Combined Fuel Cycles are Required for Sustainability

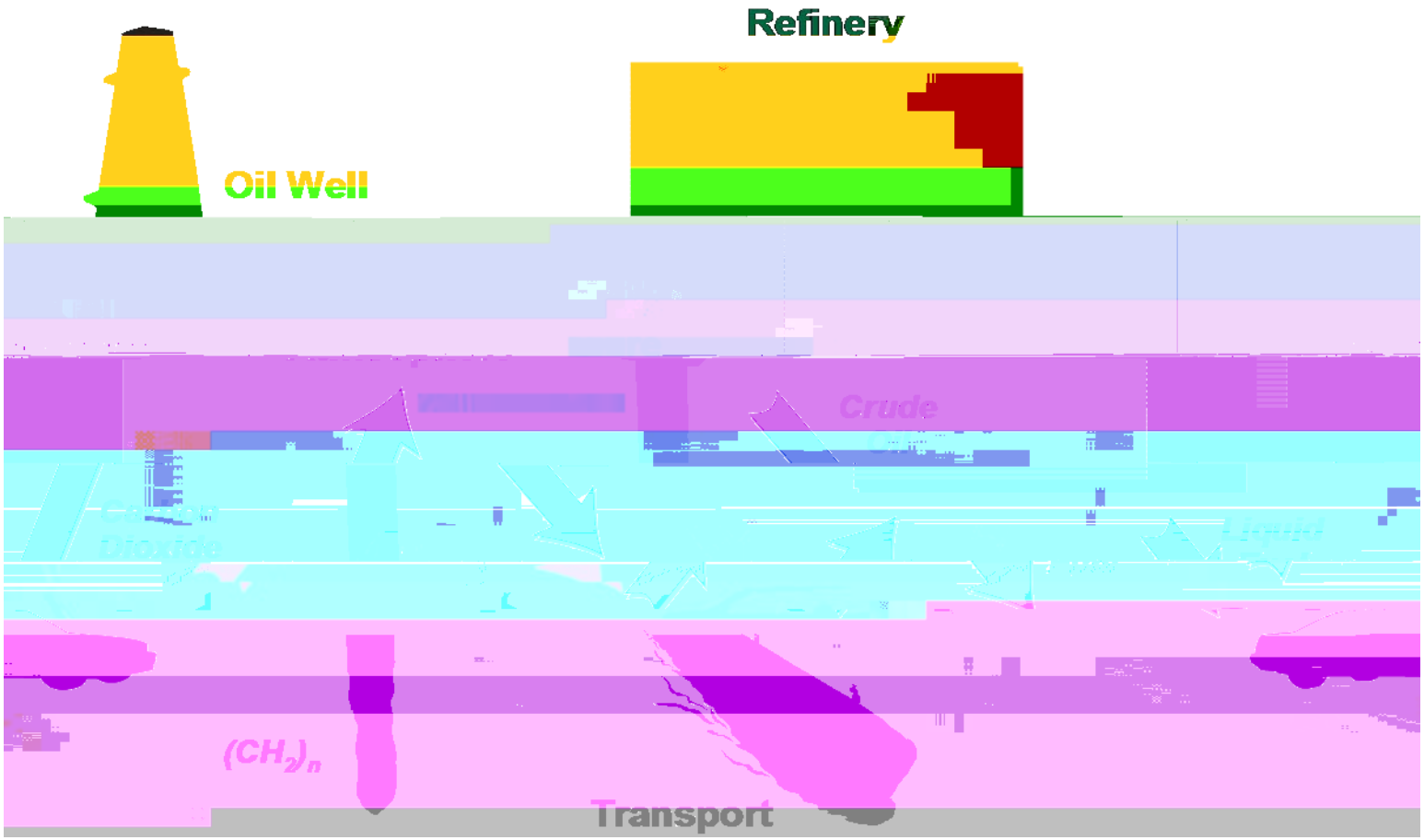
Examples of Combined Fuel Cycles

Example: Combined Nuclear-Fossil Liquid-Fuels Fuel Cycle

Underground Refining

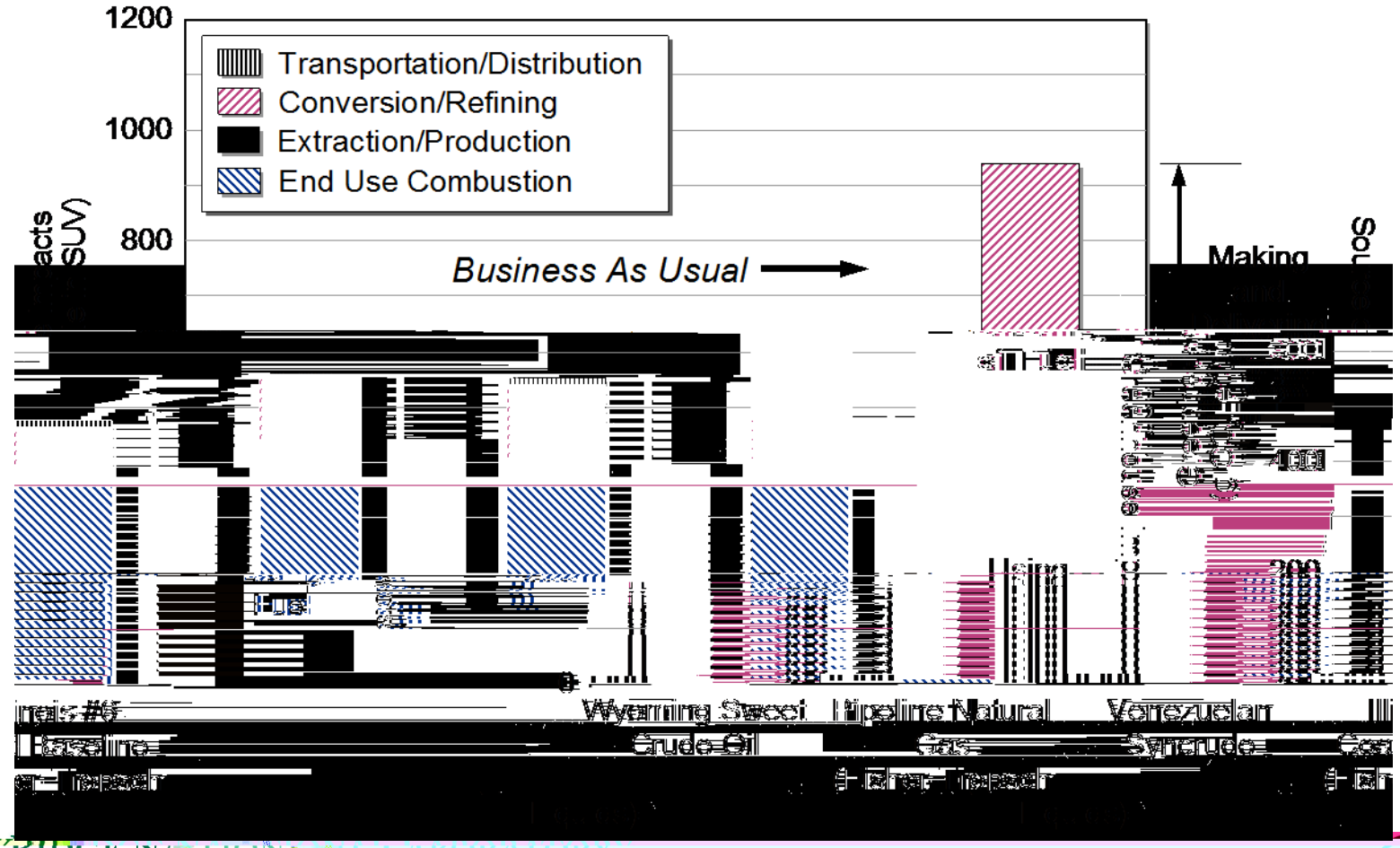
C. W. Forsberg, "Changing Biomass, Fossil, and Nuclear Fuel Cycles for Sustainability," *American Institute of Chemical Engineers Annual Meeting, Salt Lake City, Utah, November 4–9, 2007.*

Liquid-Fuels Fuel Cycle for Crude Oil



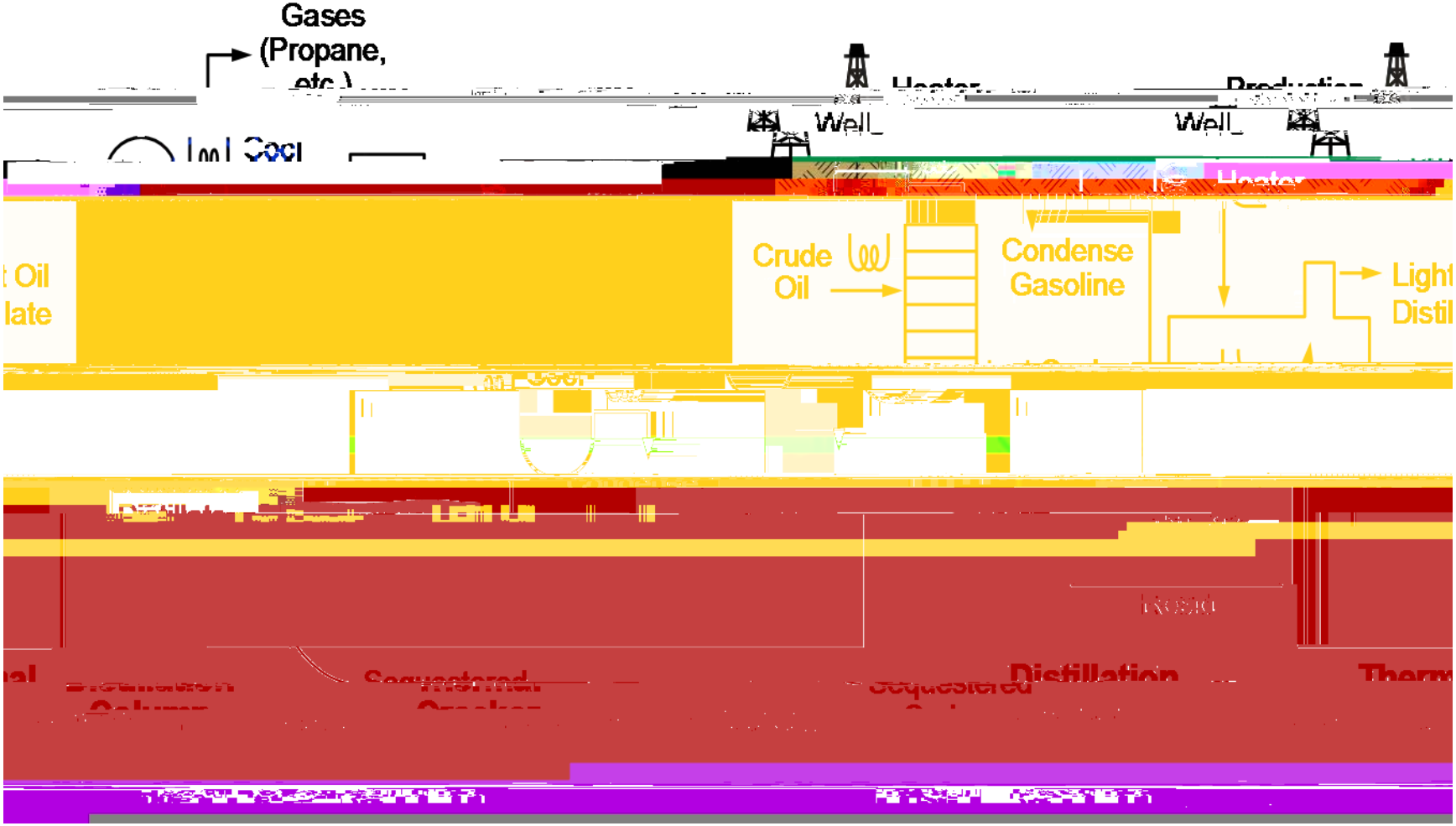
Conversion of Fossil Fuels to Liquid Fuels Requires Energy

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



In-Situ Refining May Require Nuclear Heat Source

Nuclear-Heated In-Situ Oil-Shale Conversion Process

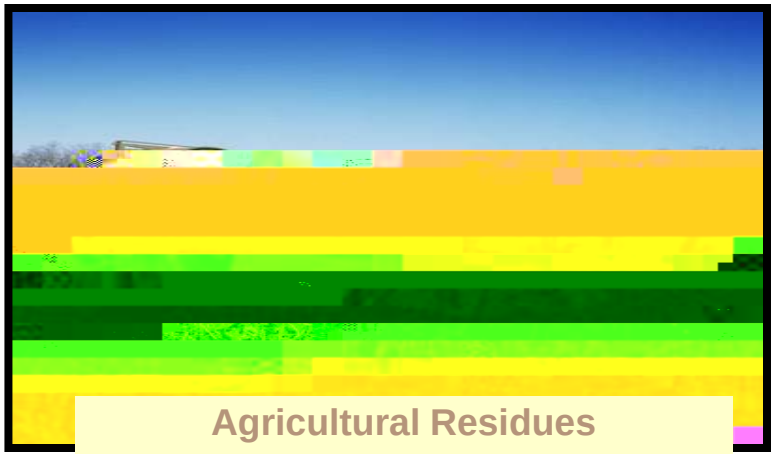
Example: Combined Nuclear-

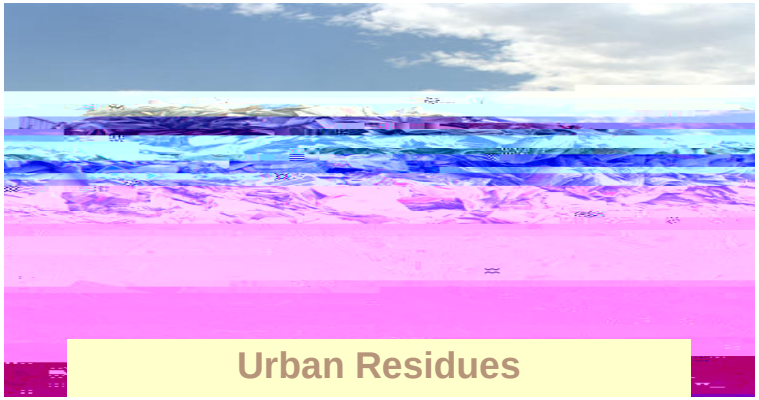
Fuel Cycle for Liquid Fuels from Biomass

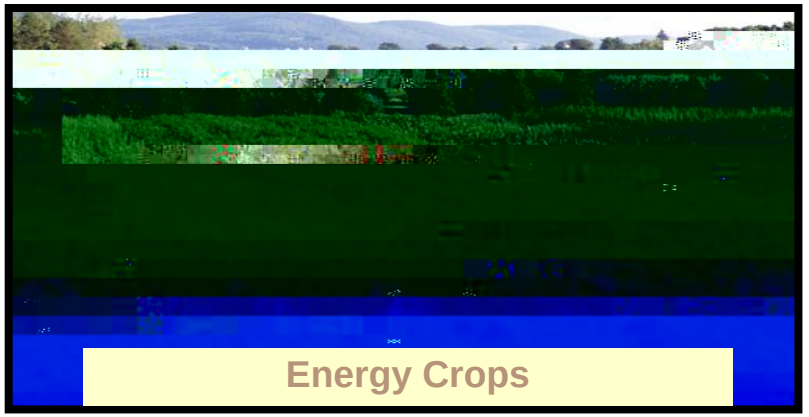
Biomass Production, Transport, and Fuel Factories Use Energy

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

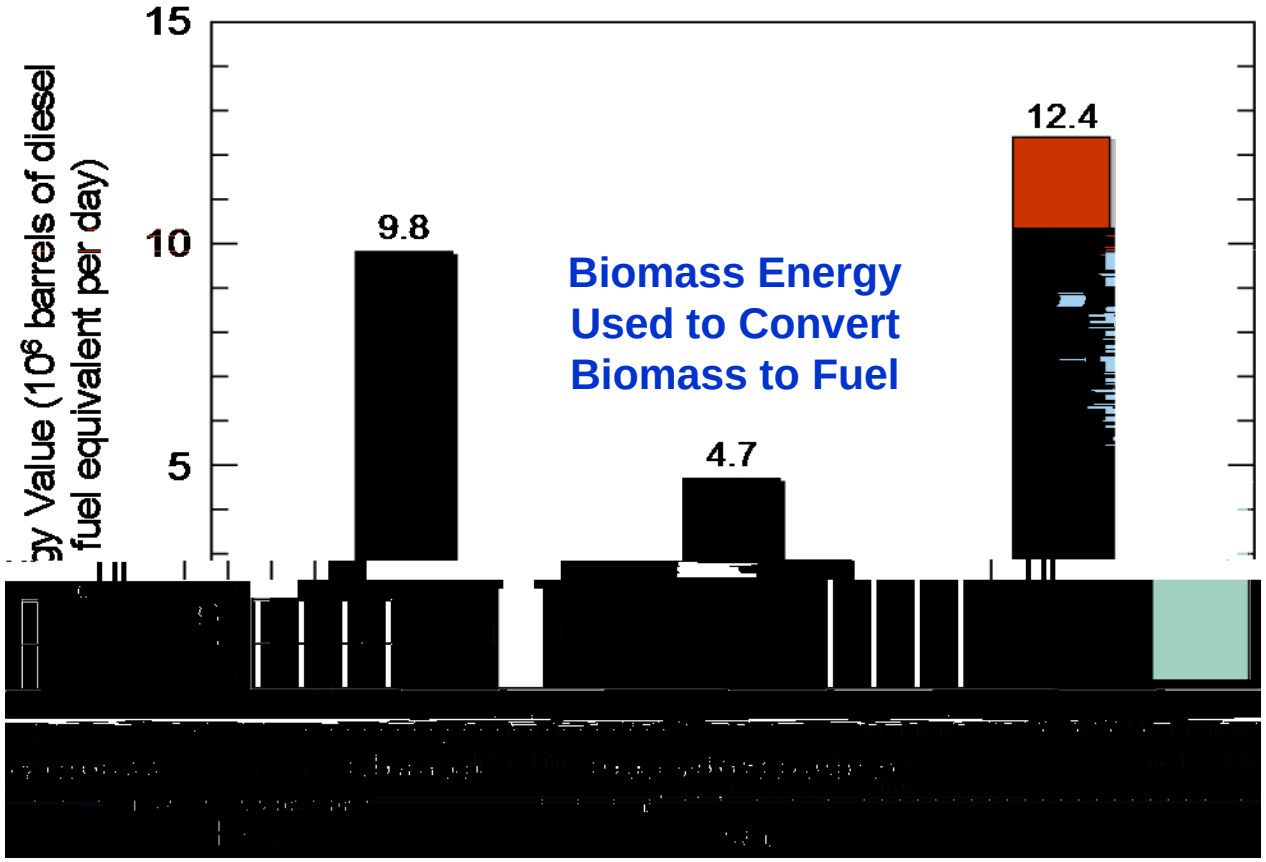






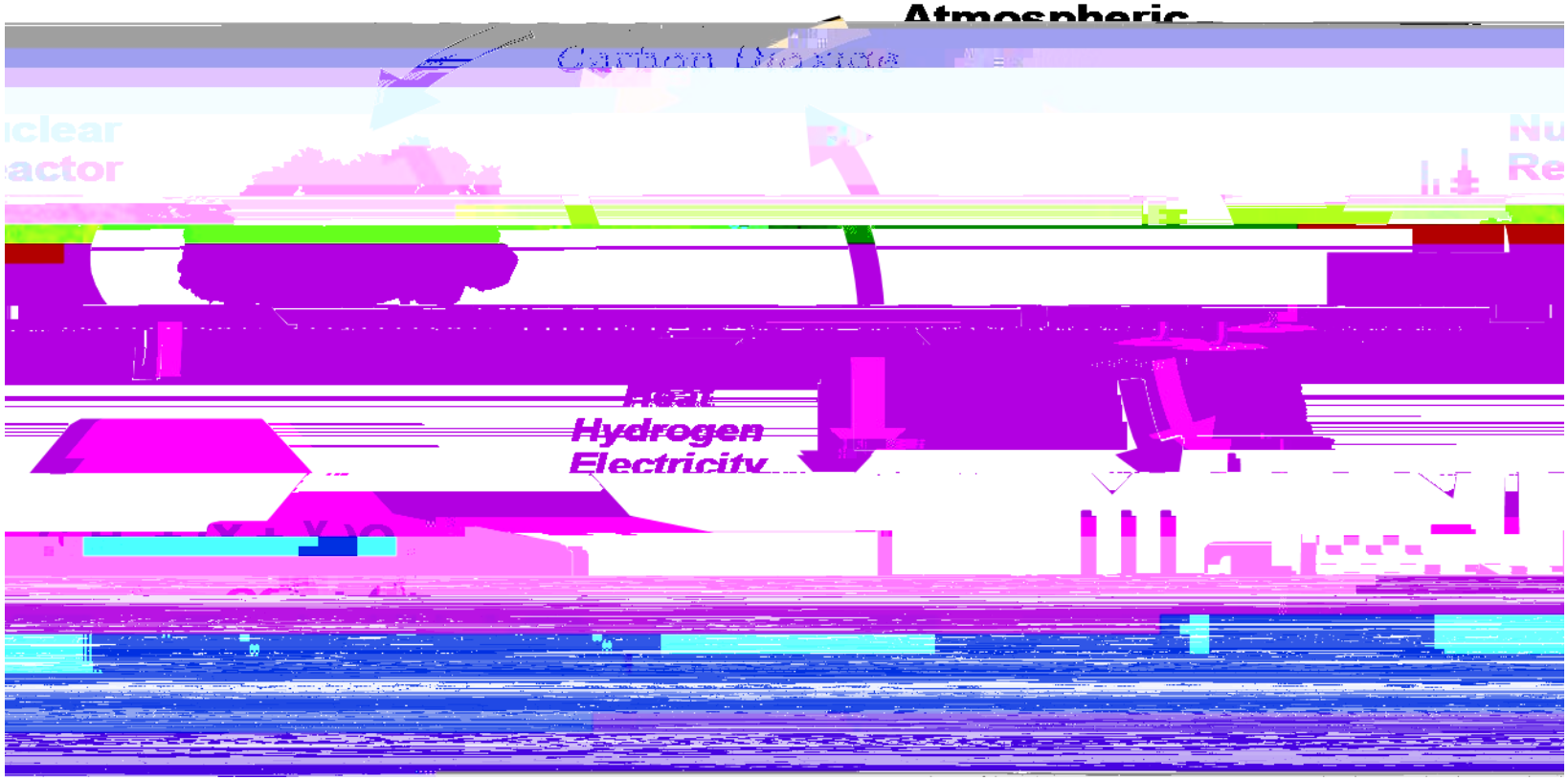
Biomass Liquid-Fuel Yield Depends Upon How the Biomass is Processed

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

The Biotech Revolution

Sugar (Sugarcane and Sugar Beets)
Sugar Ÿ Ethanol (Traditional Technology)
Process has been Used for Millennia

Starch (Corn, Barley, etc.)
Starch Ÿ Sugar Ÿ 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 Ÿ Sugar Ÿ Ethanol
Enzyme Costs Dropping Rapidly;
Precommercial Plants Operating

Starch to Ethanol

Option for Today

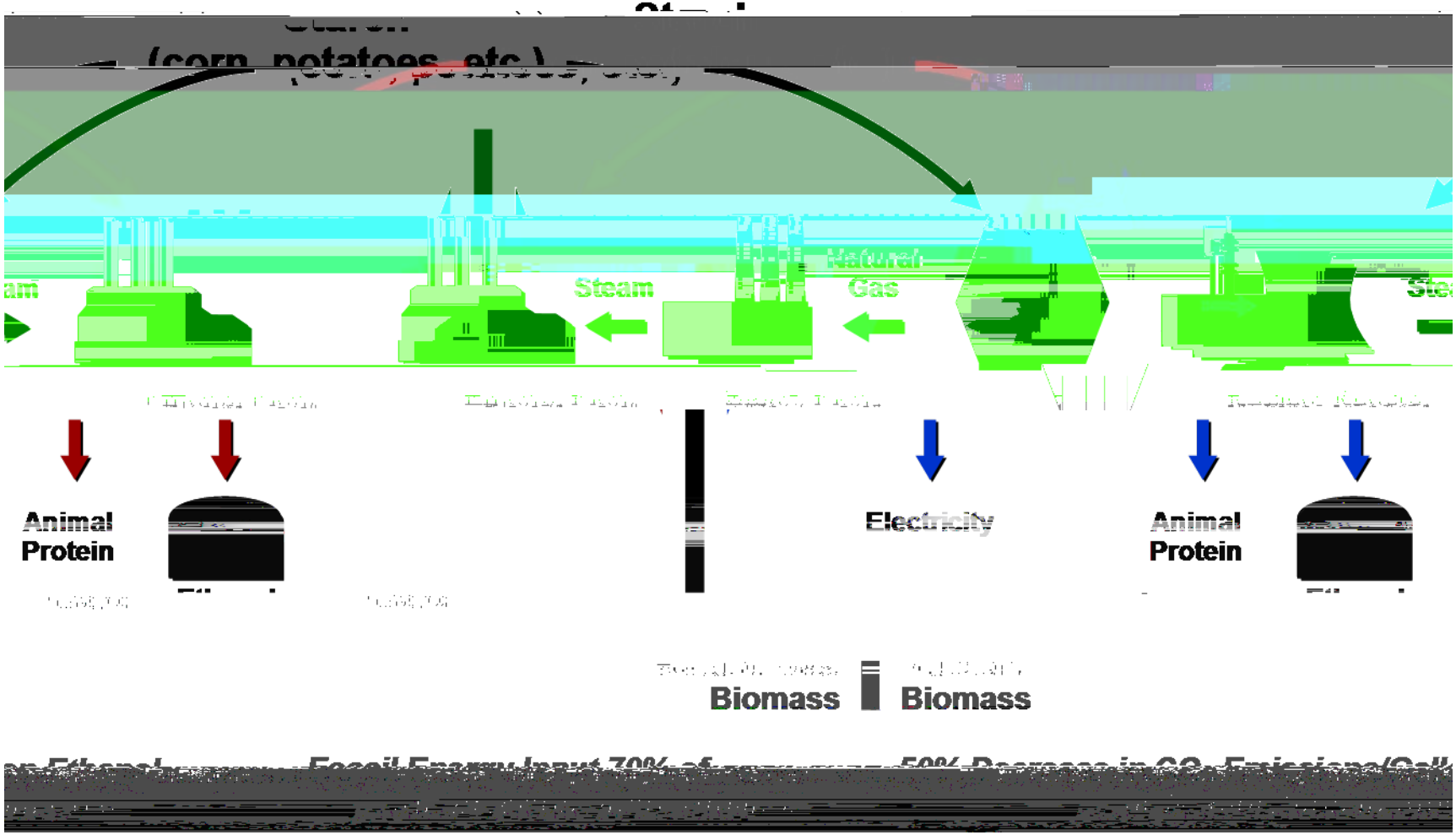
Nuclear Input: Low-Pressure Steam

(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**

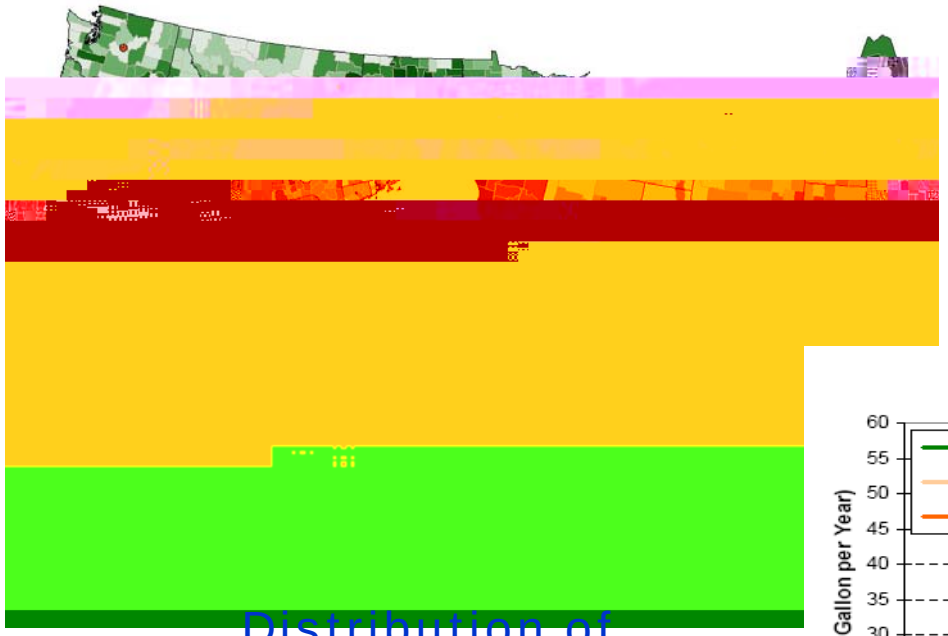
Starch to Ethanol



Economics are favorable and no new technology is required

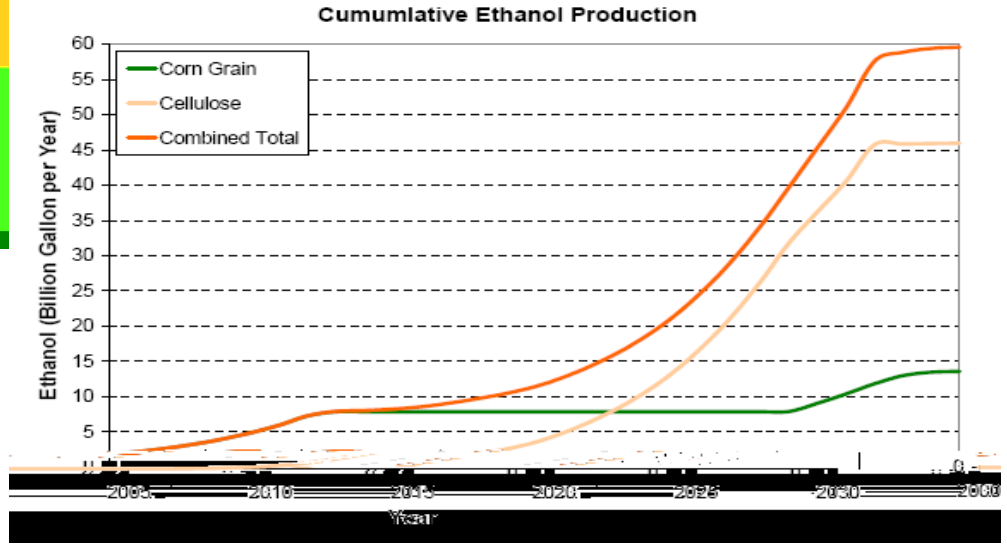
One-Third of U.S. Liquid Fuel Demand Could be Met with Ethanol By 2030

Cellulose to Ethanol and Lignin as Burnt as Fuel



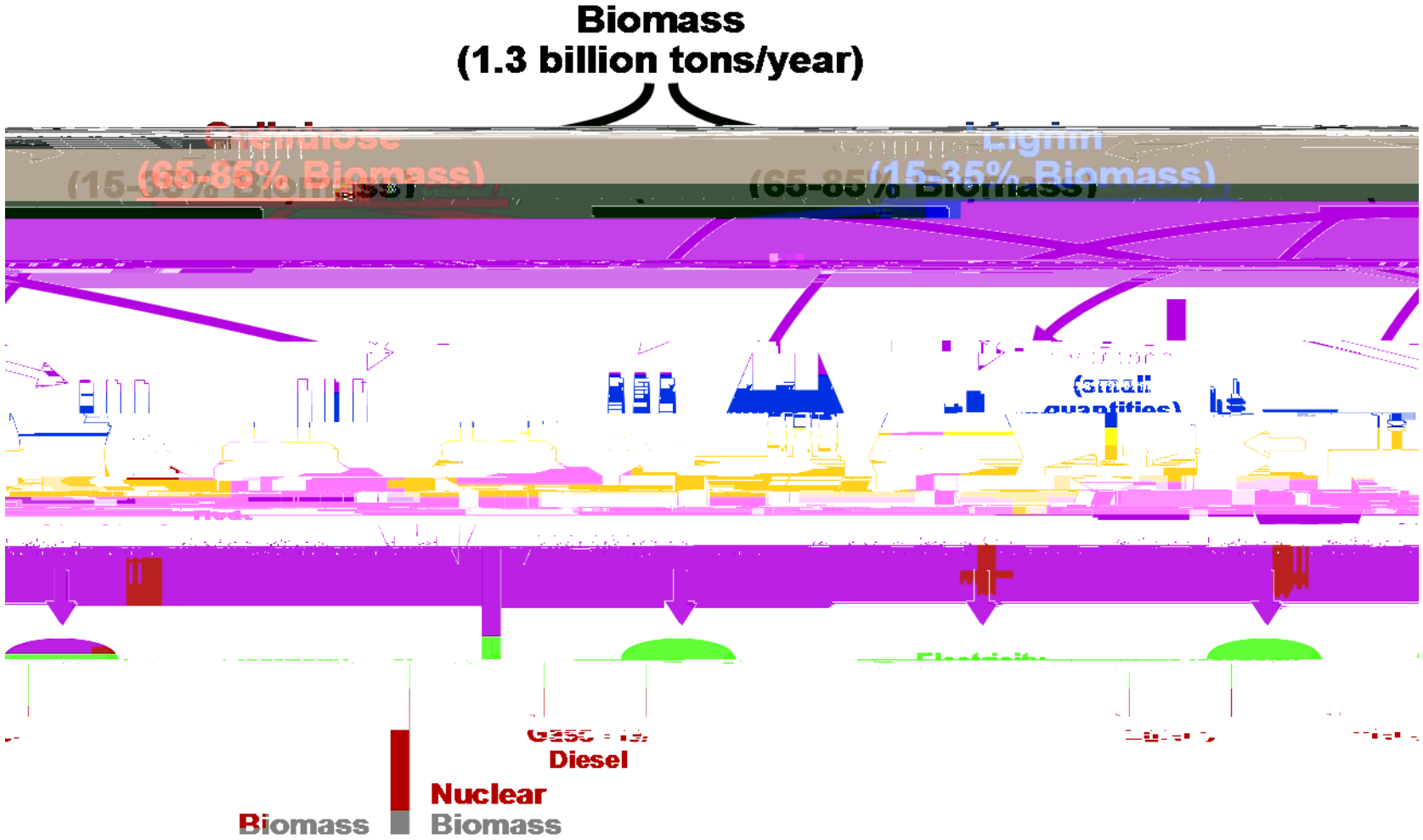
Distribution of Biomass Sources

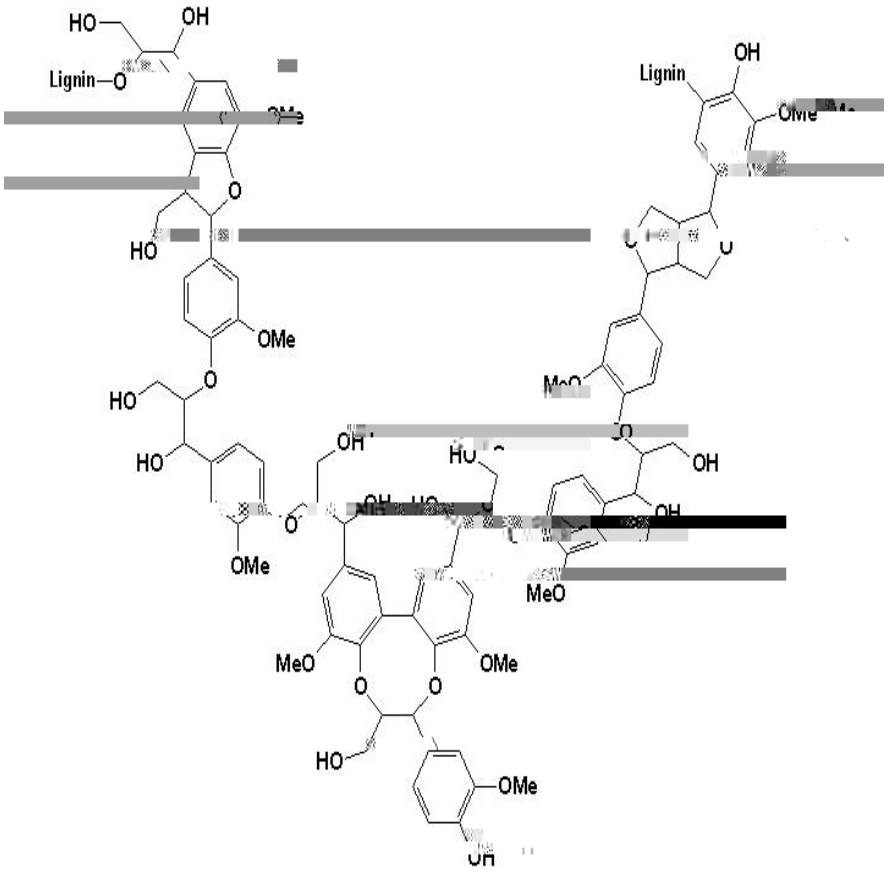
Projected Ethanol Production



Source: NREL – Bob Wooley

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

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

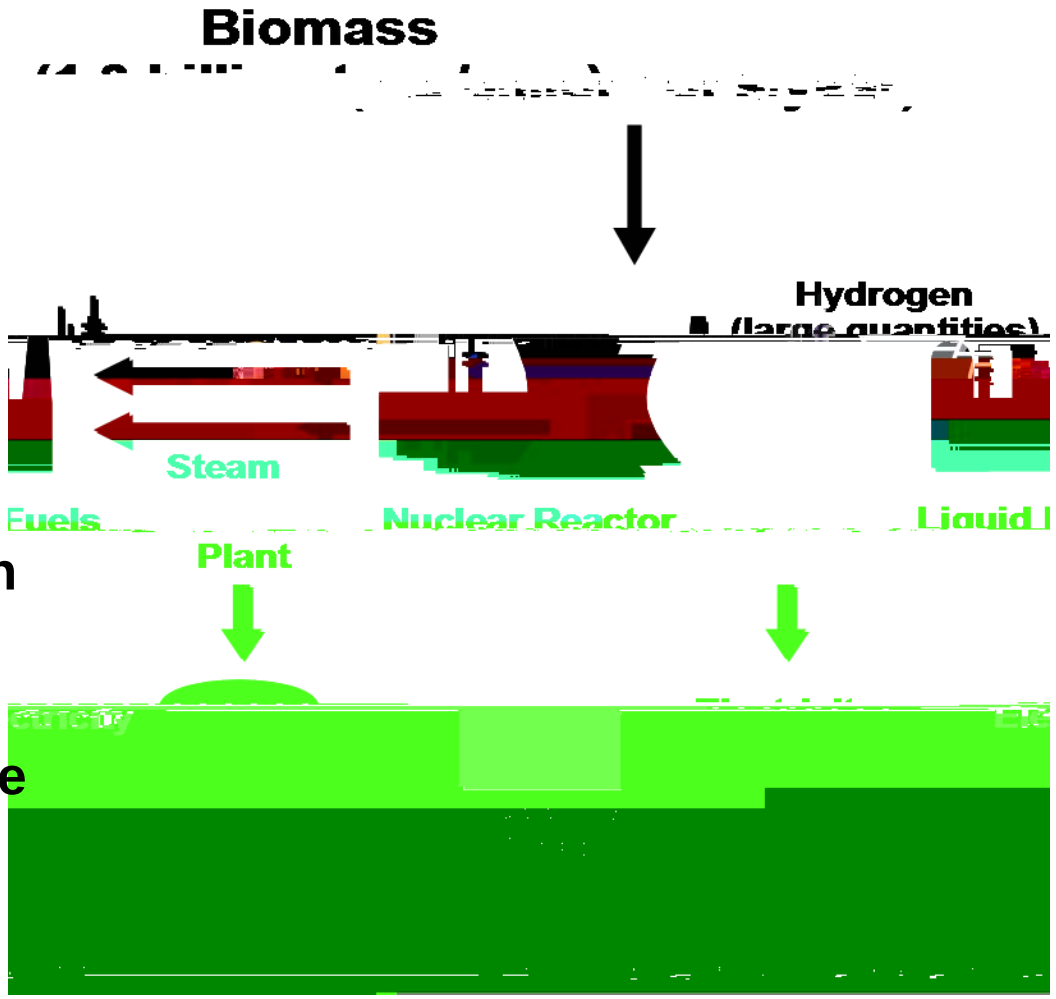
Longer-Term Option

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**



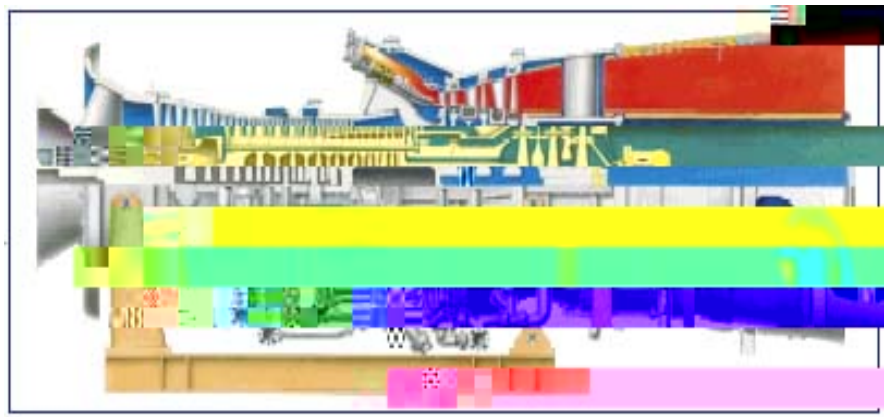
Example: Combined

Electricity Demand Varies with Time

Example: Daily Cycle

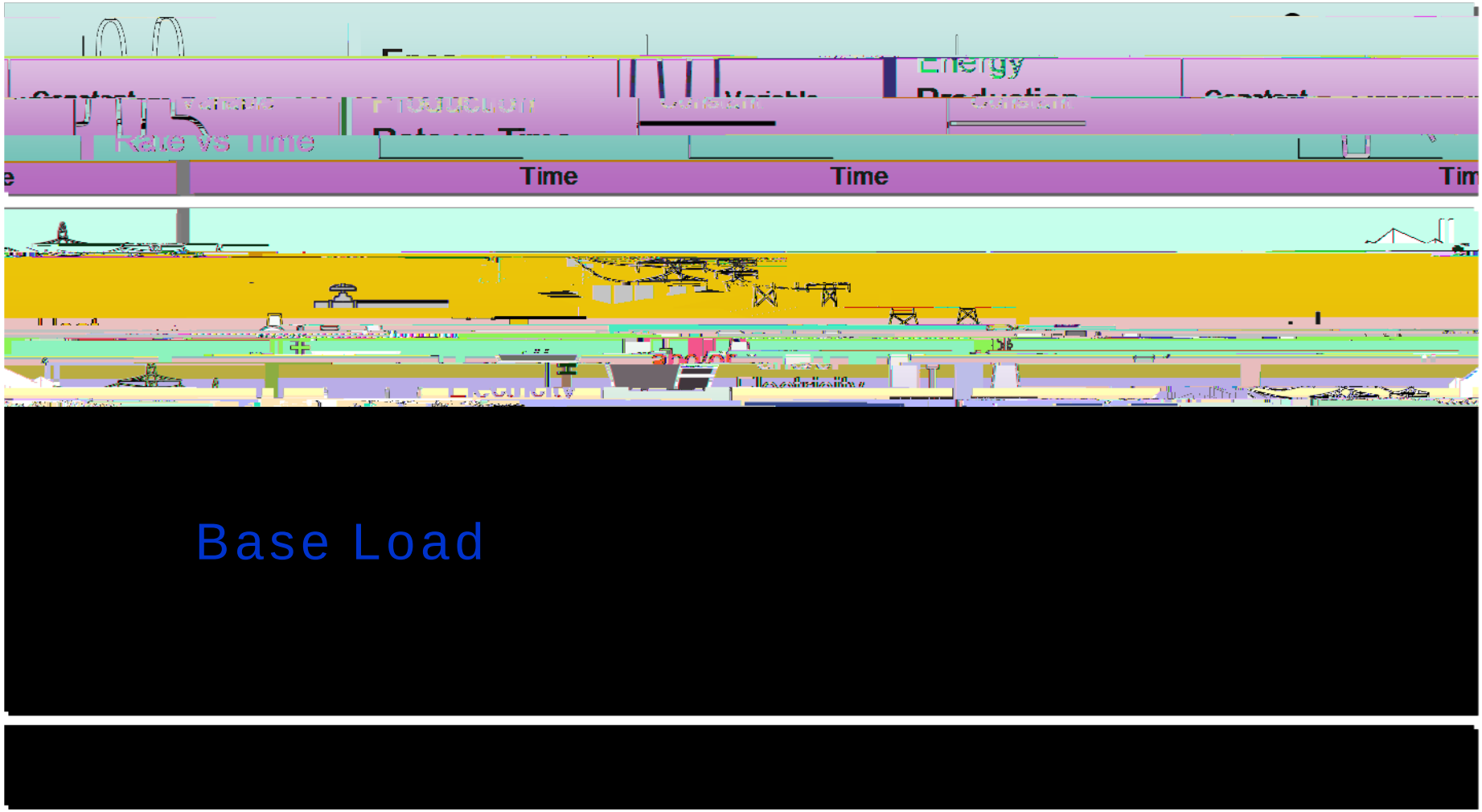
Fossil Fuels are Used Today to Match Electricity Demand with Production

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



- **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

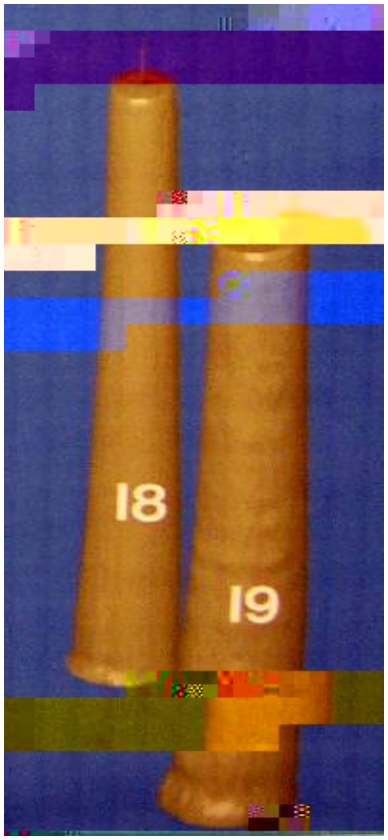
- **Near term**
  - **Electrolysis**
  - **Electricity supply options**
    - **Base load**
    - **Night time and surplus renewables**
- **Longer term**
  - **High-temperature electrolysis**
  - **Hybrid**
  - **Thermochemical**

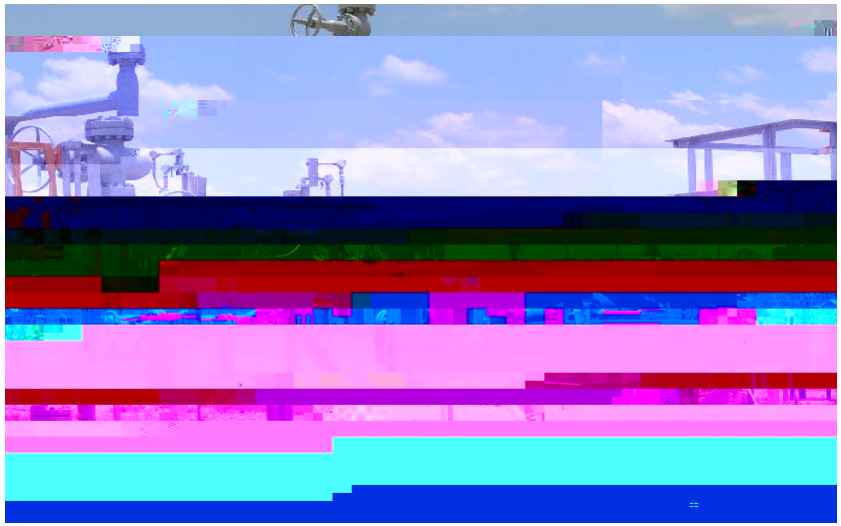
Norsk Atmospheric Electrolyser

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**





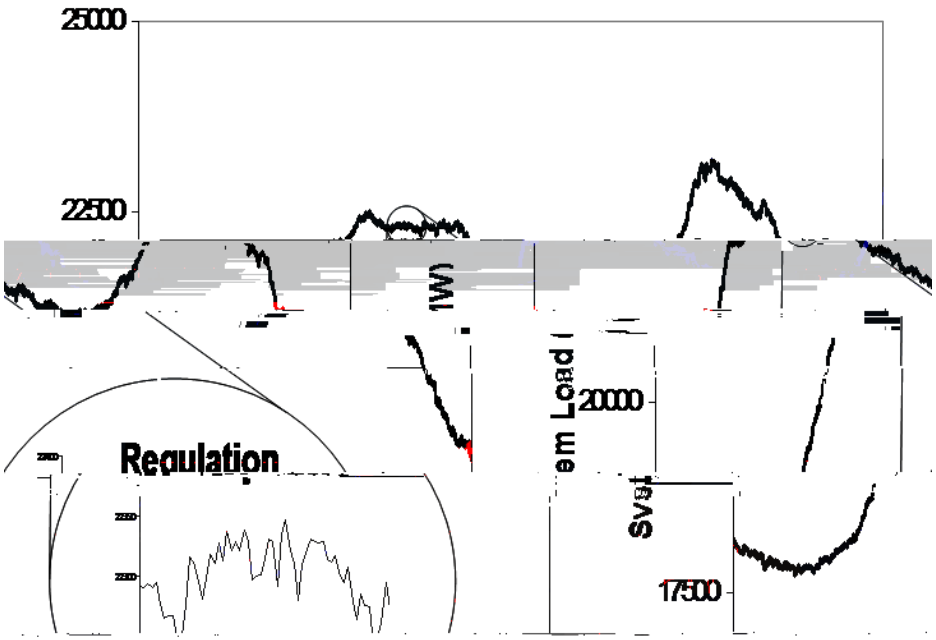
Use Same Technology for Oxygen Storage

steam

Oxy-HyTurbine for Electricity2aox

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

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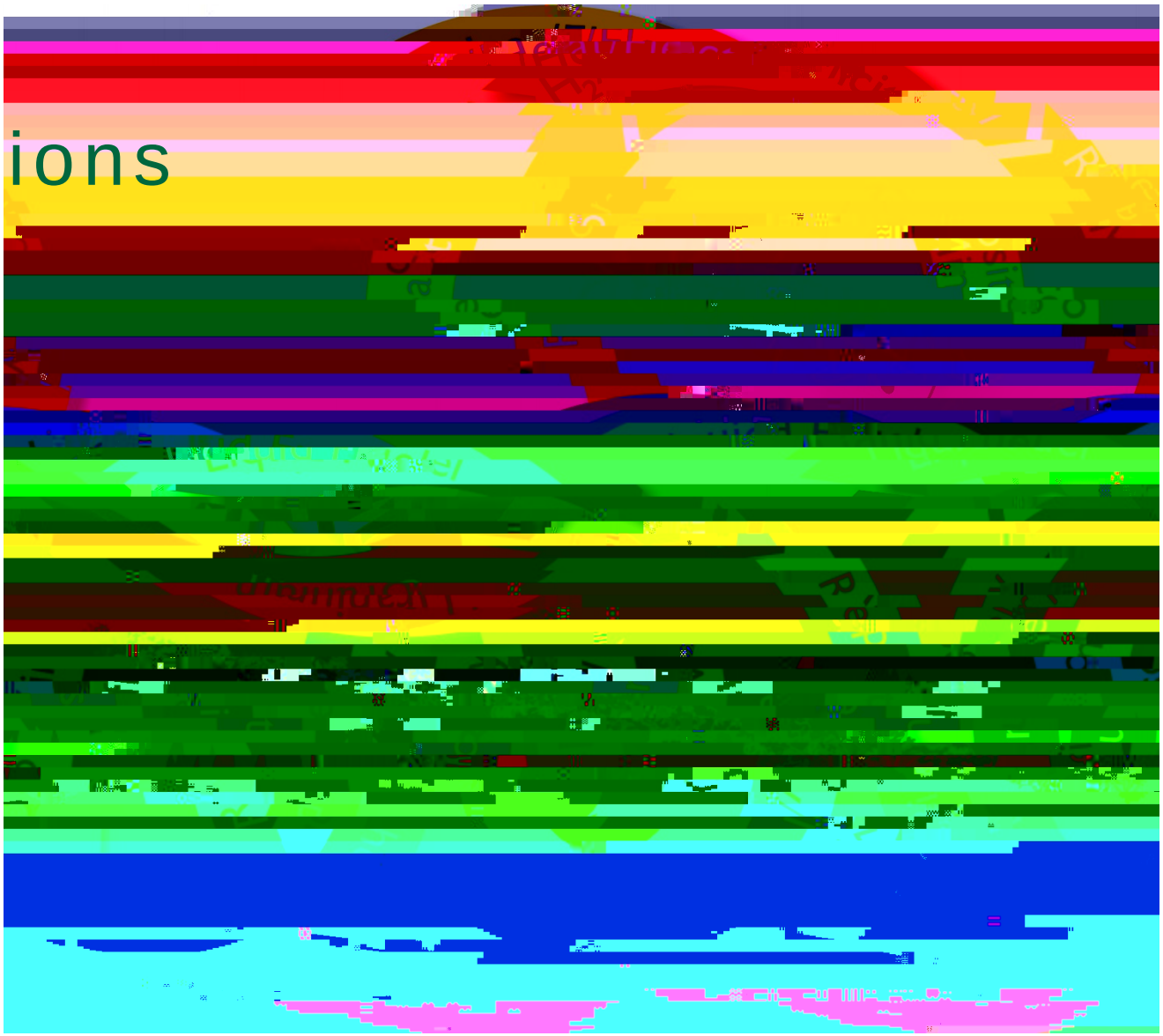
Conclusions

- **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



—Abstract—

Combining Nuclear, Renewable, and Fossil Fuel Cycles For Sustainability

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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,

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.