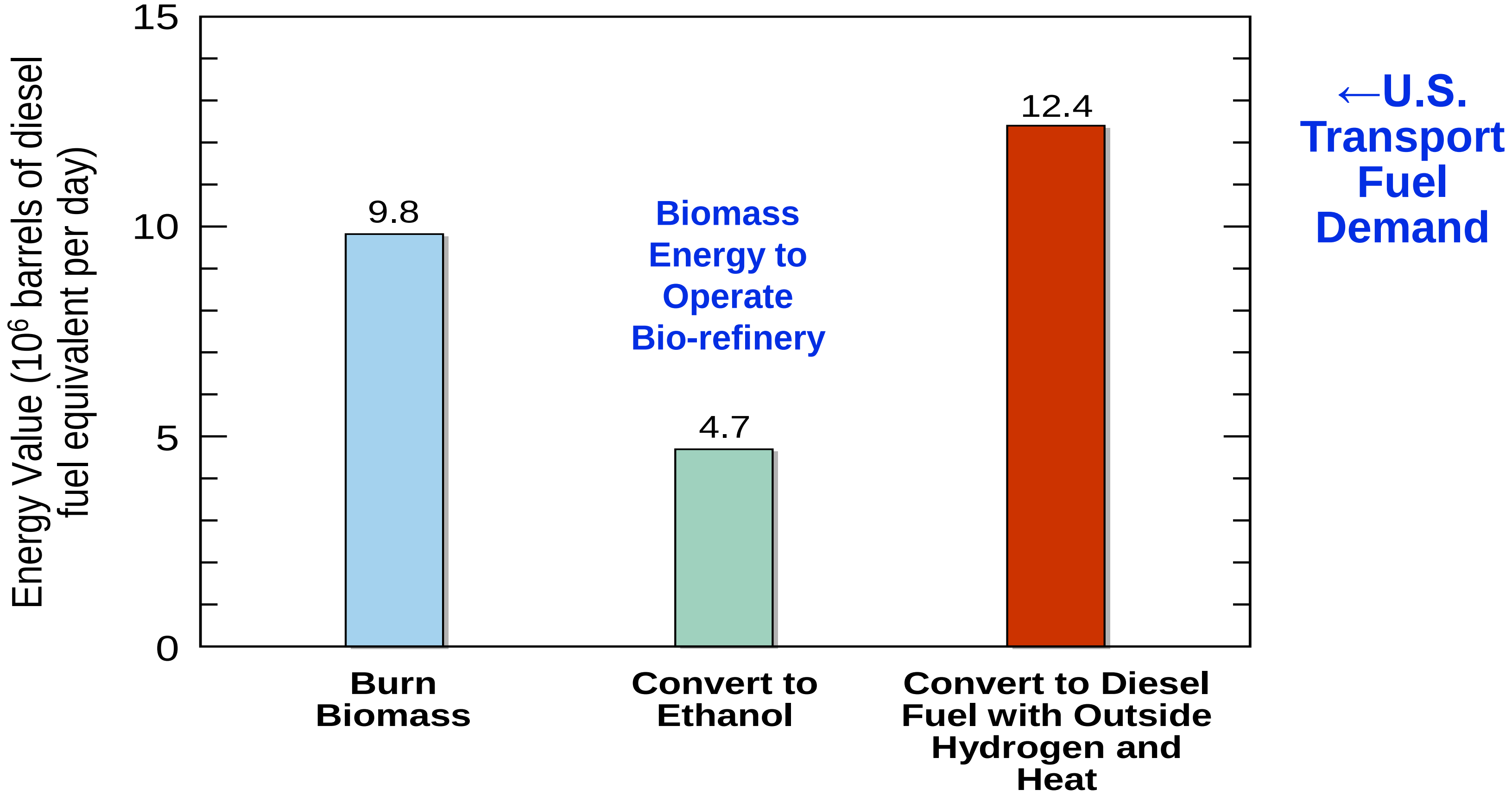
- French nuclear electricity program was driven by security concerns about Mideast oil
- The U.S. and China drive liquid fuel prices
  - High-price liquid fuels raise world natural gas prices
  - Example: Shell Pearl Project
    - $18 Billion natural gas to liquid fuel project in Qatar
    - Four-year financial payback at current oil prices
    - Abu Dubai 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

Oil Type	Heat Input as Fraction of Energy Content of Recovered Liquid Fuel
Heavy Oil	25 to 40%
Oil Sands	Up to 20%
Oil Shale	~35%
Biomass	Currently ~40%

U.S. Biomass Fuels Yield Depends On the Bio-Refinery Energy Source



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

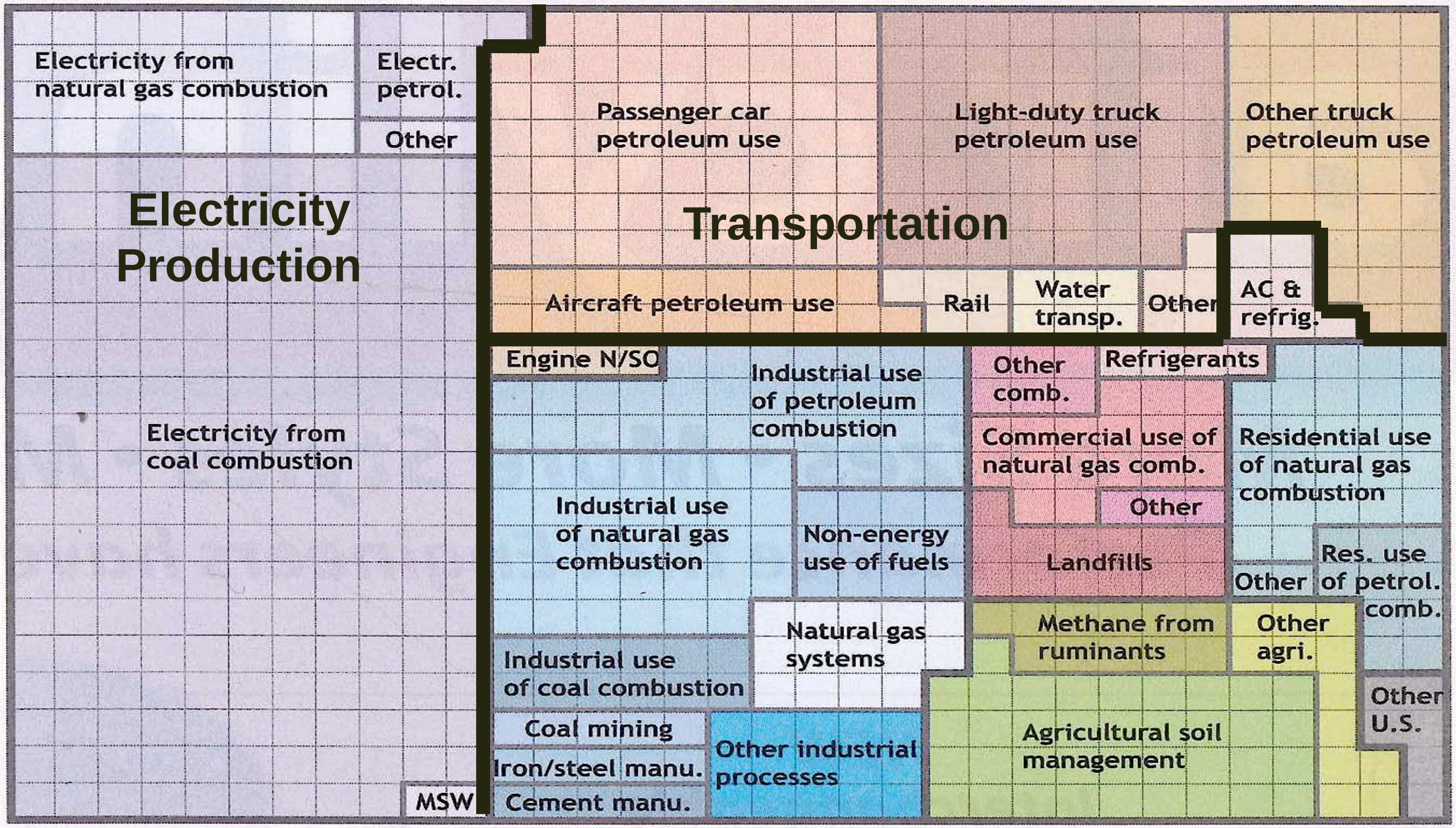
Reserves of Leading Oil and Gas Companies (2007)

Rank	Company	Total Oil/Gas Reserves: Oil Equivalent (10^9 Barrels)
1	Saudi Arabian Oil Company	303
2	National Iranian Oil Company	300
3	Qatar General Petroleum Corp.	170
4	Iraq National Oil Company	134
	Non-Government Corporations	
17	ExxonMobil Corp.	13
19	BP Corp.	13

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 CO_2.

Mechanical Engineering, September 2009

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

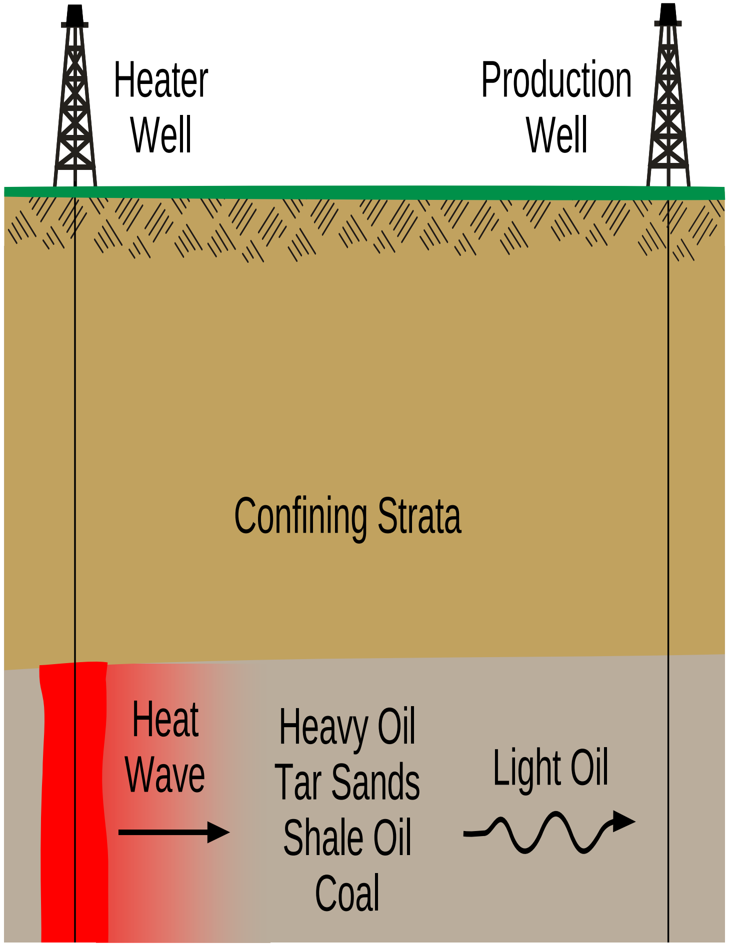
- Heavy oil (Venezuela, California) and oil sands (Canada)
  - Too thick to flow
  - Heat rock to lower oil viscosity until it flows to recovery wells
  - LWRs can often meet required temperatures
- Shale oil (U.S., Europe, etc.)
  - Contains no oil—but 2.8 to 3.3 trillion barrels of oil equivalent
  - 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

Oil Type	Heat Input as Fraction of Energy Content of Recovered Oil
Heavy Oil	25 to 40%
Oil Sands	Up to 20%
Oil Shale	~35%

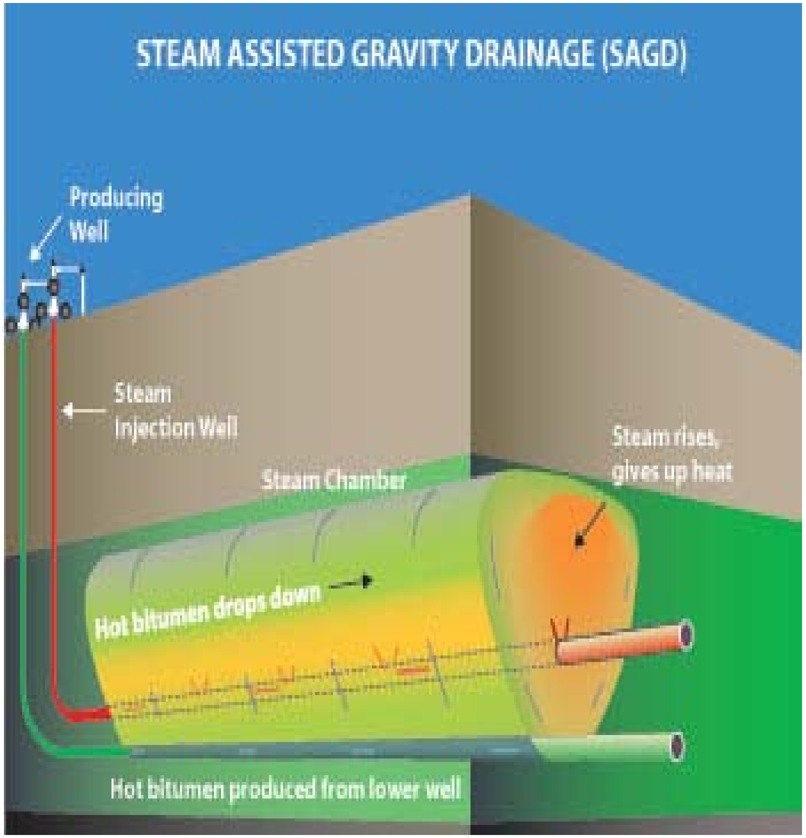
Nuclear Benefits and Characteristics for Unconventional Oil Recovery

- 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

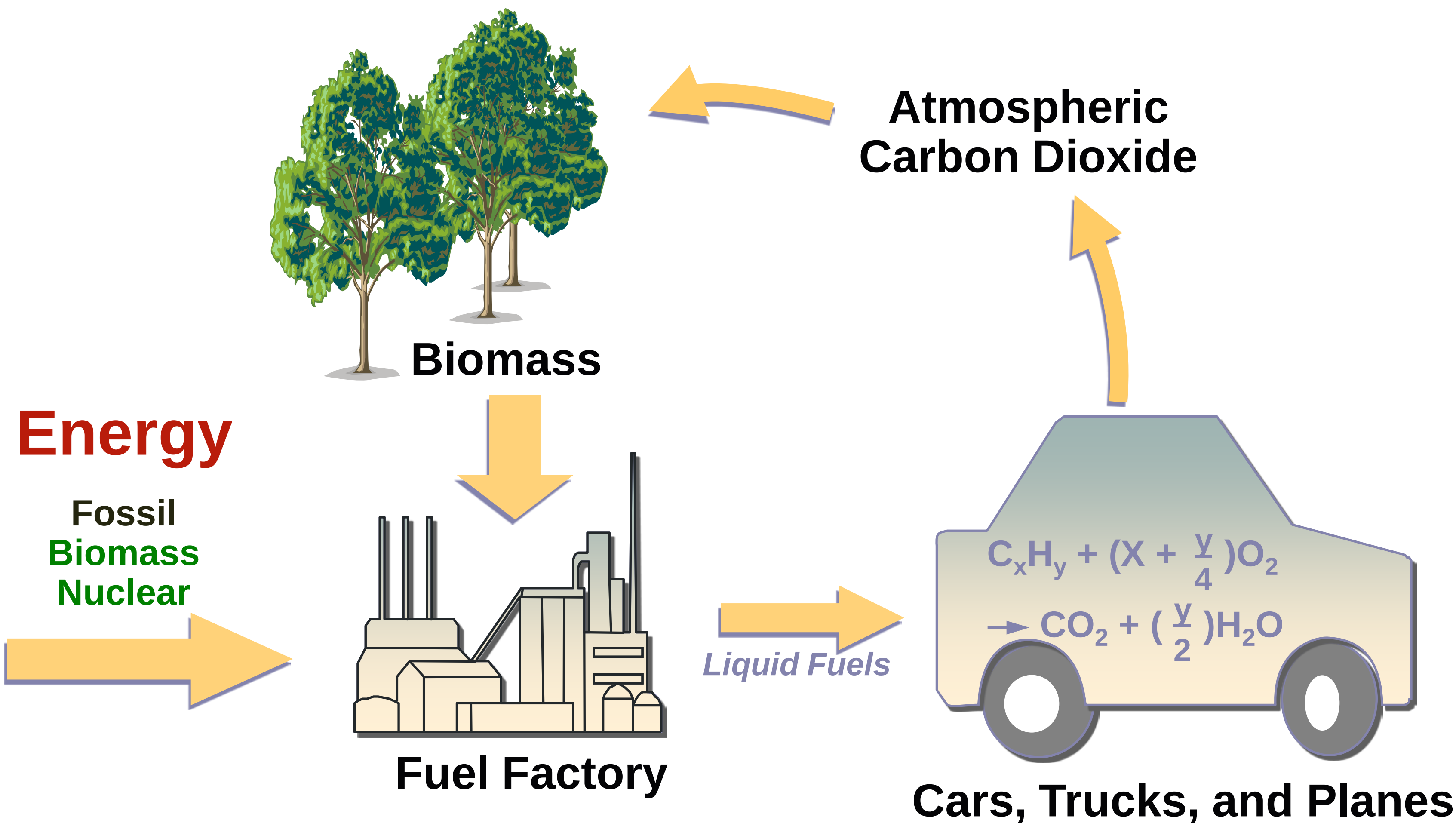
Hydrogen
- Fossil Fuel
- Biomass
- Nuclear (Water)

Feedstock Conversion Process

Products:
- Ethanol
- Biofuels
- Diesel

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



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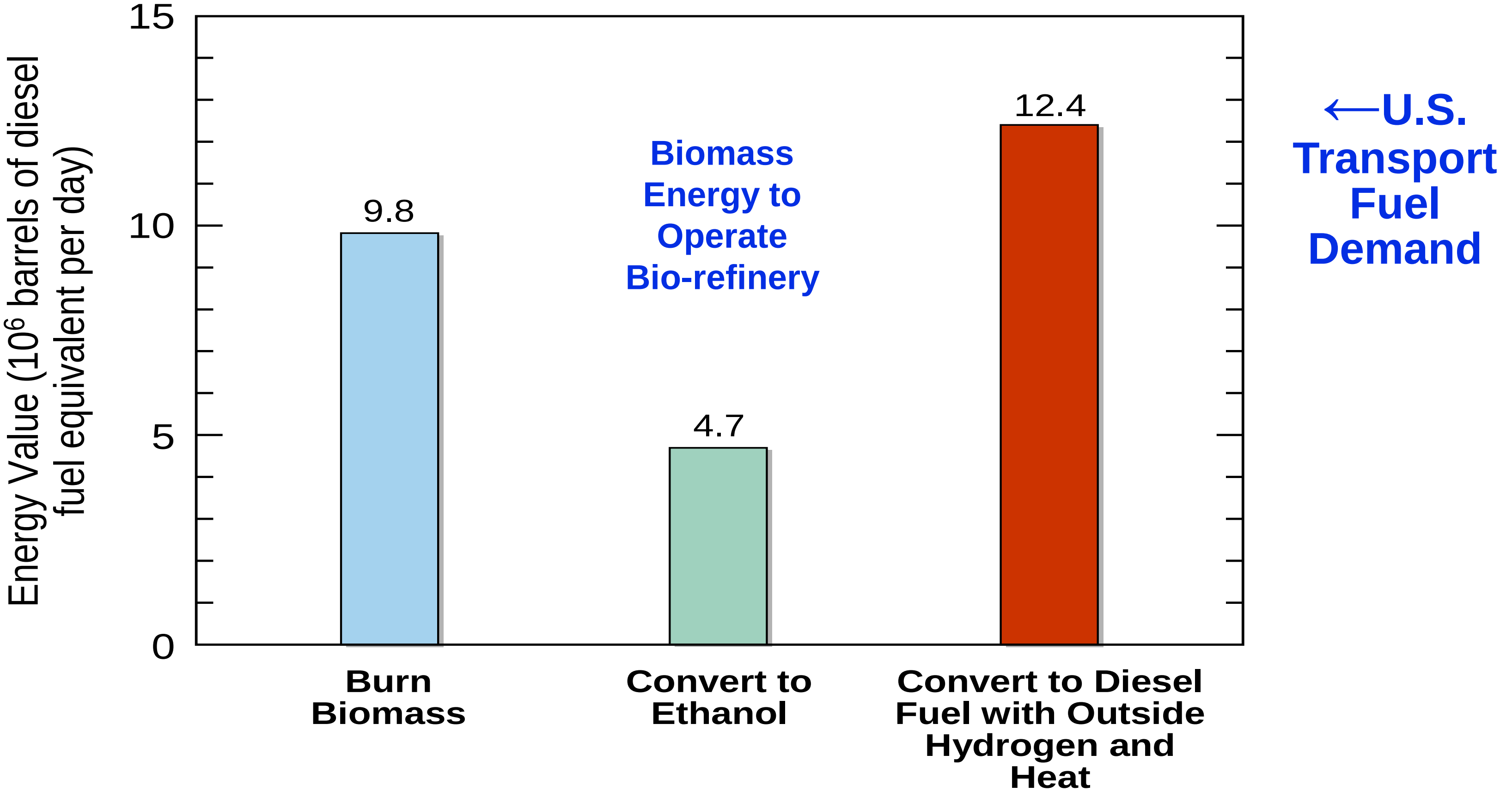


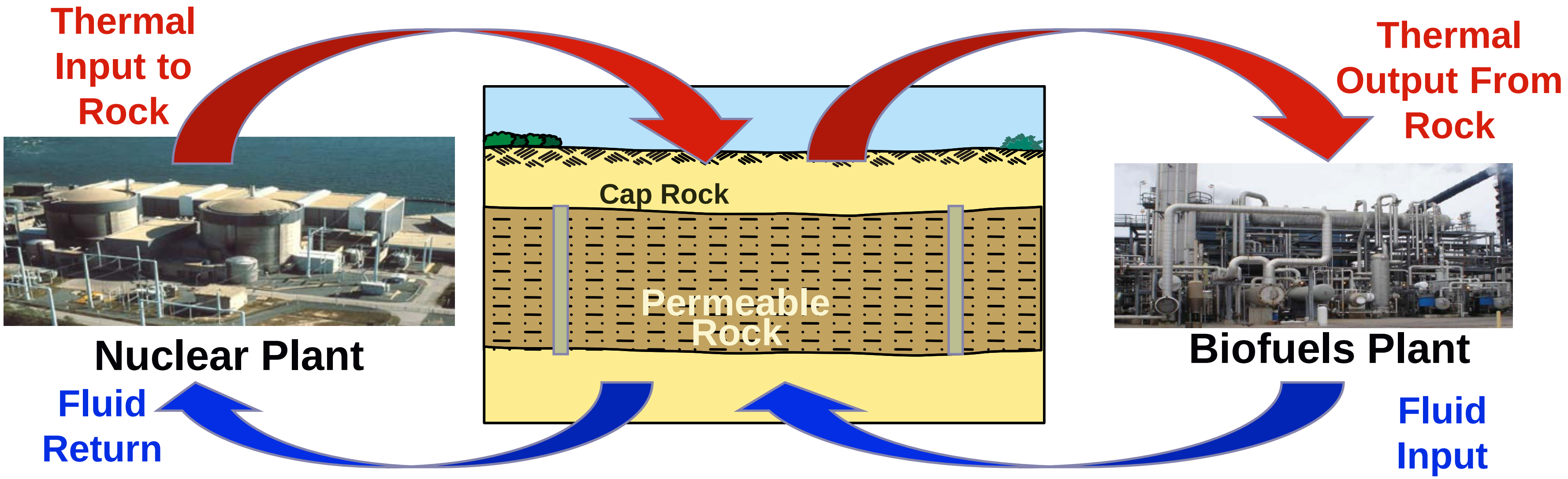
If Biofuels to Replace Oil, Need an External Biorefinery Energy Source

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



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