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Combining Nuclear, Renewable, and Fossil Fuel Cycles For Sustainability

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Outline

Global Sustainability Goals

Combined Fuel Cycles

Nuclear-Fossil Liquid Fuels

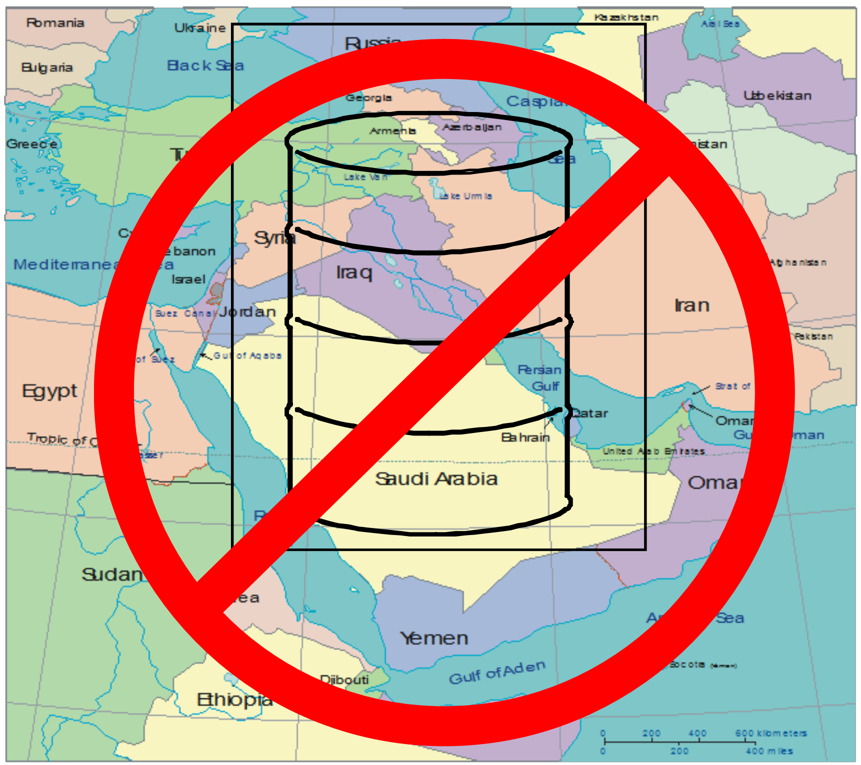
Nuclear-Biomass Liquid Fuels

Nuclear-Renewable Electricity

Chemical Engineering Challenges

Two Goals are Likely to Determine What is Required for Sustainability

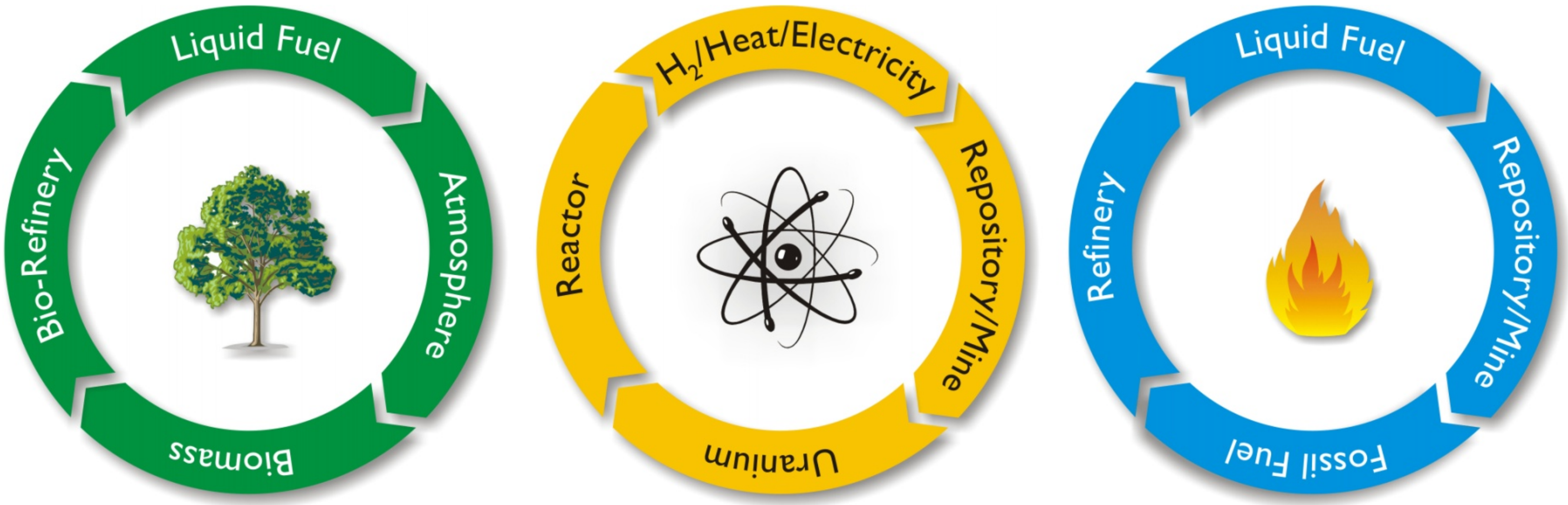
No Crude Oil



No Climate Change

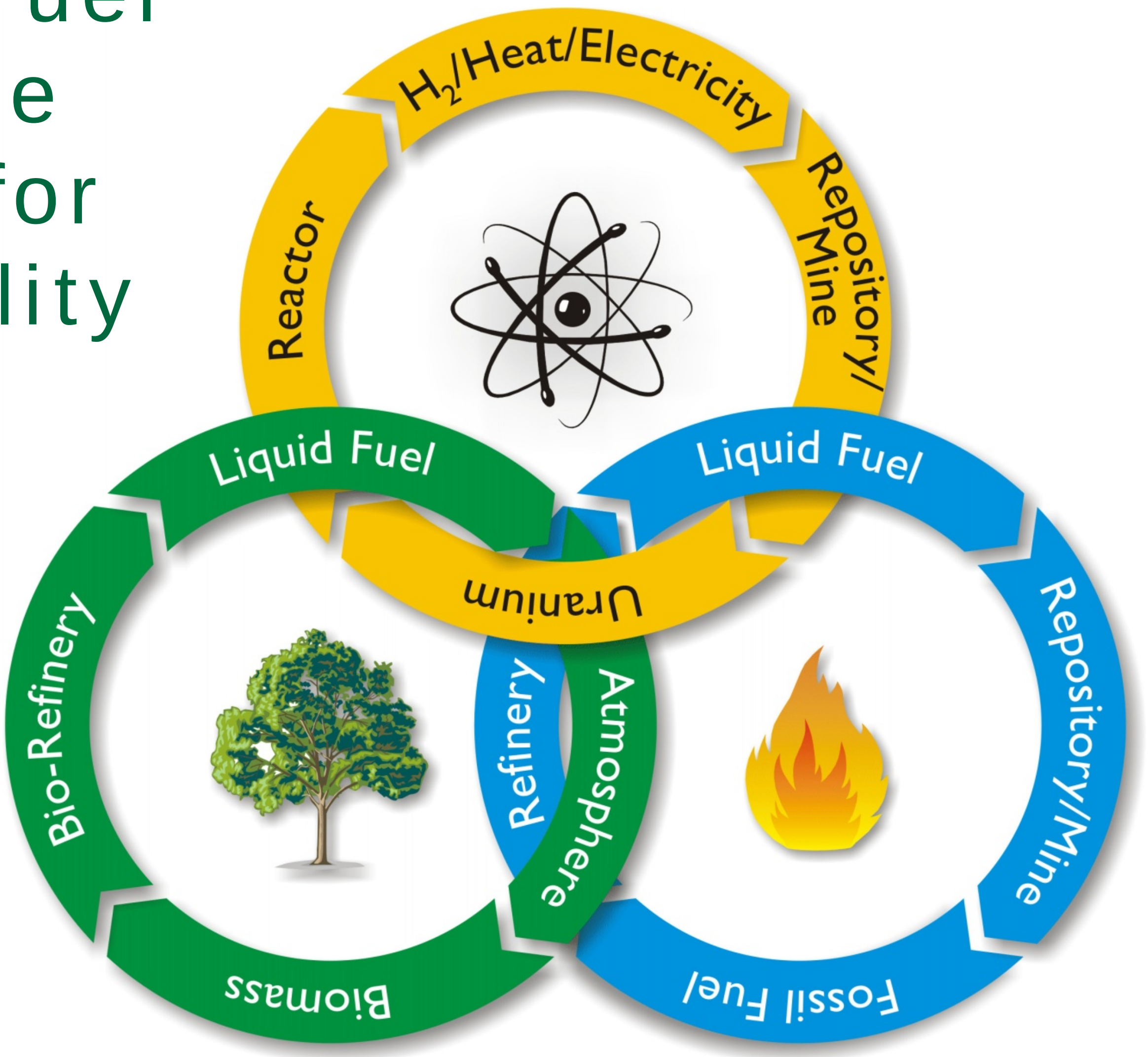
Athabasca Glacier, Jasper National Park, Alberta, Canada
Photo provided by the National Snow and Ice Data Center

Traditional Sustainability Strategies Treat Each Fuel Cycle Separately



Separate Fuel Cycles will not Eliminate Oil or Stop Climate Change

Combined Fuel Cycles are Required for Sustainability

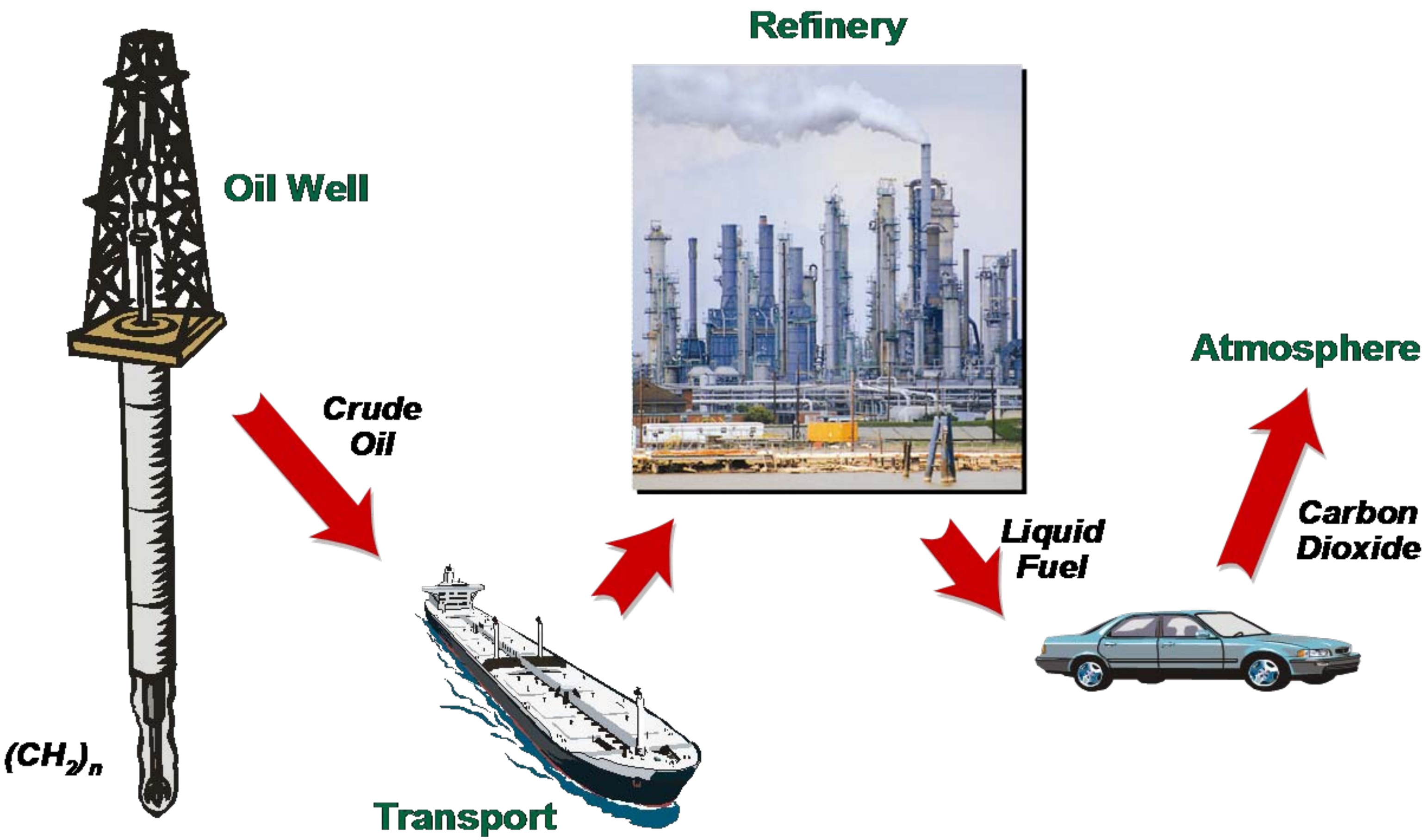


Examples of Combined Fuel Cycles

Example: Combined Nuclear-Fossil Liquid-Fuels Fuel Cycle

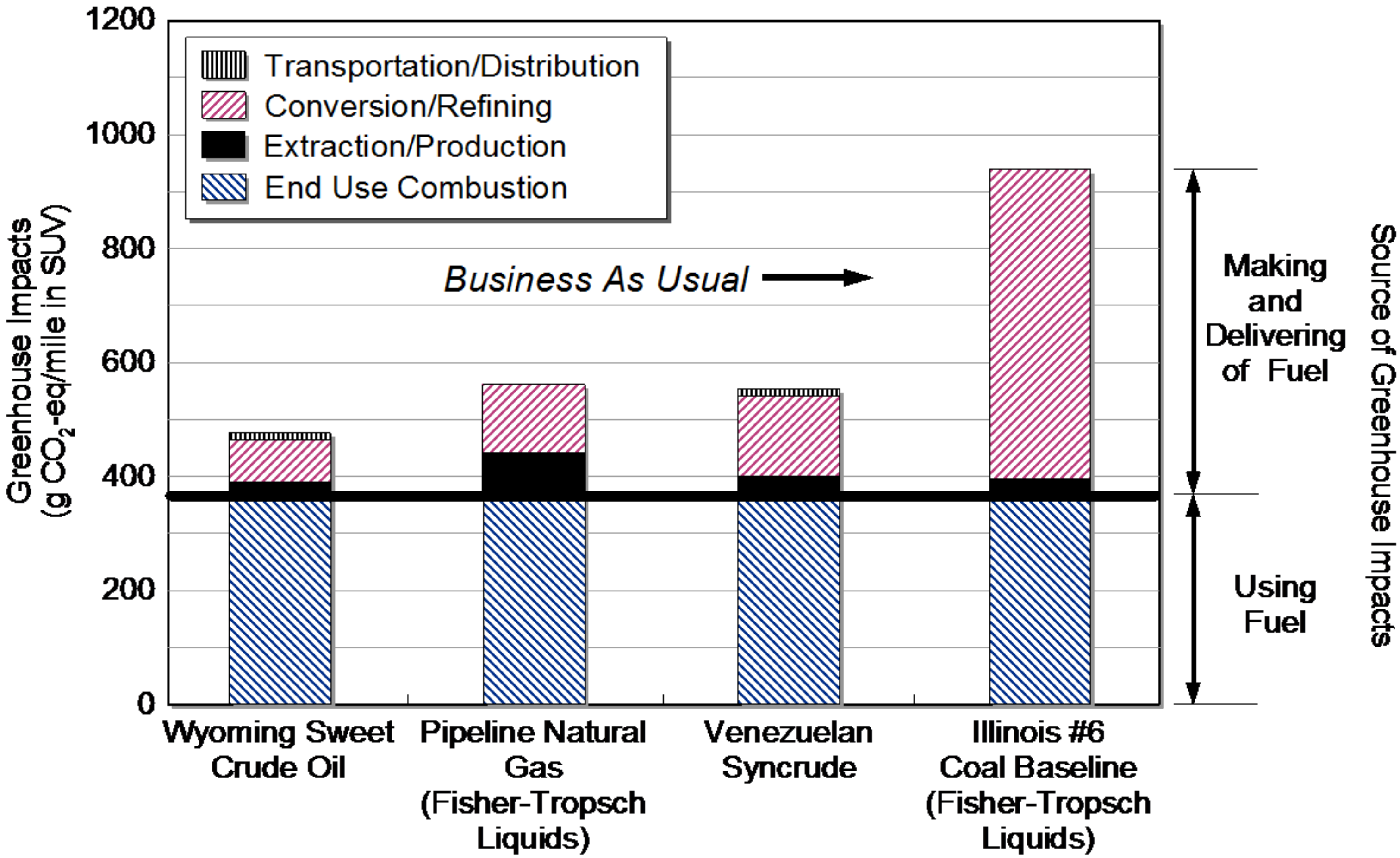
Underground Refining

Liquid-Fuels Fuel Cycle for Crude Oil



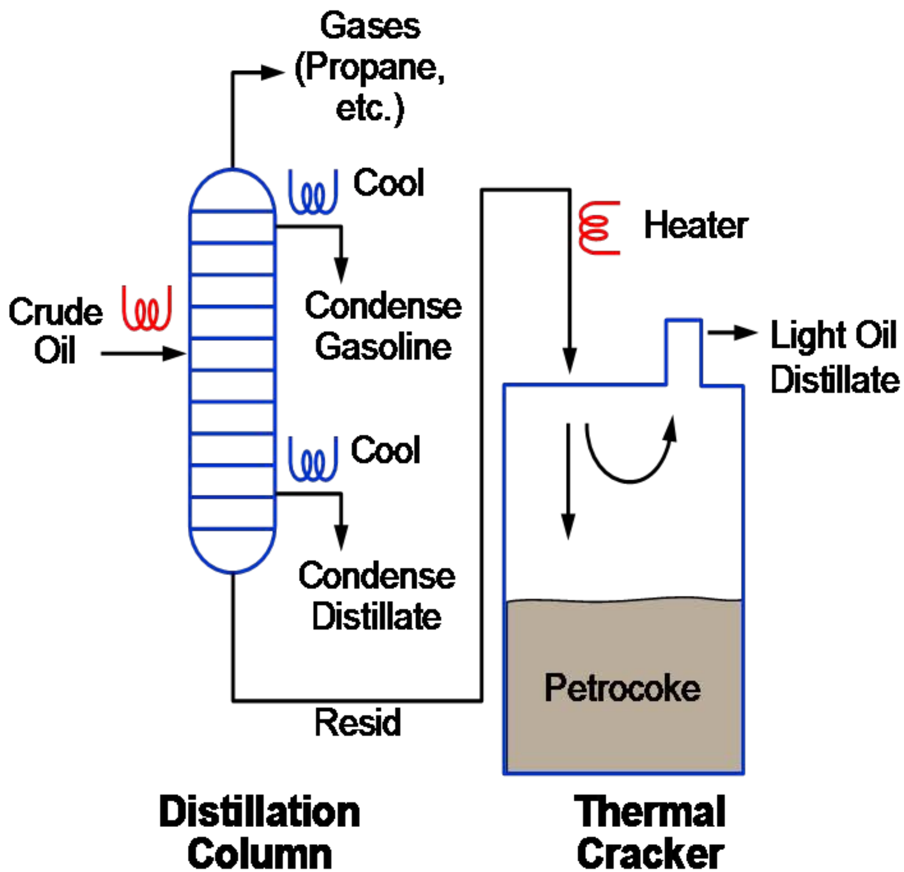
Conversion of Fossil Fuels to Liquid Fuels Requires Energy

Greenhouse Gas Releases and Energy Use in Fuel Processing Increase as Use Lower-Quality Feedstocks

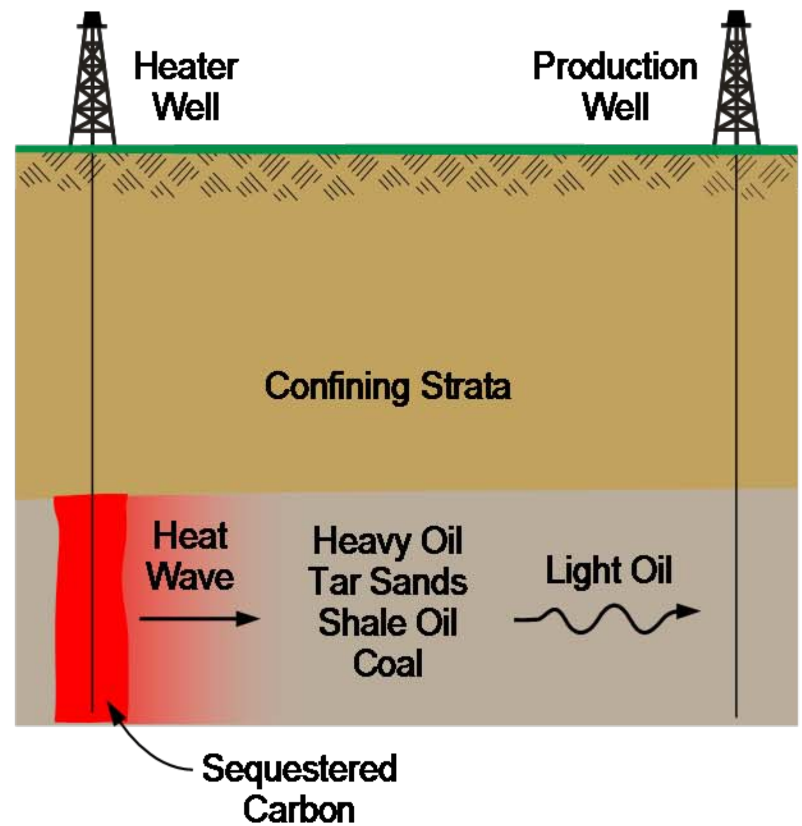


An Alternative: Underground Refining

Produces Light Crude Oil While Sequestering Carbon From the Production and Refining Processes as Carbon



Traditional Refining

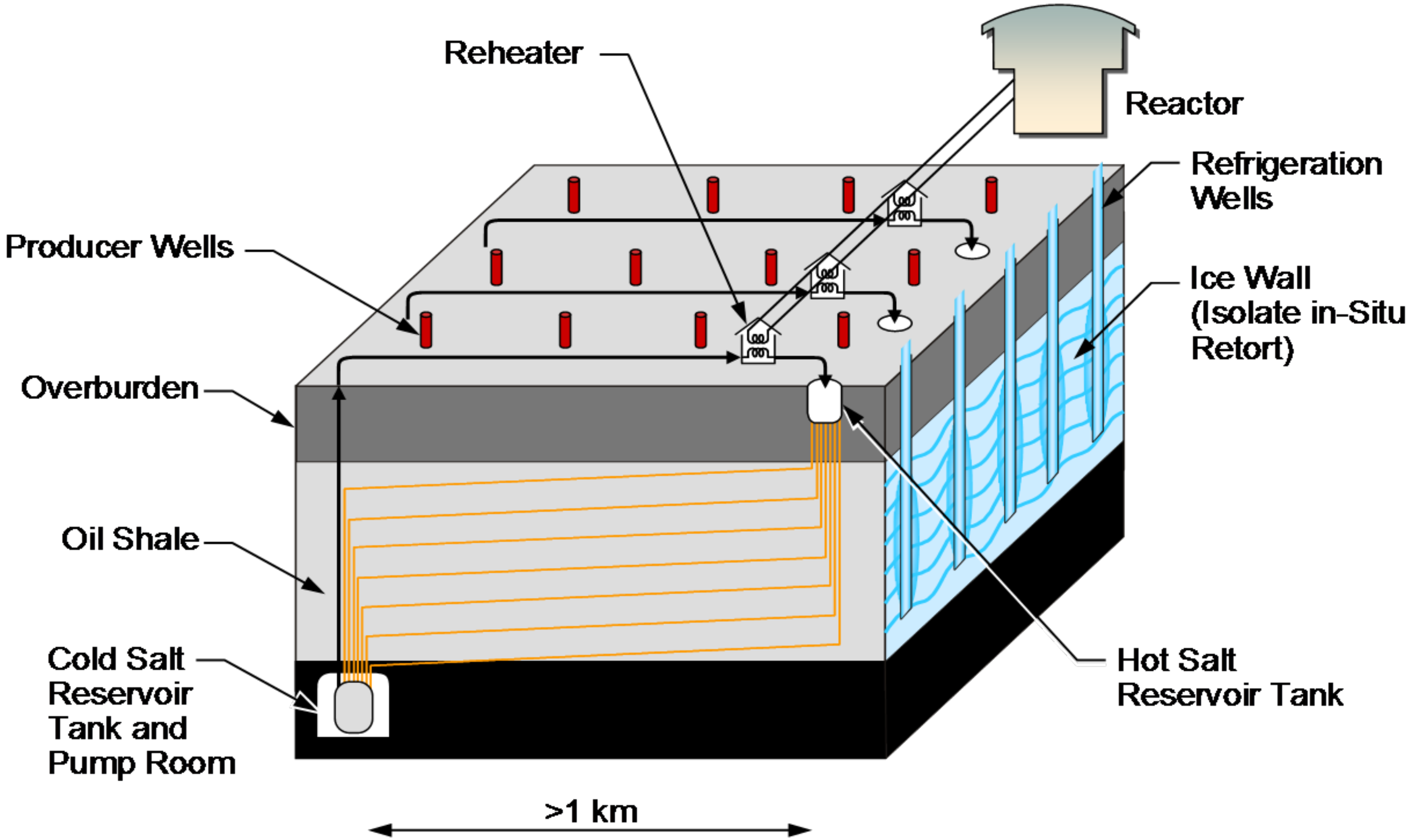


In-Situ Refining

In-Situ Refining May Require Nuclear Heat Source

Nuclear-Heated In-Situ Oil-Shale Conversion Process

Nuclear Heat Avoids Greenhouse-Gas Releases from Oil Production

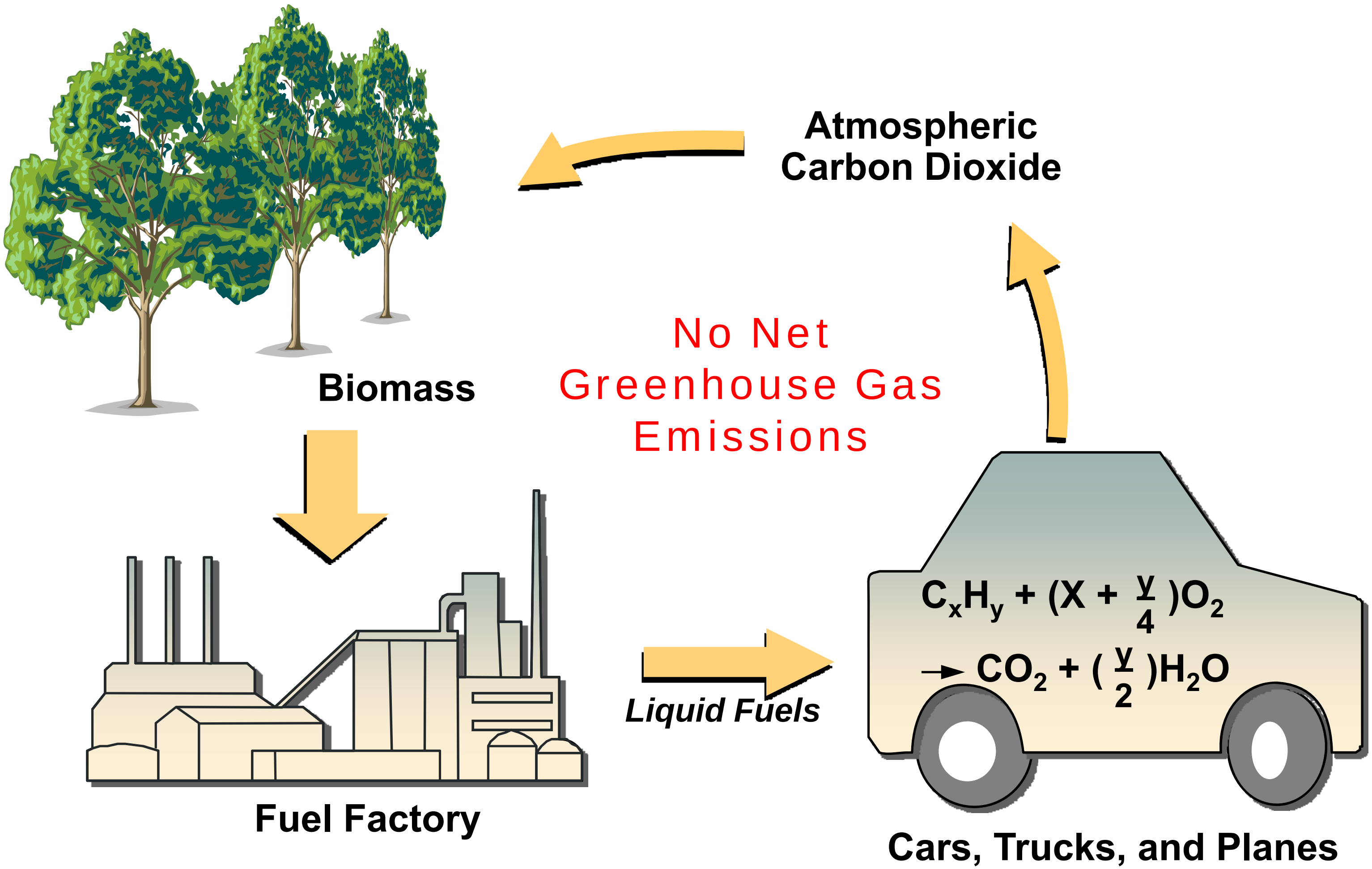


Example: Combined Nuclear-Biomass Liquid-Fuels Fuel Cycle

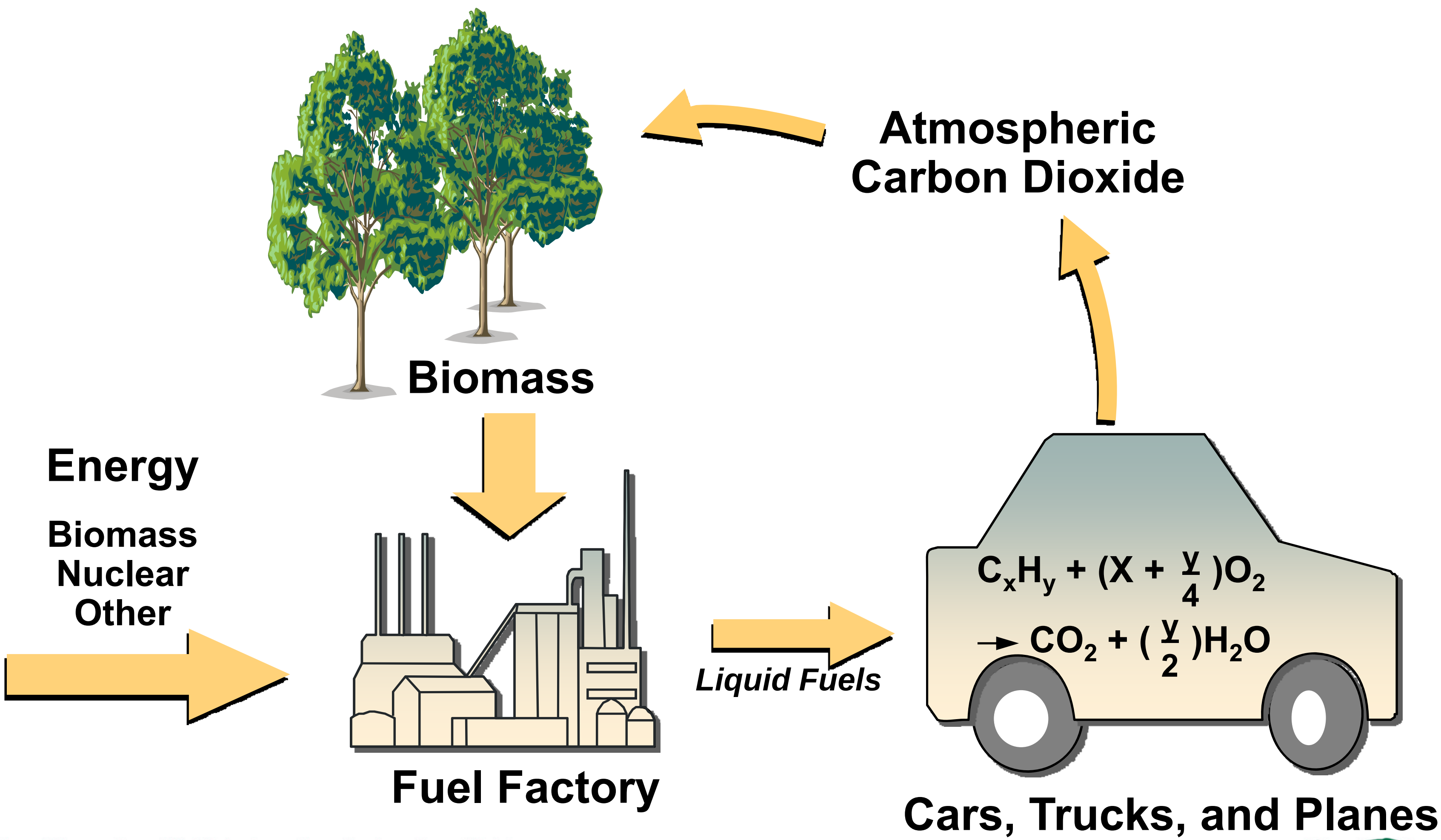
Process Energy from a Nuclear Reactor

C. W. Forsberg, "Meeting U.S. Liquid Transport Fuel Needs with a Nuclear Hydrogen Biomass System', *American Institute of Chemical Engineers Annual Meeting, Salt Lake City, Utah, November 4-9, 2007*.

Fuel Cycle for Liquid Fuels from Biomass



Biomass Production, Transport, and Fuel Factories Use Energy

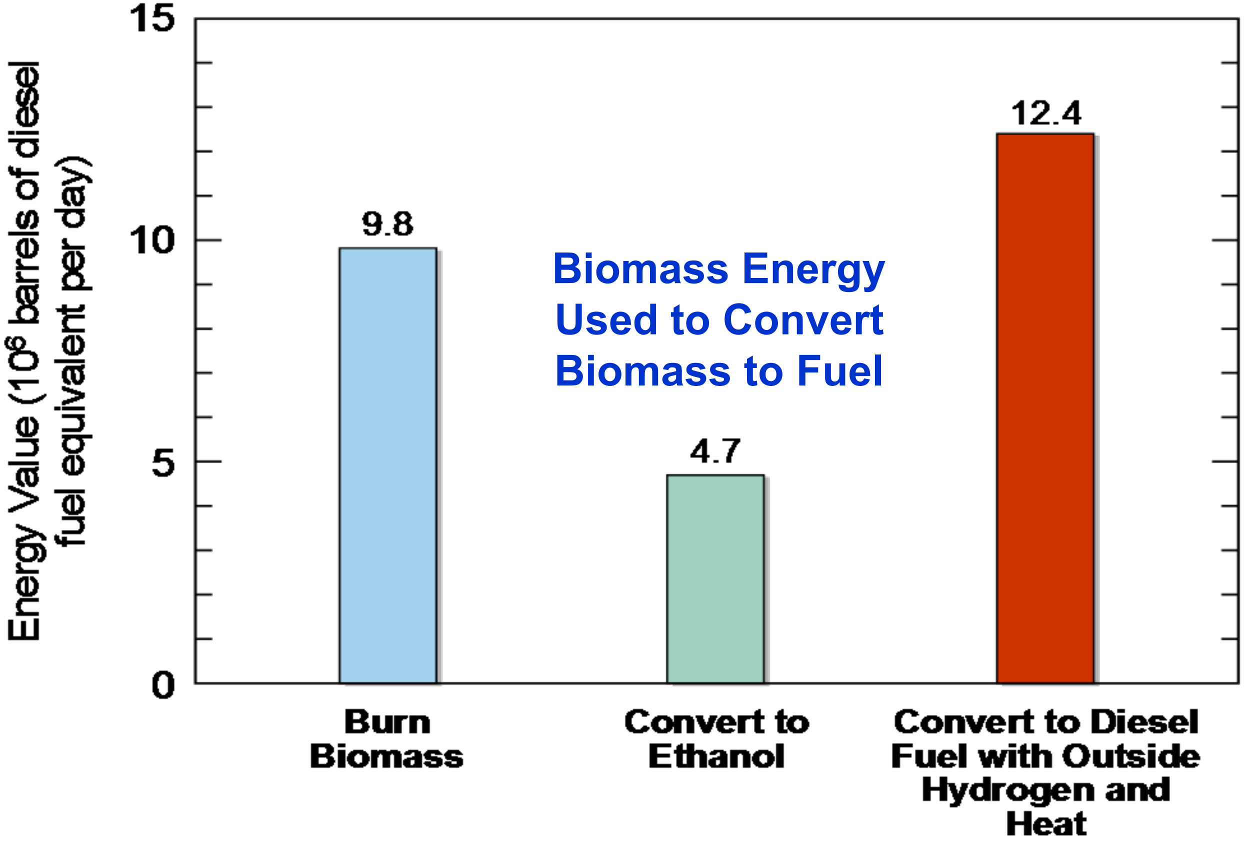


1.3-Billion-Tons Biomass are Available per Year to Produce Liquid Fuels

Available Biomass in the United States without Significantly Impacting Food, Fiber, and Timber

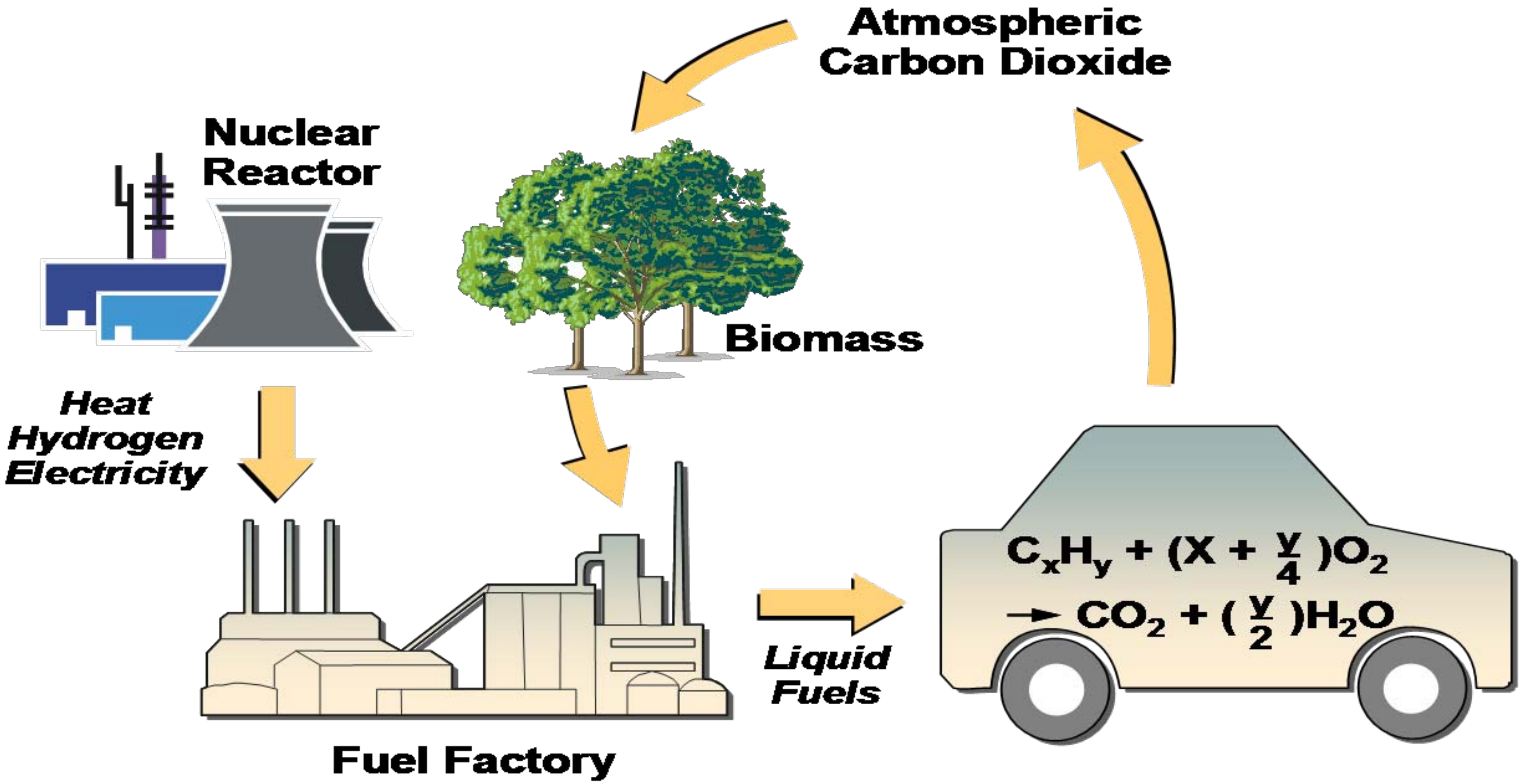
Biomass Liquid-Fuel Yield Depends Upon How the Biomass is Processed

Measured in Equivalent Barrels of Diesel Fuel/Day



Can Meet U.S. Liquid-Fuel Demand If an Outside Energy Source for Processing Biomass

The Nuclear-Hydrogen-Biomass Liquid-Fuel Cycle



Nuclear Energy with Biomass Liquid Fuels
Could Replace Oil-Based Transport Fuels in the United States

Nuclear Biomass Liquid Fuels

The Details

Three Step Strategy to a Nuclear-Biomass Liquid-Fuels Economy

- **Three implementation steps**
  - **Starch (corn, potatoes, etc.) to ethanol**
  - **Cellulose to ethanol and gasoline and diesel**
  - **Biomass to diesel**
- **Basis of implementation strategy**
  - **Economics and ease of implementation**
  - **Each step**
    - **Larger biomass resource available**
    - **More liquid fuel production**
    - **Increased liquid fuel yield per unit of biomass**
  - **Nuclear energy input from simple to complex**
    - **Steam (Starch)**
    - **Steam and hydrogen (Cellulose)**
    - **Hydrogen (All biomass)**

The Biotech Revolution

Sugar (Sugarcane and Sugar Beets)

Sugar → Ethanol (Traditional Technology)

Process has been Used for Millennia

Starch (Corn, Barley, etc.)

Starch → Sugar → Ethanol

Process has been Used for Millennia

New Low-Cost Enzymes for Rapid Starch-to-Sugar Conversion (Corn-to-Ethanol Boom)

Cellulose (Trees, Agricultural Waste, Etc.)

Cellulose → Sugar → Ethanol

Enzyme Costs Dropping Rapidly; Precommercial Plants Operating

Starch to Ethanol

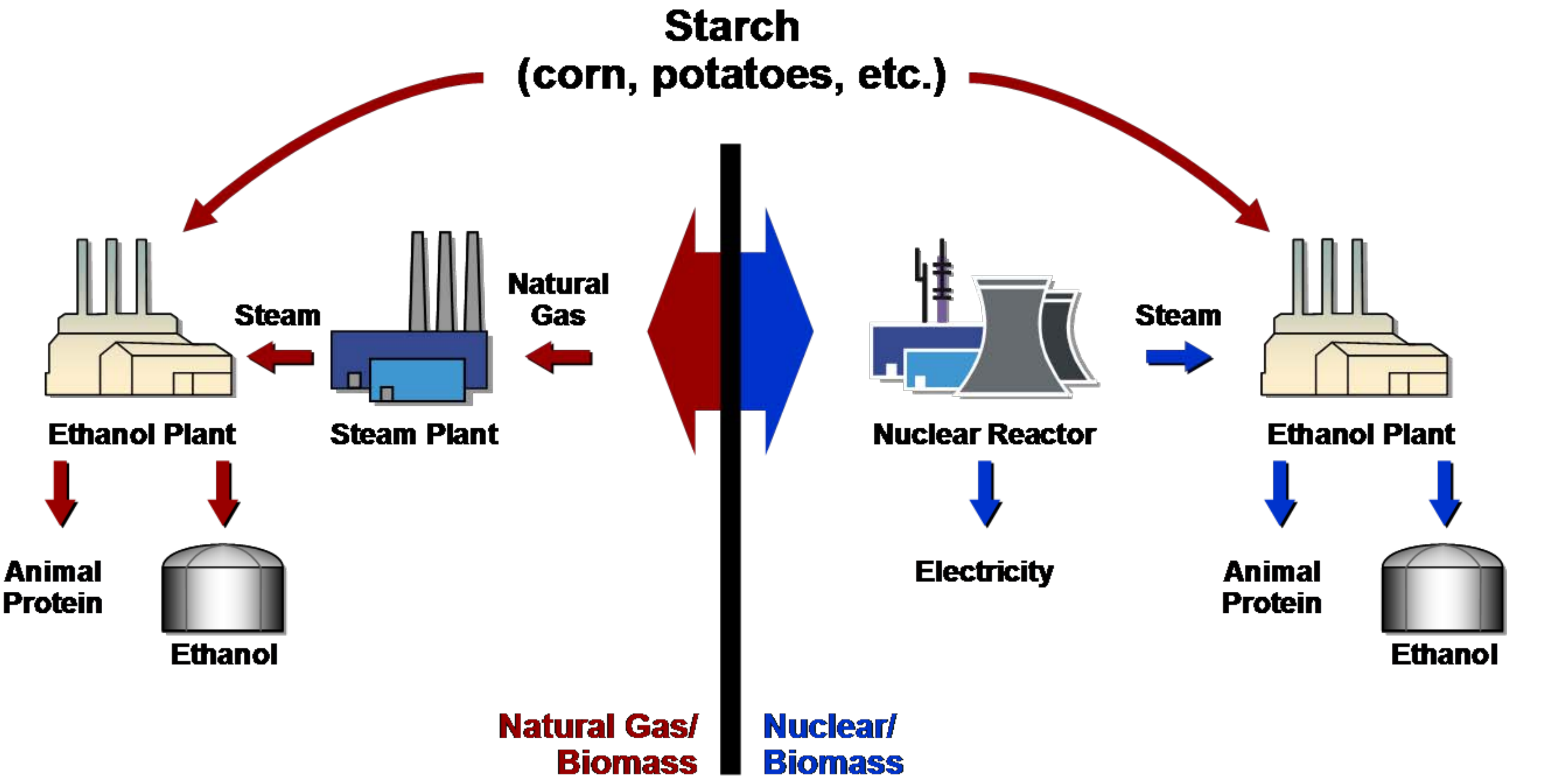
Option for Today

Nuclear Input: Low-Pressure Steam
(Experience outside the United States)

Starch to Ethanol Requires Low-Temperature Steam

- **Energy input to grow corn and convert it to ethanol is 70% of the energy value of the ethanol**
- **Low-pressure (150 psi) steam for distillation and other uses is half the nonsolar energy input**
- **Nuclear plants can provide this steam**
  - **Cuts fossil inputs and greenhouse gas releases from ethanol production in half**
  - **Cost of nuclear heat is about half that of natural gas (~$\$3/10^6$ MBTU)**
- **Production of one billion liters of ethanol/year requires 260 MW(t) of steam**
- **Ethanol production limited by availability of corn, potatoes, and other feedstocks**

Starch to Ethanol



Fossil Energy Input 70% of Energy Content of Ethanol

50% Decrease in CO_2 Emissions/Gallon Ethanol
50% Reduction in Steam Cost

Economics are favorable and no new technology is required

Cellulose to Ethanol
Lignin to Hydrocarbon Fuel

Midterm Option

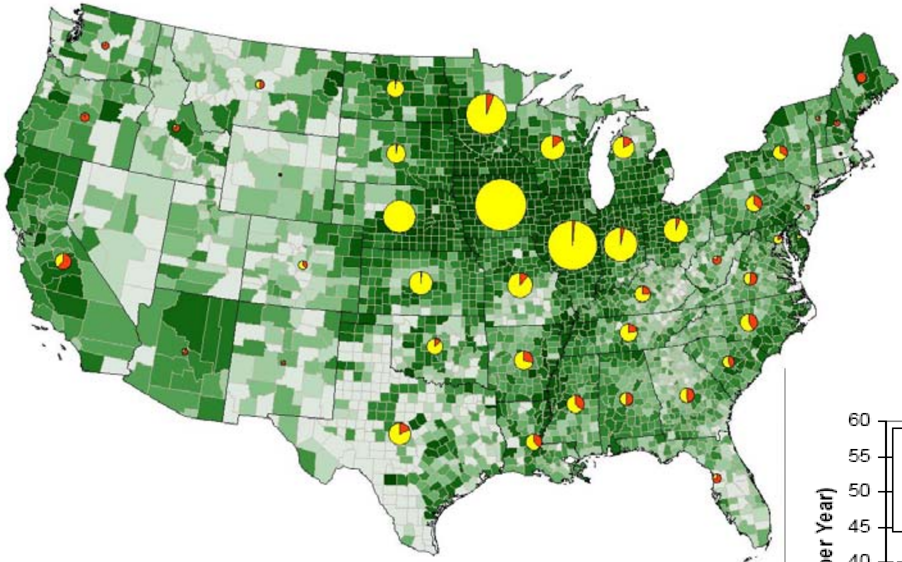
Nuclear Inputs

Low-Pressure Steam

Hydrogen for Hydrocracking Lignin

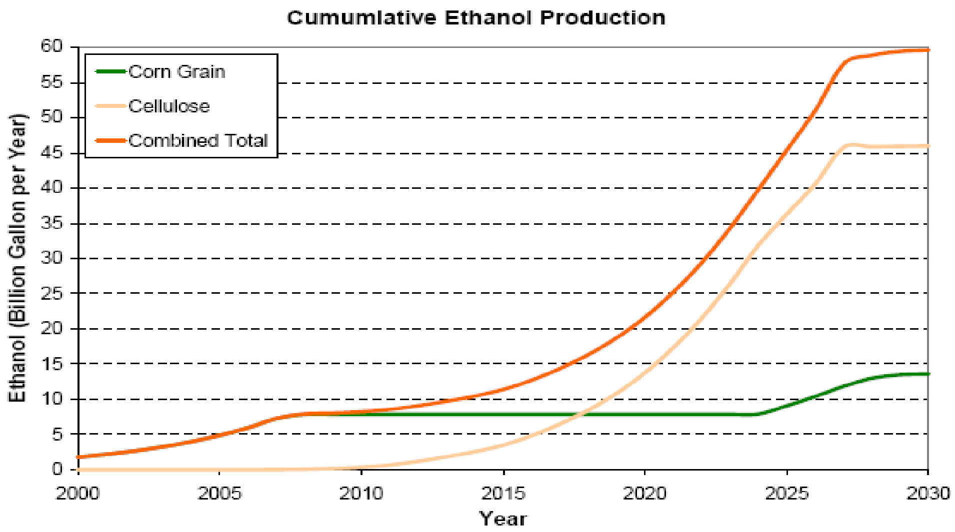
One-Third of U.S. Liquid Fuel Demand Could be Met with Ethanol By 2030

Cellulose to Ethanol and Lignin as Burnt as Fuel



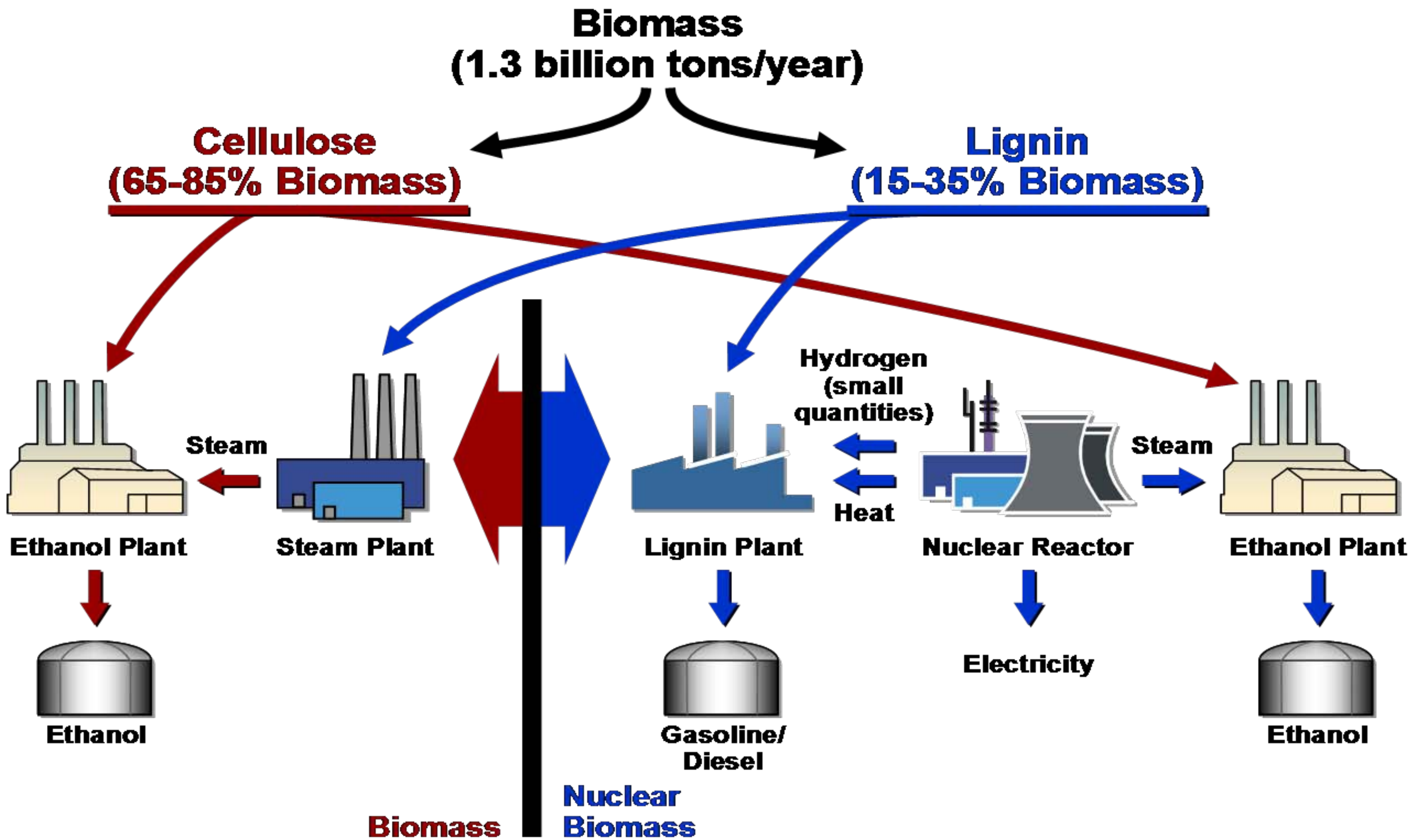
Distribution of Biomass Sources

Projected Ethanol Production



Source: NREL – Bob Wooley

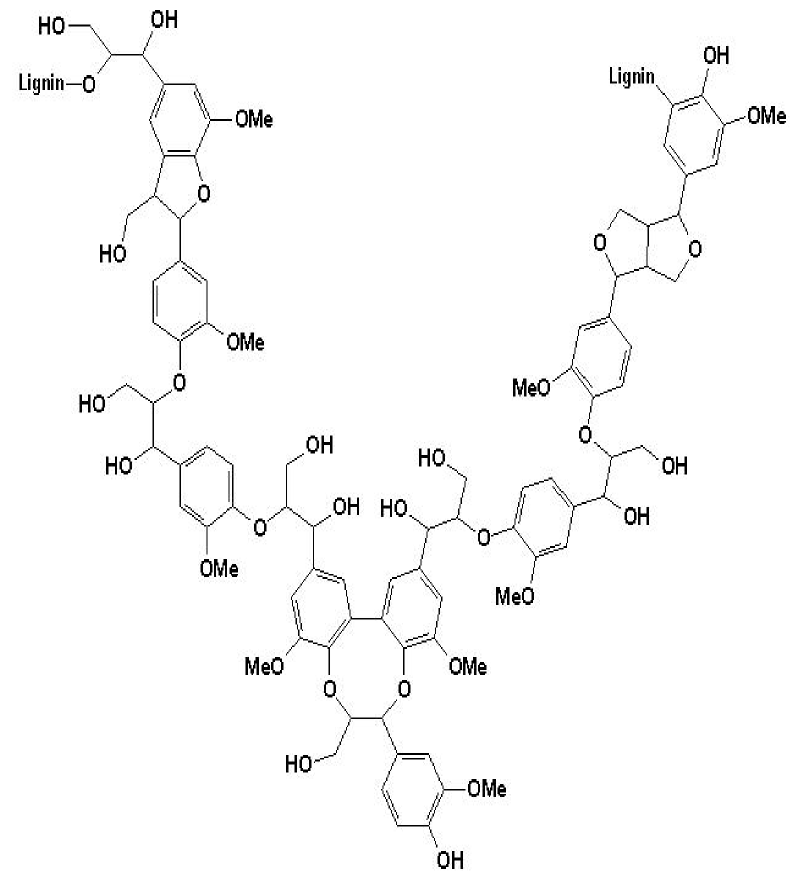
Cellulosic Liquid Fuel Yields Increased by 50% Using Nuclear Heat and Hydrogen



50% Increase Liquid Fuel/Unit Biomass

Nuclear-Cellulosic Liquid Fuels Requires Lignin Conversion to a Liquid Fuel

- **Conventional cellulose-to-ethanol process burns plant lignin for energy**
- **Nuclear cellulose ethanol option**
  - **Nuclear steam is an option for cellulose feedstock only if a use is found for lignin**
  - **Lignin conversion to liquid fuels required (no other market large enough)**
  - **Hydrogen required to hydrocrack lignin to gasoline-type fuel**
  - **Processes under development**



Lignin (Biological precursor to crude oil)

Biomass to Hydrocarbon Fuels (Gasoline, Diesel, Jet Fuel)

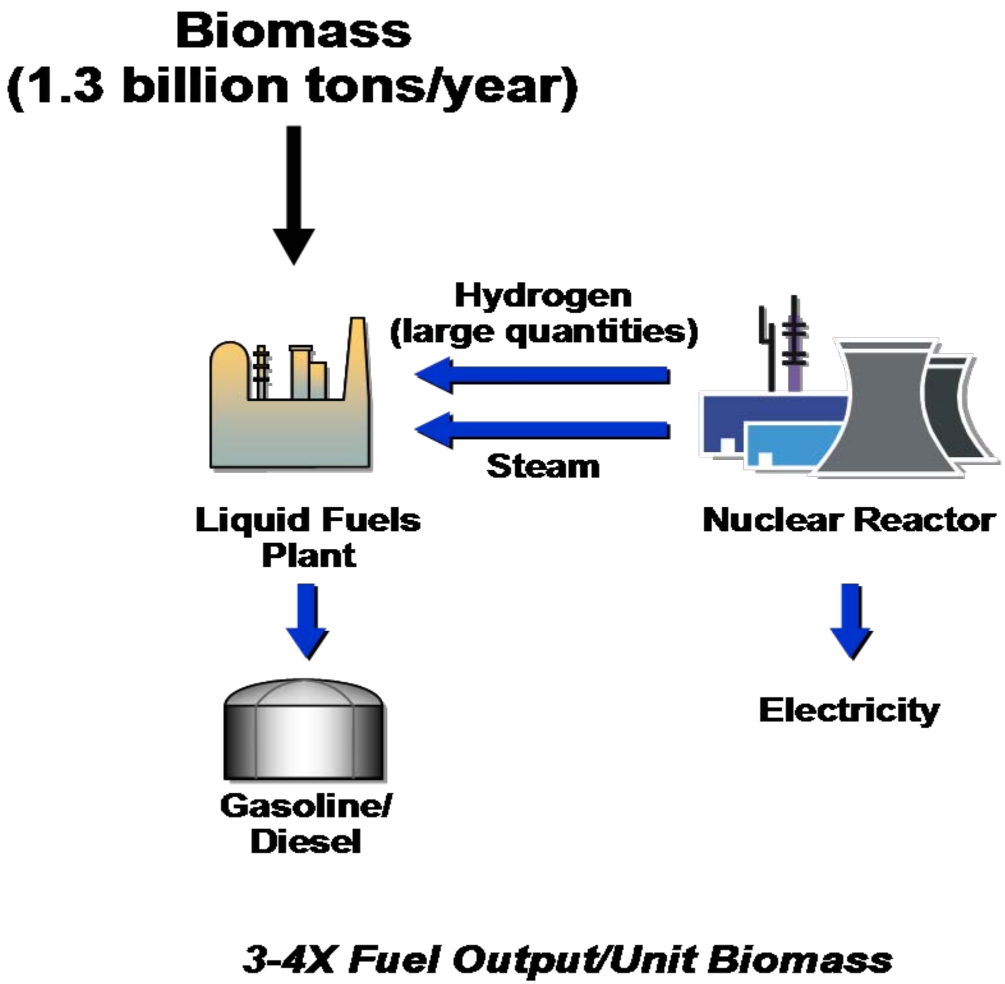
Longer-Term Option

Nuclear Input:

Large Quantities of Hydrogen

Conversion of Biomass to Diesel Fuel

- Biomass is a carbon feedstock
- Full conversion to hydrocarbon fuels to maximize liquid fuels production per unit of biomass
- Requires large quantities of hydrogen
- Several process options including Fischer-Tropsch (same as coal liquefaction)
- Economics depends upon hydrogen costs



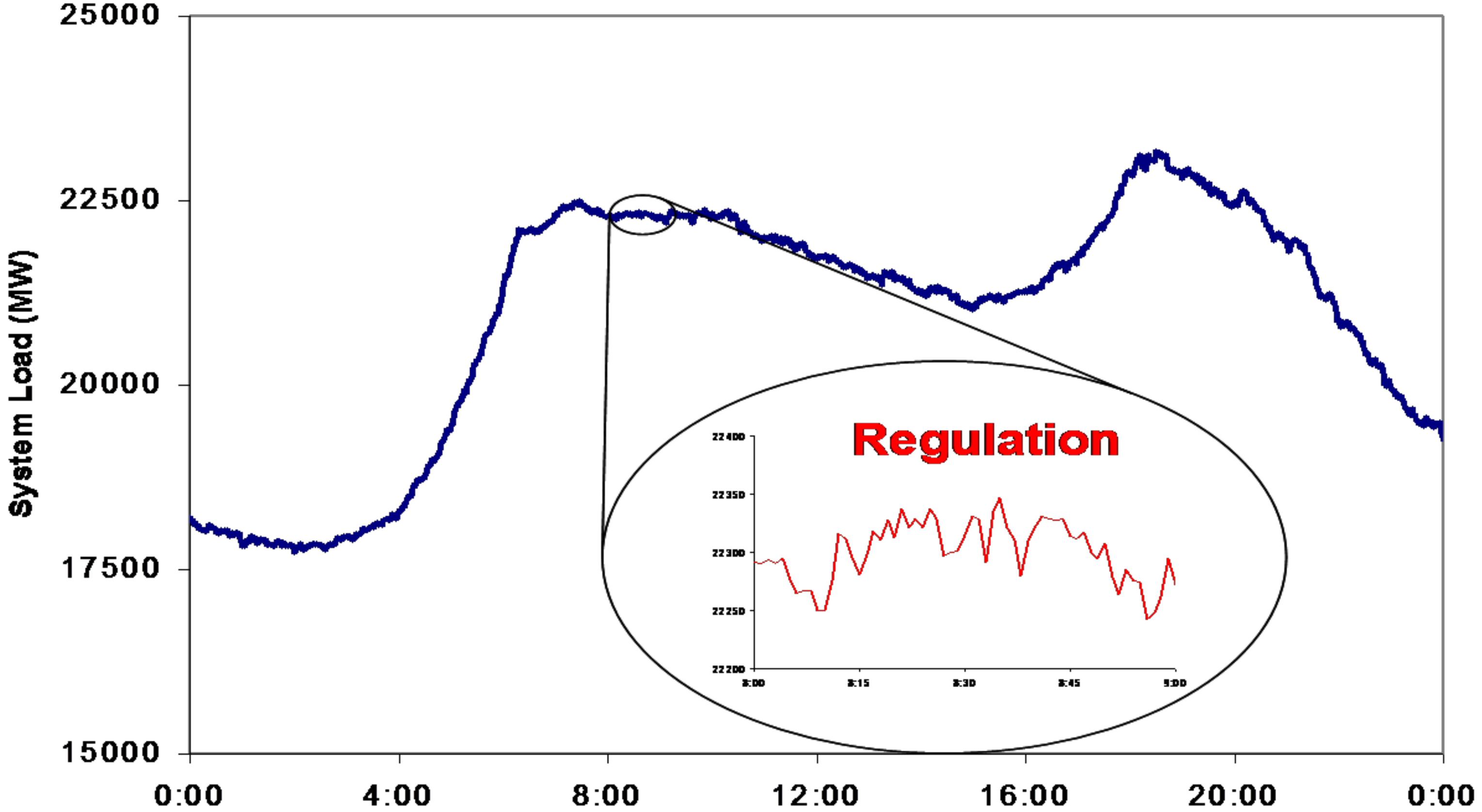
Example: Combined Nuclear-Renewable Electricity

Peak Electricity Production

C. W. Forsberg, "Economics of Meeting Peak Electricity Demand Using Nuclear Hydrogen and Oxygen," *Proc. International Topical Meeting on the Safety and Technology of Nuclear Hydrogen Production, Control, and Management, Boston, Massachusetts, June 24–28, 2007*, American Nuclear Society, La Grange Park, Illinois. See backup slides for nuclear-fossil peak electricity options

Electricity Demand Varies with Time

Example: Daily Cycle

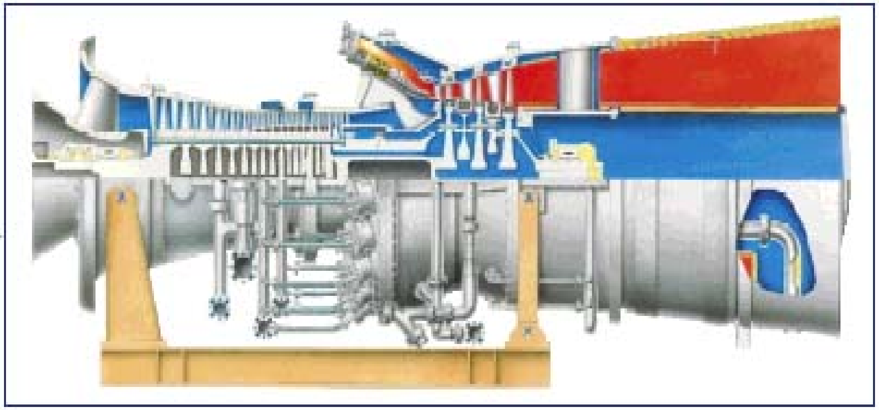


Large-Scale Renewable Electric Production may not be Viable without Electricity Storage

- **Renewable electric output does not match electric demand**
- **Problems exist on windless days, cloudy days, and at night**
- **Low-cost backup power options are required**

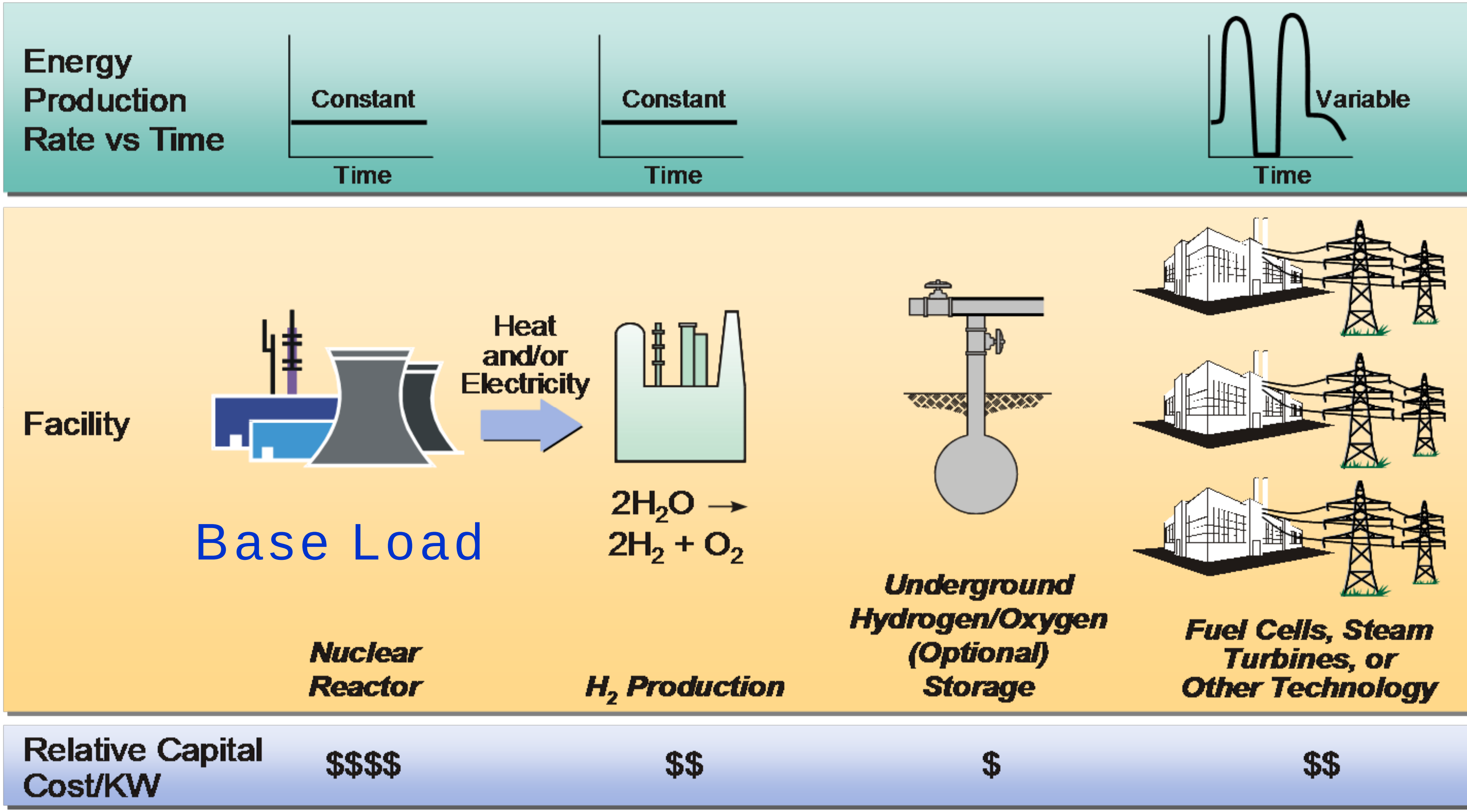
Fossil Fuels are Used Today to Match Electricity Demand with Production

- **Fossil fuels are inexpensive to store (coal piles, oil tanks, etc.)**
- **Systems to convert fossil fuels to electricity have relatively low capital costs**



- **Carbon dioxide sequestration is likely to be very expensive for peak-load fossil-fueled plants**
- **If fossil fuel consumption is limited by greenhouse or cost constraints, what are the alternatives for peak power production?**

Hydrogen Intermediate and Peak Electric System (HIPES)



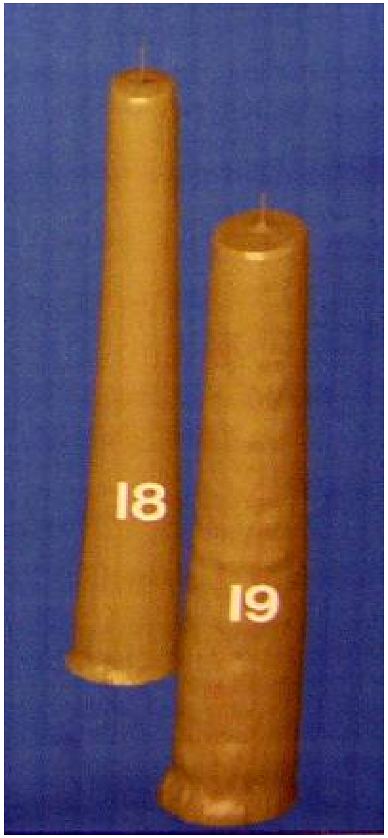
Nuclear Hydrogen Production Options

- **Near term**
  - **Electrolysis**
  - **Electricity supply options**
    - **Base load**
    - **Night time and surplus renewables**
- **Longer term**
  - **High-temperature electrolysis**
  - **Hybrid**
  - **Thermochemical**

Norsk Atmospheric Electrolyser

Key Nuclear Hydrogen Characteristics (H_2, O_2, Heat, Centralized Delivery) are Independent of the Nuclear Hydrogen Technology

Bulk Hydrogen Storage is a Low-Cost Commercial Technology



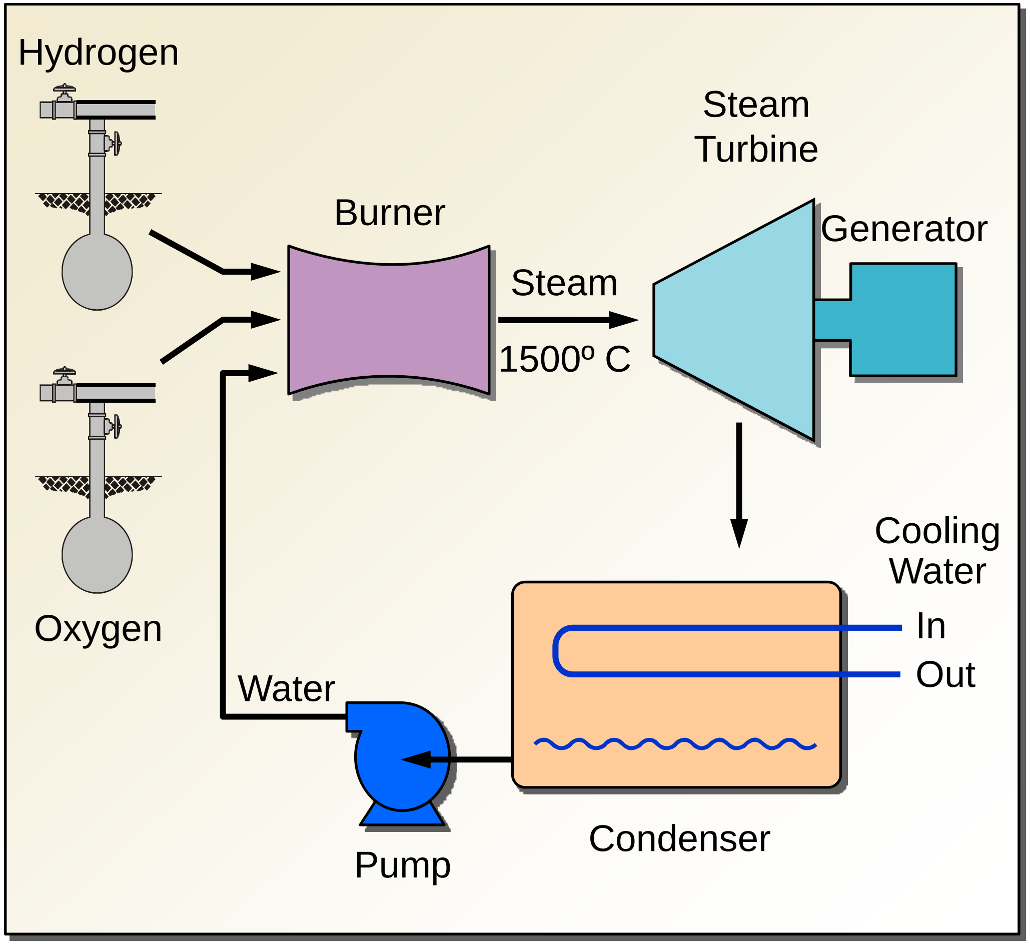
- Chevron Phillips H_2 Clemens Terminal
- 160 x 1000 ft cylinder salt cavern
- Same technology used for natural gas
- In the United States, one-third of a year's supply of natural gas is in 400 storage facilities in the fall

Use Same Technology for Oxygen Storage

Oxy-Hydrogen Turbine for Electricity

Low-Capital-Cost Efficient Conversion of H_2 and O_2 to Electricity for a Limited Number of Hours per Year

- **High-temperature steam cycle**
  - $2H_2 + O_2 \rightarrow$ Steam
- **Low cost**
  - No boiler
  - High efficiency (70%)
- **Unique feature: Direct production of high-pressure high-temperature steam**



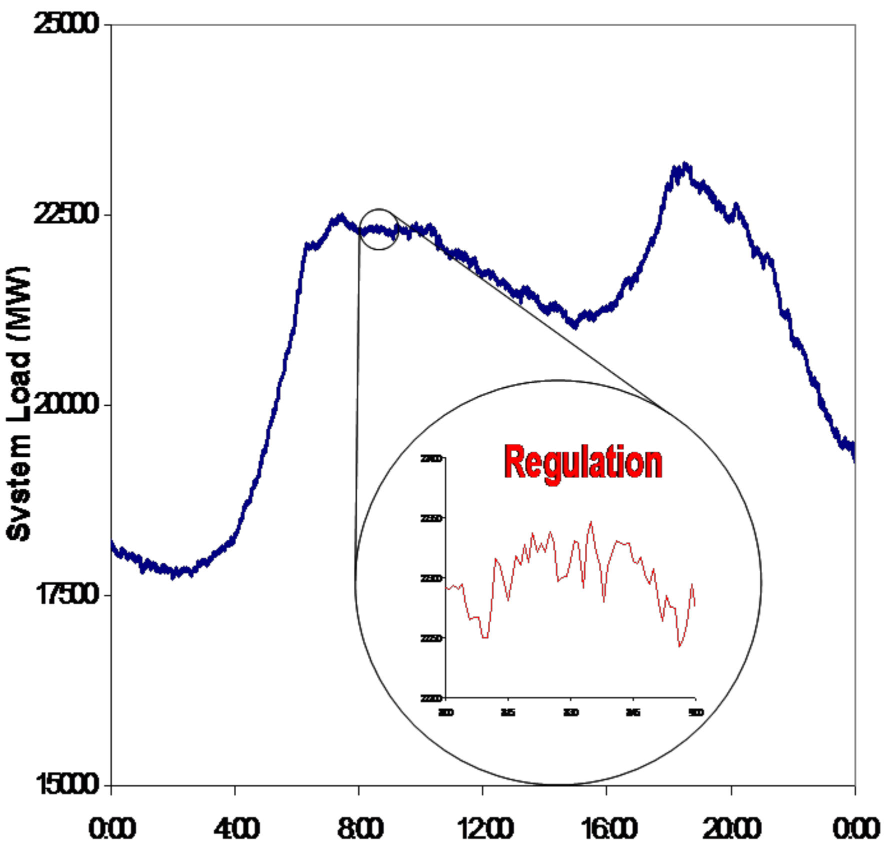
Oxy-Fuel Combustors are Being Developed for Advanced Fossil Plants

- **A hydrogen-oxygen combustor similar to natural gas–oxygen combustor**
- **CES test unit**
  - **20 MW(t)**
  - **Pressures from 2.07 to 10.34 MPa**
  - **Combustion chamber temperature: 1760ºC**

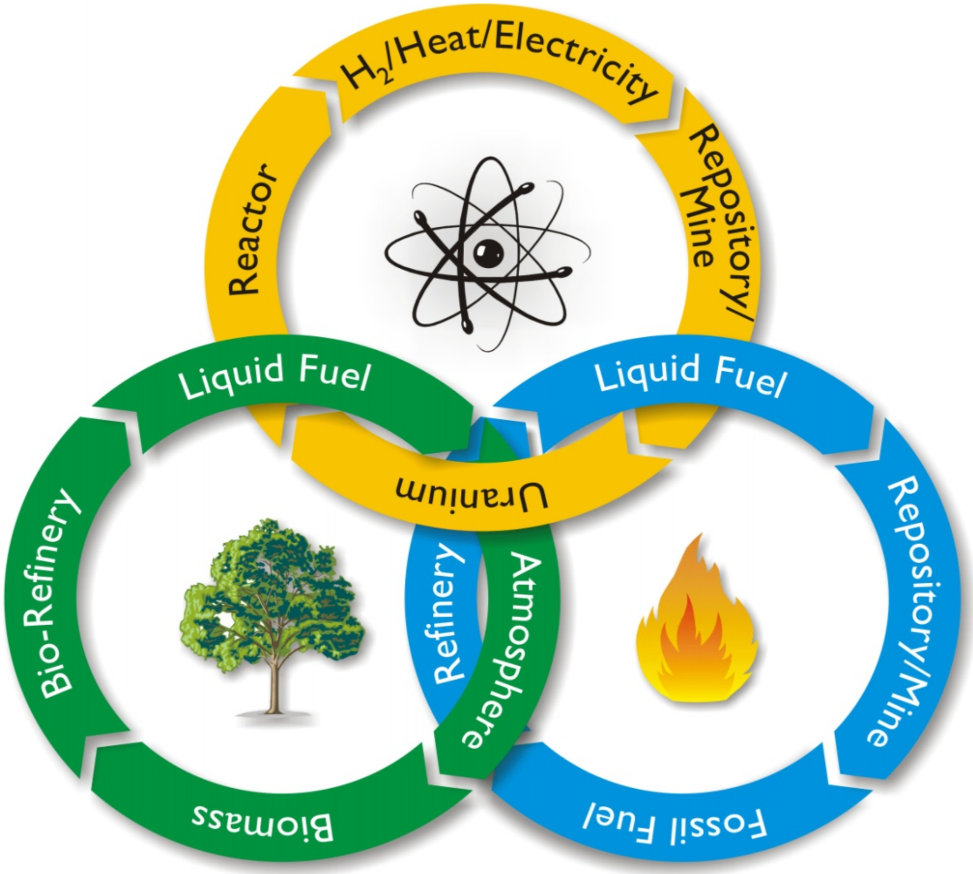
Courtesy of Clean Energy Systems (CES)

HIPES may Enable Large-Scale Nuclear-Renewable Electricity

- **HIPES strategy**
  - **Low-cost daily, weekly, and seasonal bulk H_2 and O_2 storage**
  - **Low-cost conversion to electricity**
- **Match production with demand**
  - **Renewables have highly variable power output**
  - **Can adjust to rapidly varying renewables output (full utilization)**



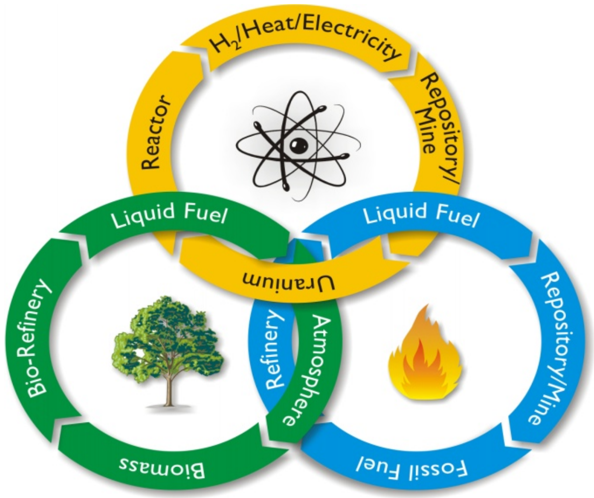
Combined Fuel Cycles have Implications for Nuclear Energy and Chemical Engineering



There are Significant Chemical Engineering Challenges

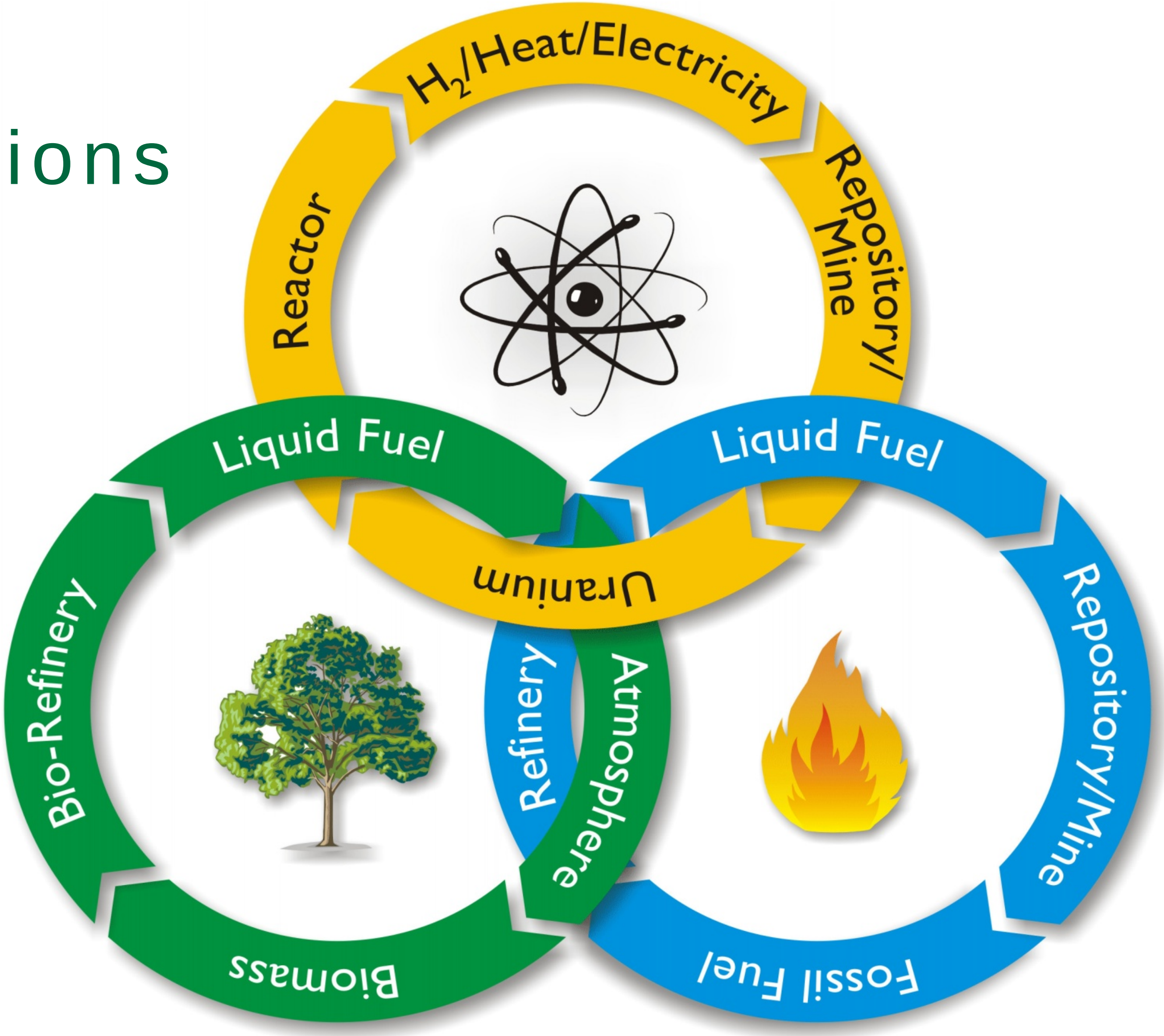
- **Underground Refining**
  - **High-temperature heat-transfer loops**
  - **Process development (heating rates, etc.)**
- **Nuclear-Biomass Liquid Fuels**
  - **Hydro cracking of lignin biomass to gasoline**
    - **Cellulose to ethanol with nuclear heat**
    - **Lignin to hydrocarbon fuels with hydrogen**
  - **Direct hydrogenation of cellulosic feedstock to gasoline and diesel (replace Fischer-Tropsch)**
- **Nuclear-Renewable Peak Electricity**
  - **Underground oxygen storage**
  - **Hydrogen production**

Conclusions



- **Sustainability goals**
  - **No oil consumption**
  - **No climate change**
- **Sustainability will require integration of fossil, biomass, and nuclear fuel cycles with different nuclear products**
  - **Steam**
  - **High-temperature heat**
  - **Hydrogen**
- **Combined fossil, renewable, nuclear fuel cycles include challenges for chemical engineers**
  - **Development of “underground refining”**
  - **Lignin to hydrocarbon fuel**
  - **Better methods to convert biomass to hydrocarbon fuels**
  - **Oxygen storage**

Questions


H2/Heat/Electricity
Reactor
Repository/Mine
Uranium
Liquid Fuel
Bio-Refinery
Biomass
Atmosphere
Liquid Fuel
Refinery
Repository/Mine
Fossil Fuel

—Abstract—

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The energy and chemical industries face two great sustainability challenges: the need to avoid climate change and the need to replace crude oil as the basis of our transport and chemical industries. These challenges can be met by changing and synergistically combining the fossil, biomass, renewable, and nuclear fuel cycles.

Fossil fuel cycles. Fossil fuel cycles must be changed to reduce greenhouse impacts and will require options beyond carbon-dioxide sequestration. In situ thermal cracking of heavy oils, oil shale, and coal may enable the production of high-quality transport fuels while sequestering the byproduct carbon from the production processes without moving it from the original underground deposits. These options require integration of non-greenhouse-gas producing high-temperature heat from nuclear reactors with fossil systems for oil production.

Biomass fuel cycles. The use of biomass for production of liquid fuels and chemicals avoids the release of greenhouse gases. However, biomass resources are insufficient to (1) meet liquid fuel demands and (2) provide the energy required to process biomass into liquid fuels and chemicals. For biomass to ultimately meet our needs for liquid fuels and chemicals, outside sources of heat and hydrogen are required for the production facilities with biomass limited to use as a feedstock to maximize liquid-fuels production per unit biomass.

Renewable electric fuel cycles. Nuclear energy can economically provide base-load but not peak-load electricity. Increased use of renewable electric systems implies variable electricity production (depending upon wind and solar) that does not match electric demand. Today, peak electricity is produced using fossil fuels—an option that may not be viable if there are constraints on greenhouse gas emissions. Nuclear-produced hydrogen combined with underground hydrogen storage may create new methods to meet peak electric power production needs and thus enable the larger-scale use of renewable electricity production technologies.

It is the combined nuclear-fossil-renewable fuel cycles that can meet our energy needs, replace crude oil, and avoid excess greenhouse gas releases.

Biography: Charles Forsberg

Dr. Charles Forsberg is a Corporate Fellow at Oak Ridge National Laboratory, a Fellow of the American Nuclear Society, 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 and the Oak Ridge National Laboratory Engineer of the Year Award. 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 10 patents and has published over 200 papers.