Combined Nuclear, Renewable, and Fossil Fuel-Cycles For Sustainability: Implications for Research

Charles Forsberg

Corporate Fellow
Nuclear Science and Technology Division
Oak Ridge National Laboratory
forsbergcw@ornl.gov; (865) 574-6783

Opportunities for Fundamental Research and Breakthroughs in Fission
Massachusetts Institute of Technology
Cambridge, Massachusetts
Thursday, November 29, 2007

*Managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725. The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes. File name: MIT Nuc Renewable Fossil Fuel Cycles

Outline

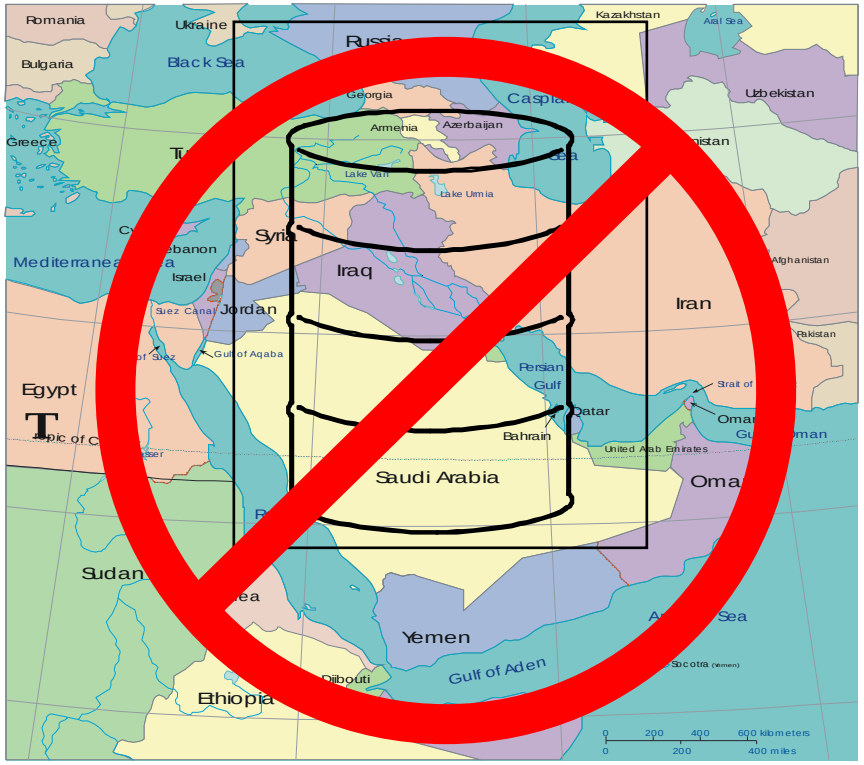
Goals and Strategies
Combined Fuel Cycles

Nuclear-Fossil Liquid Fuels
Nuclear-Biomass Liquid Fuels
Nuclear-Renewable Electricity

Research Implications

Two Goals are Likely to Determine What is Required for Sustainability

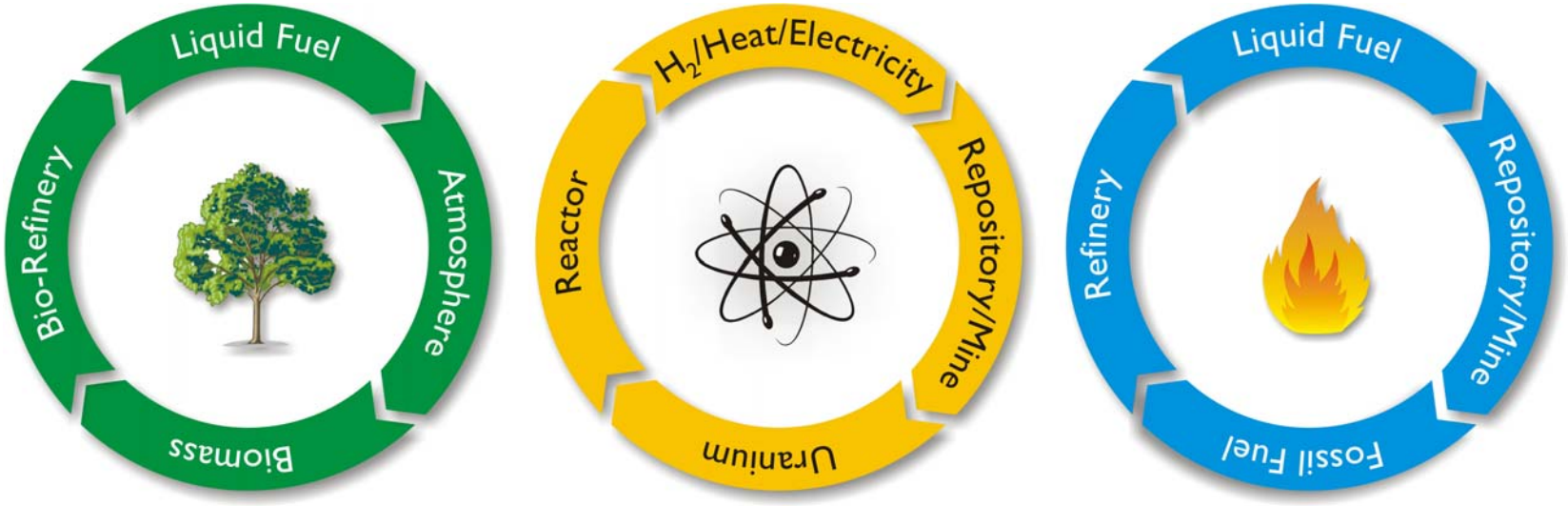
No Crude Oil



No Climate Change

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

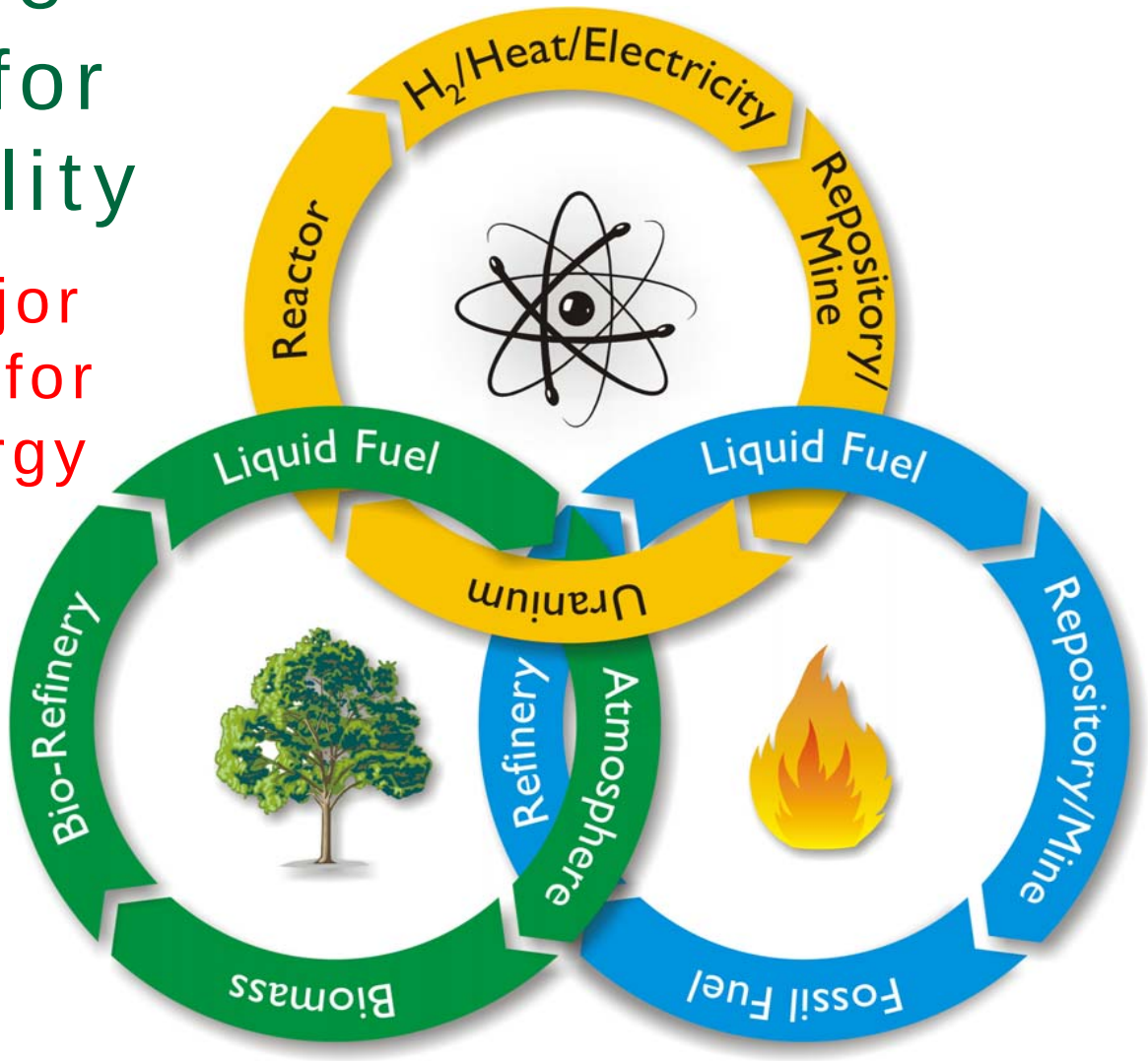
Traditional Sustainability Strategies Treat Each Fuel Cycle Separately



Separate Fuel Cycles will Not Eliminate Oil or Stop Climate Change

Combined Fuel Cycles are Required for Sustainability

That has Major Implications for Nuclear Energy

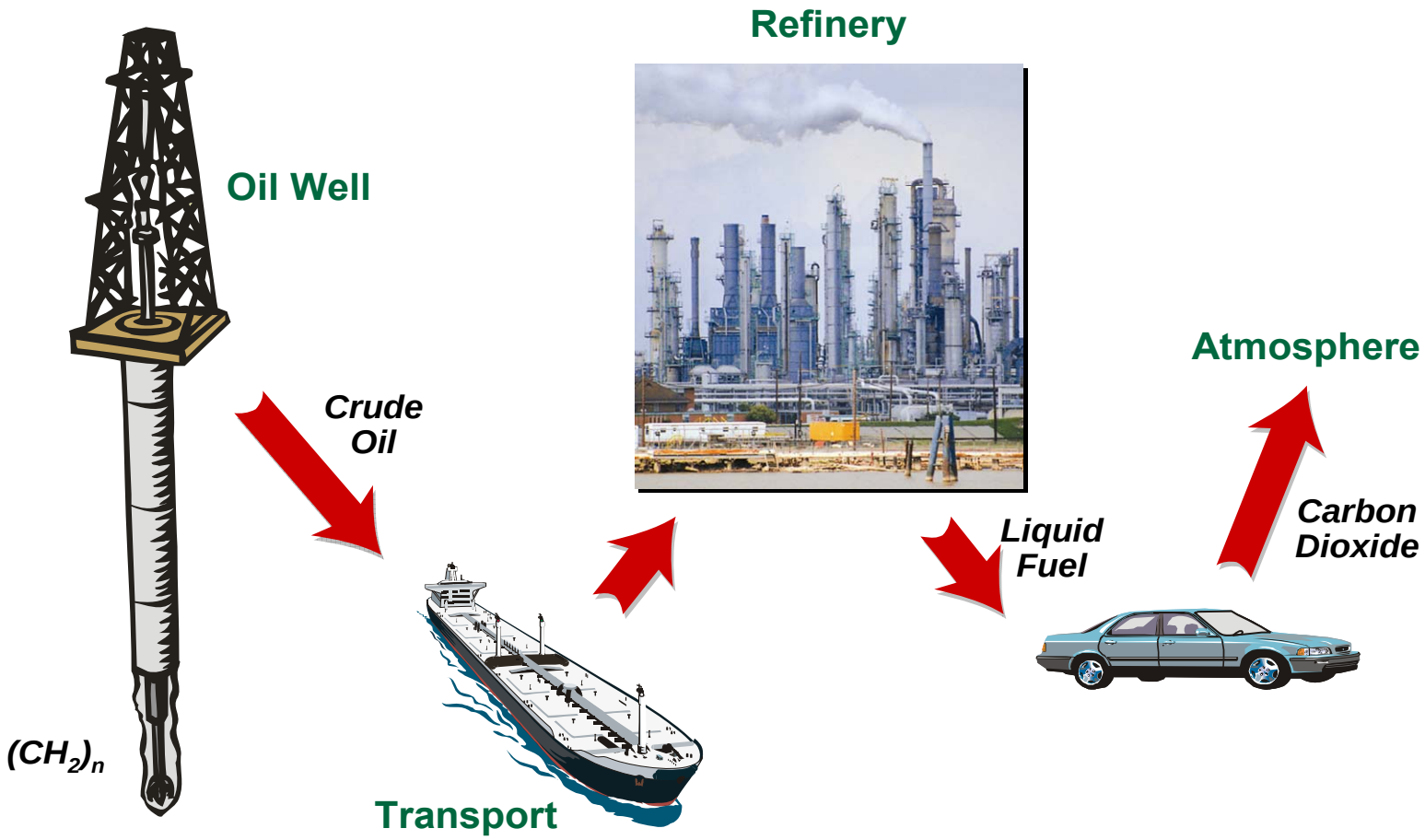


Examples of Combined Fuel Cycles

Example: Combined Nuclear-Fossil Liquid-Fuels Fuel Cycle

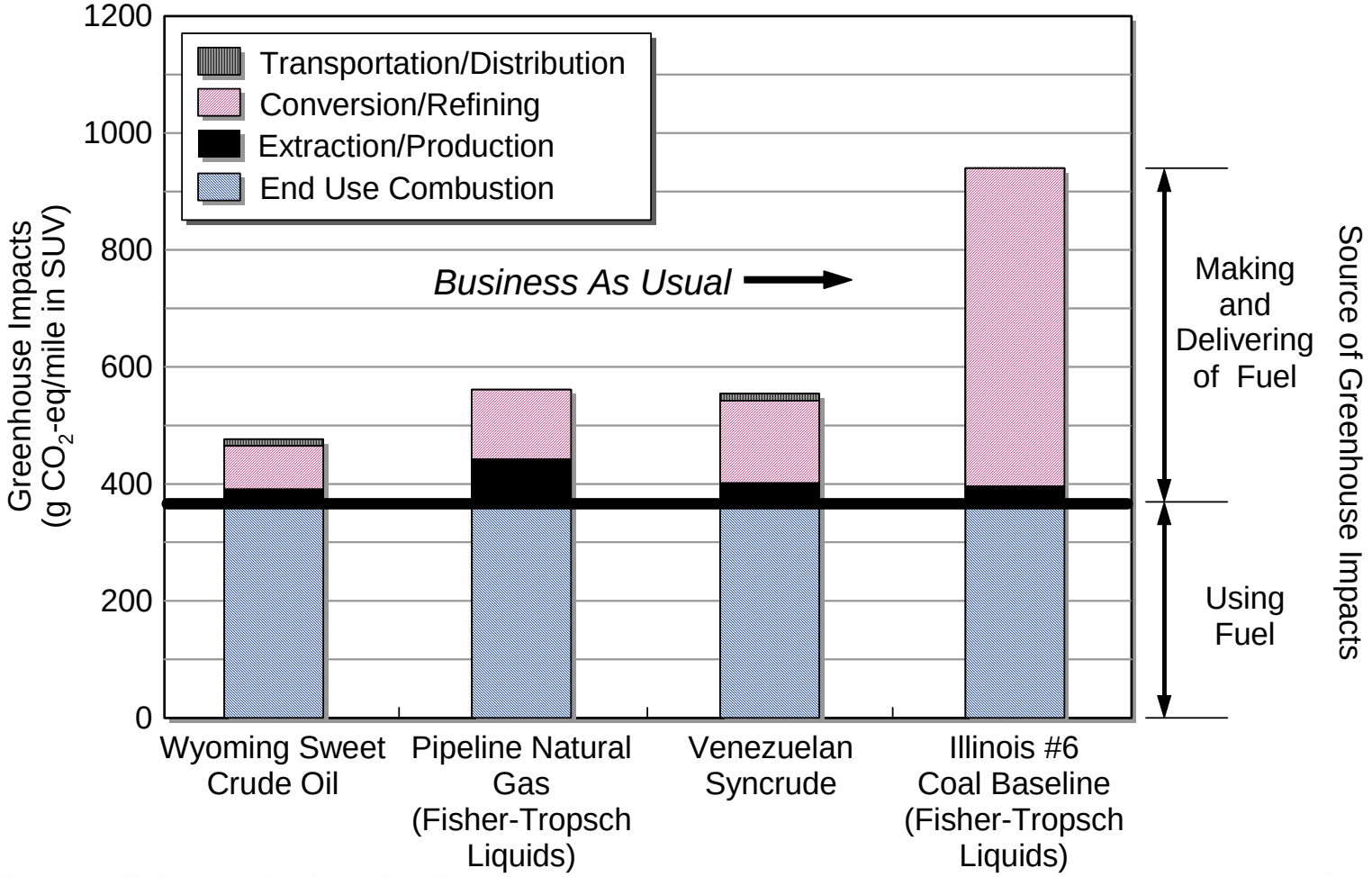
Underground Refining

Liquid-Fuels Fuel Cycle for Crude Oil



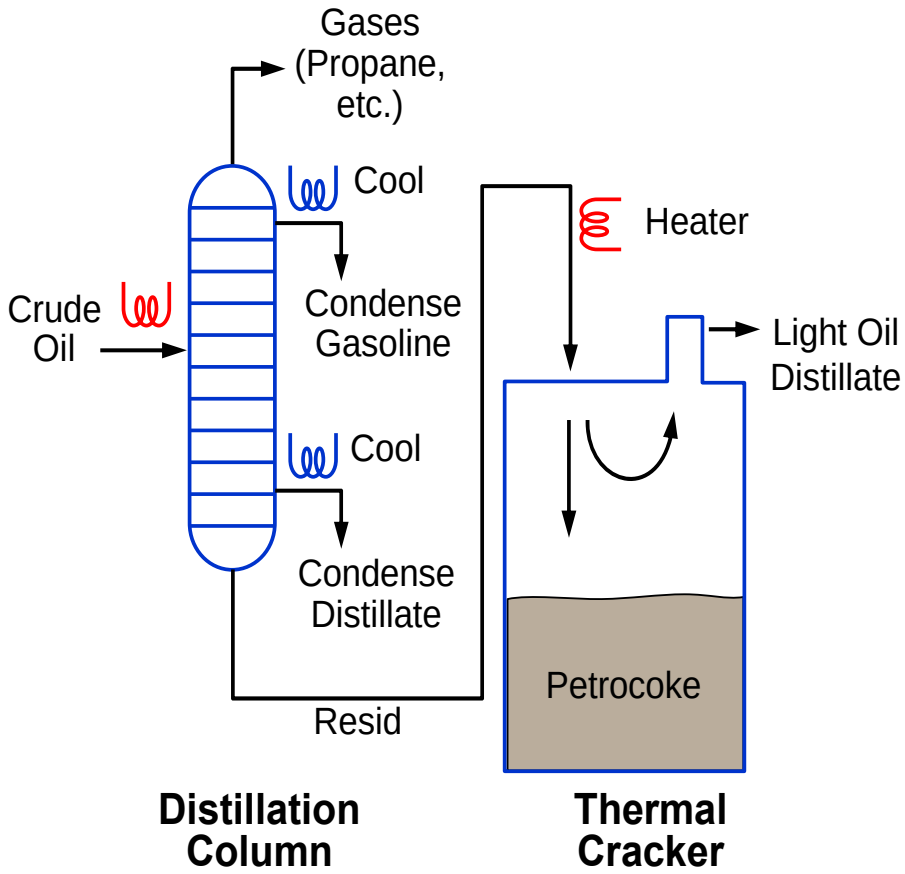
Conversion of Fossil Fuels to Liquid Fuels Requires Energy

Greenhouse Gas Releases and Energy Use Increase As Use Lower-Quality Feedstocks

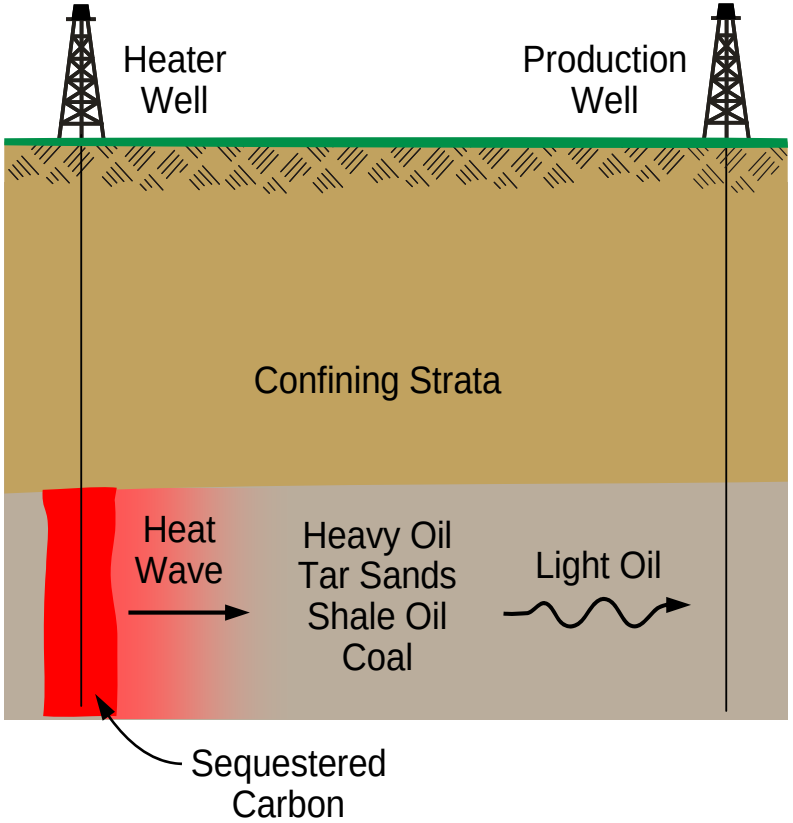


An Alternative: Underground Refining

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



Traditional Refining

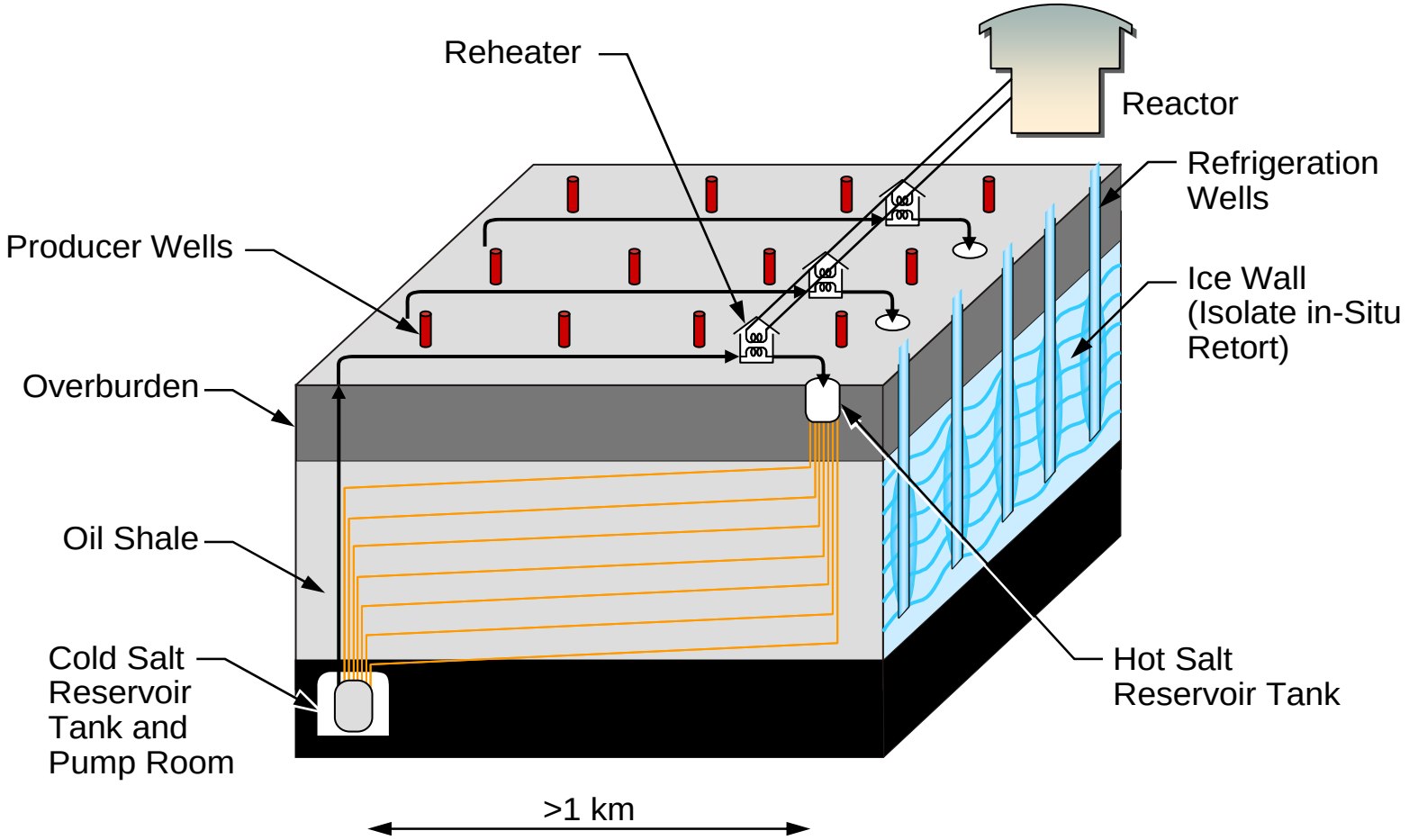


In-Situ Refining

In-Situ Refining May Require a Nuclear Heat Source

Nuclear-Heated In-Situ Oil-Shale Conversion Process

Liquid-Salt Intermediate Heat-Transport Loop

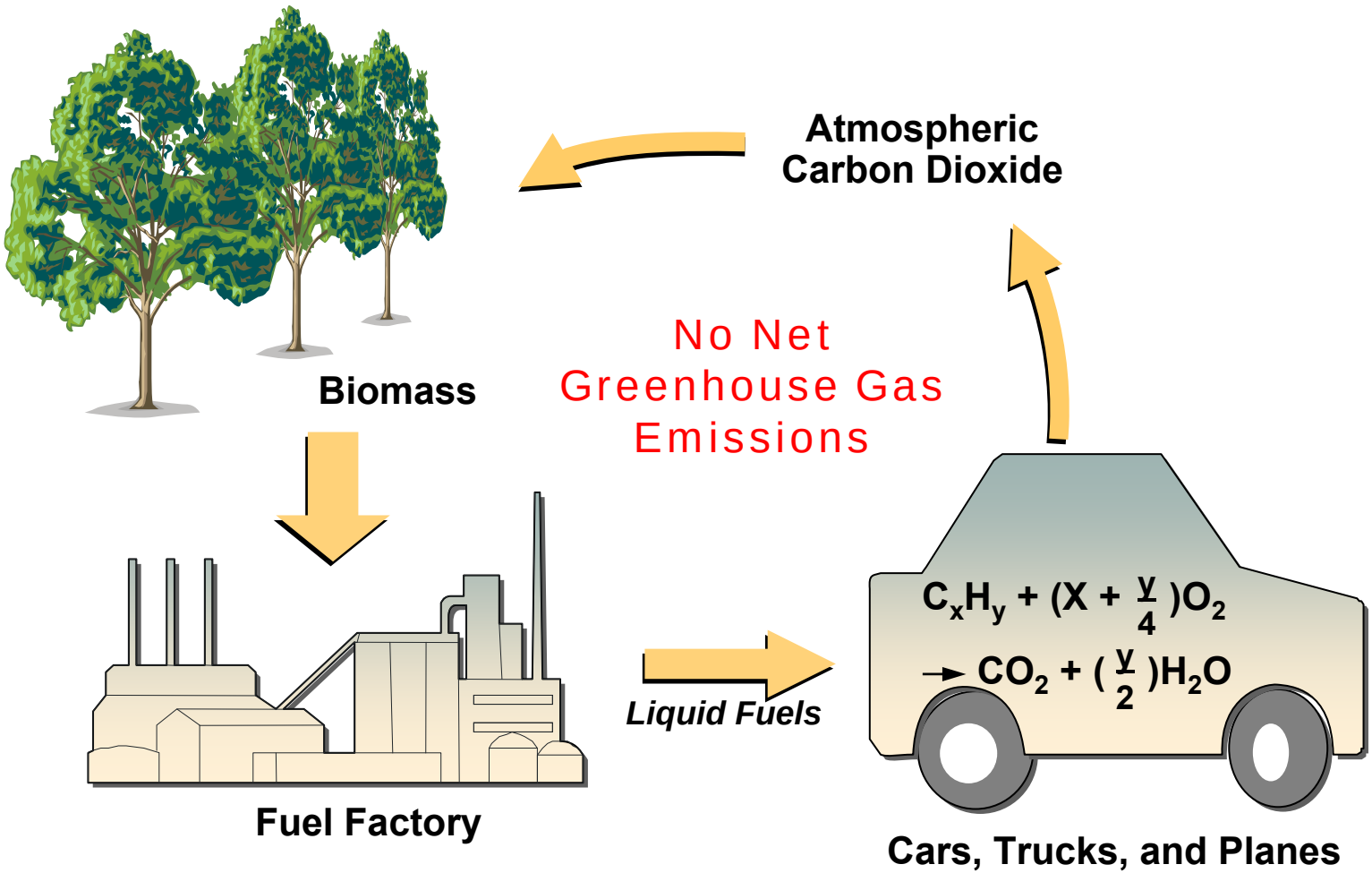


Example: Combined Nuclear-Biomass Liquid-Fuels Fuel Cycle

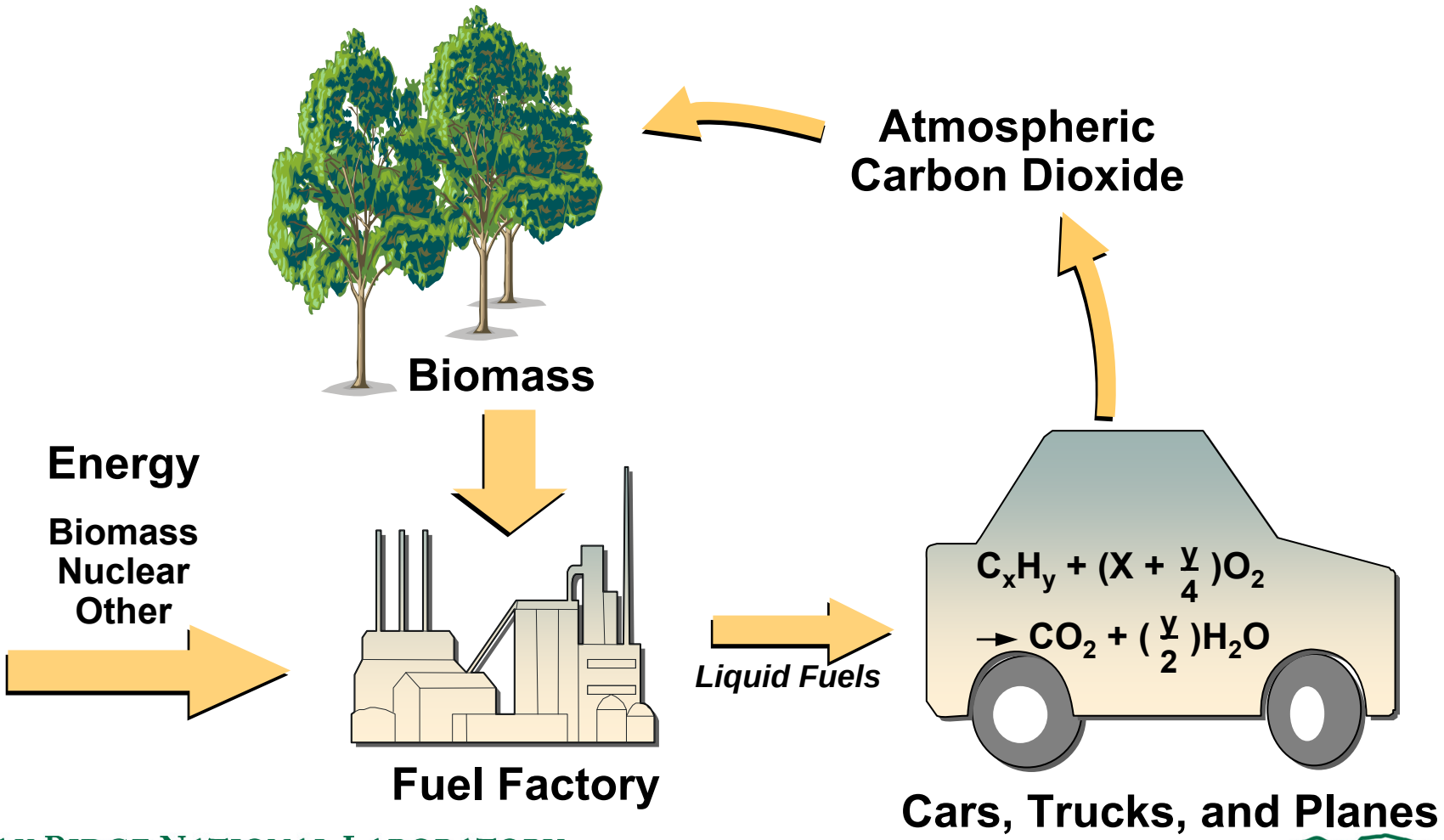
Process Energy from a Nuclear Reactor

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

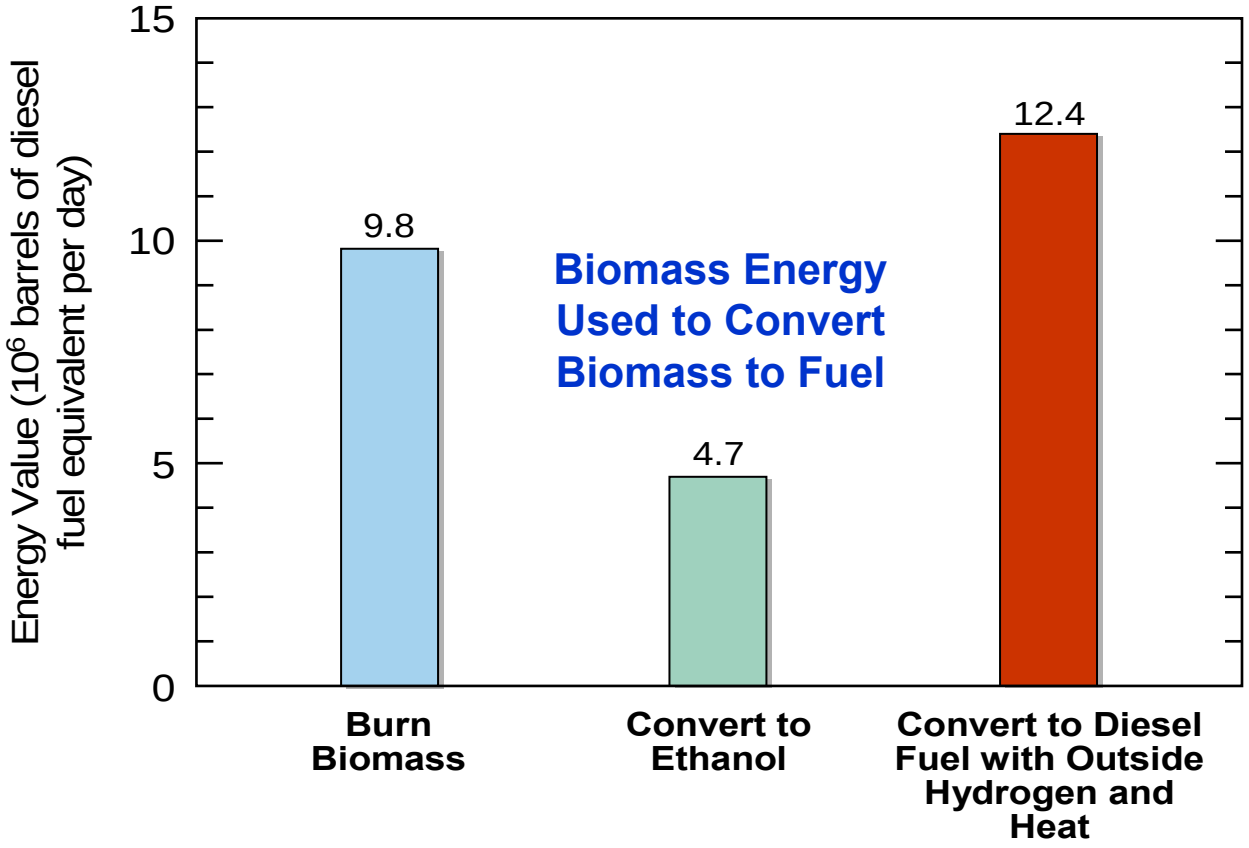


1.3 Billion Tons Biomass are Available per Year to Produce Liquid Fuels

Available Biomass without Significantly Impacting U.S. Food, Fiber, and Timber

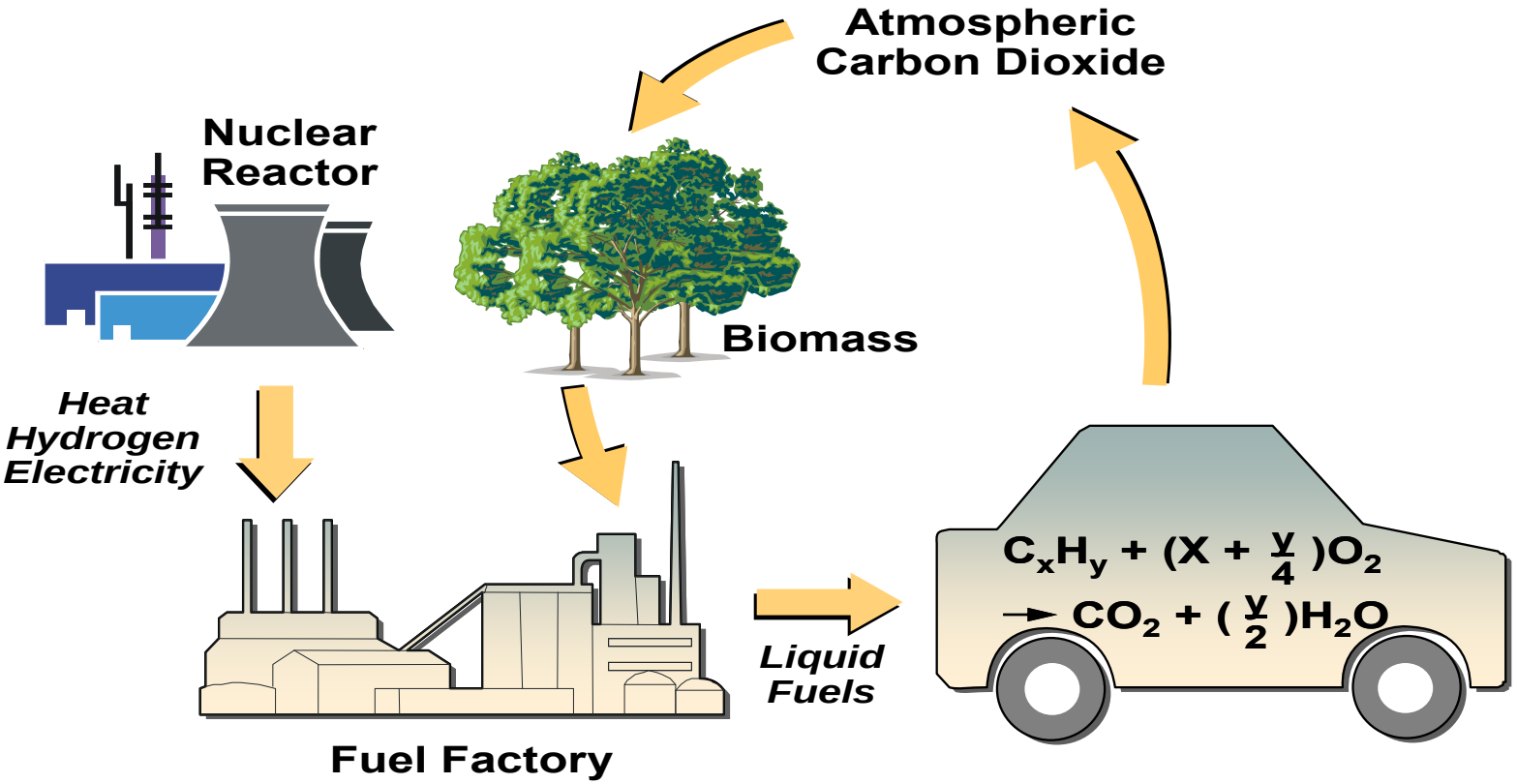
Liquid Fuel Value From Biomass Depends Upon How It is Processed

Measured in Equivalent Barrels of Diesel Fuel/Day



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

The Nuclear-Hydrogen-Biomass Liquid-Fuel Cycle



If Nuclear Energy Provides Energy to Operate Fuel Factories, Sufficient Biomass Liquid Fuels To Replace Oil-Based Transport Fuels

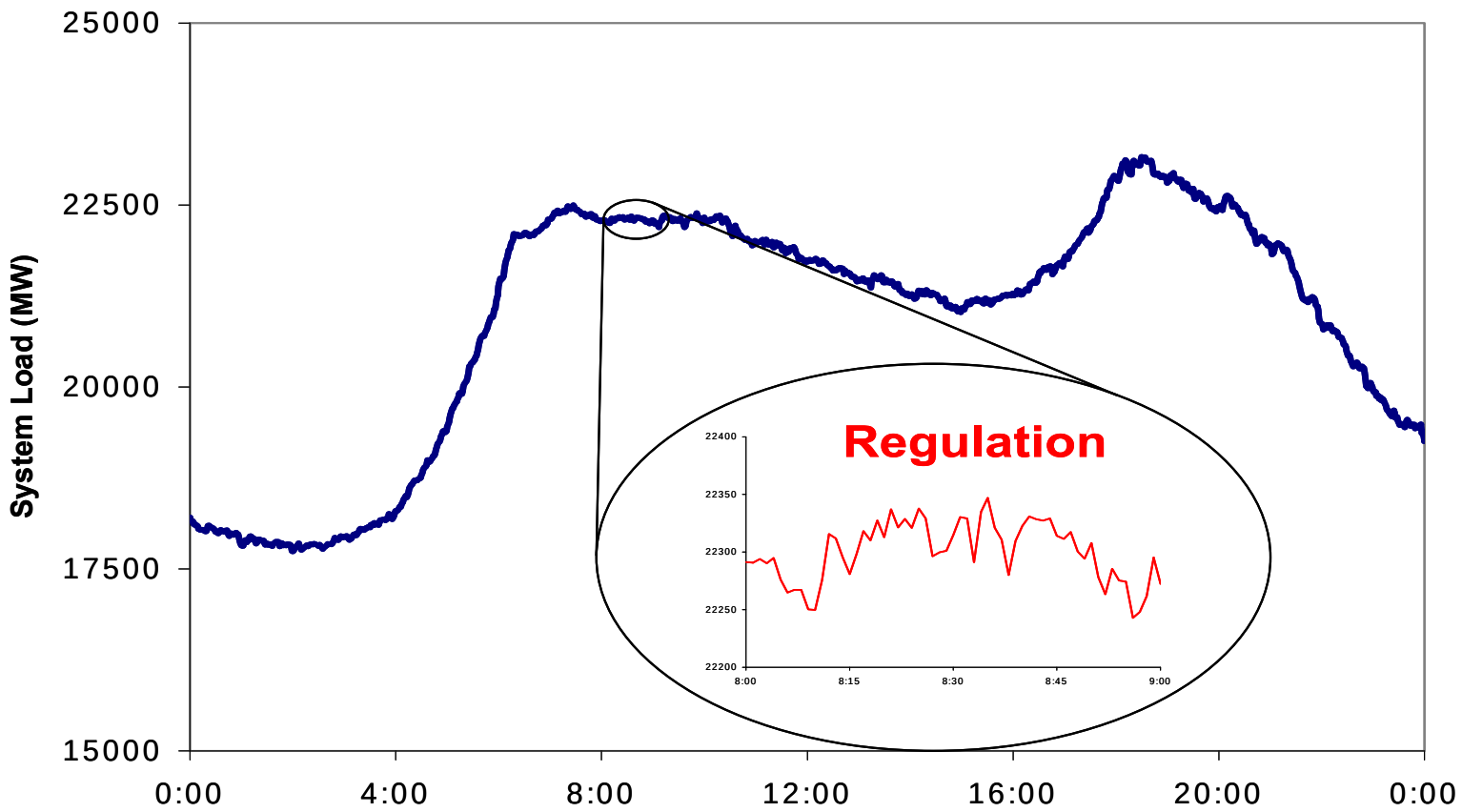
Example: Combined Nuclear-Renewable Electricity

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.

Electricity Demand Varies with Time

Example: Daily Cycle

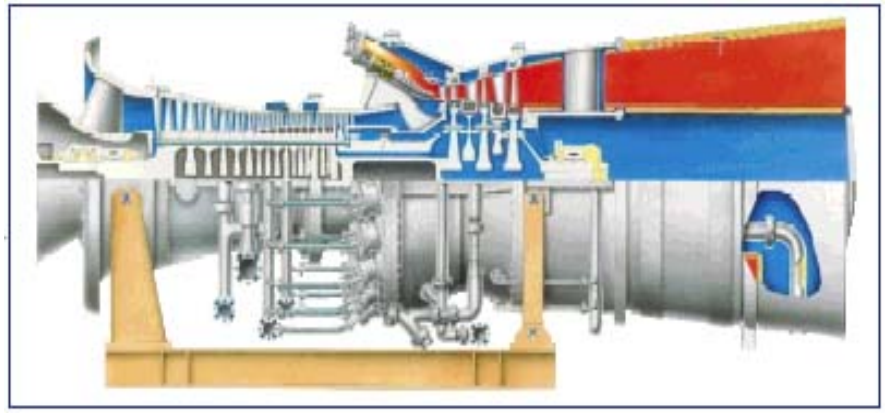


Large-Scale Renewable Electric Production may not be Viable without Electricity Storage

- **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**

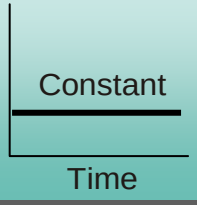
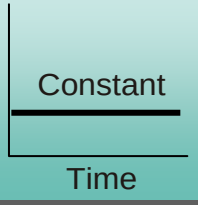
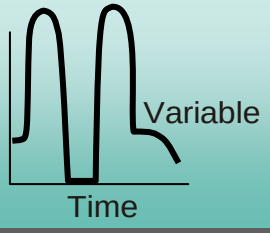
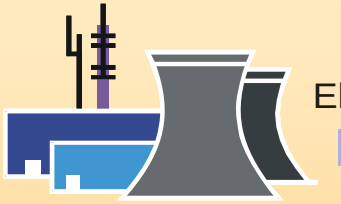
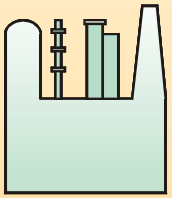
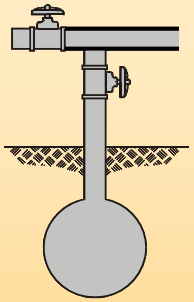
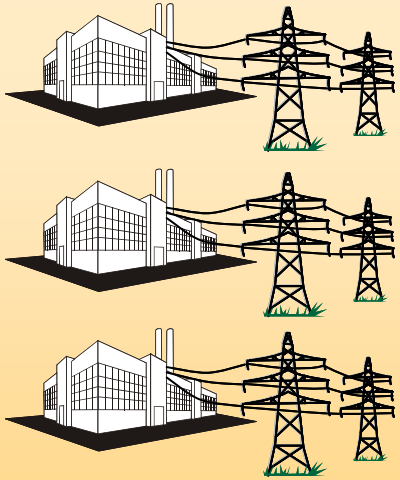
Fossil Fuels are Used Today to Match Electricity Demand with Production

- **Fossil fuels are <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)

Energy Production Rate vs Time				
Facility		Heat and/or Electricity  $2H_2O \rightarrow 2H_2 + O_2$		
	Nuclear Reactor	***H_2 Production***	***Underground Hydrogen/Oxygen (Optional) Storage***	***Fuel Cells, Steam Turbines, or Other Technology***
Relative Capital Cost/KW	$$$$	$$	$	$$

Nuclear Hydrogen Production Options

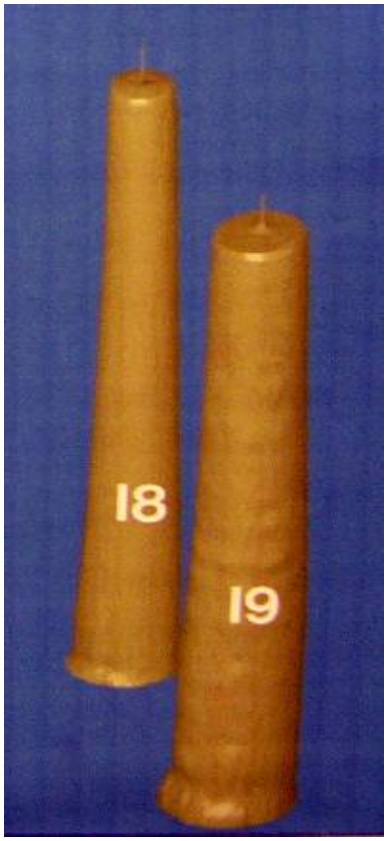
- **Near term**
  - **Electrolysis**
  - **Electricity supply options**
    - **Base load**
    - **Night time and surplus renewables**
- **Longer term**
  - **High-temperature electrolysis**
  - **Hybrid**
  - **Thermochemical**

Norsk Atmospheric Electrolyser

Key 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, where one-third of a year's supply is in storage in the fall**

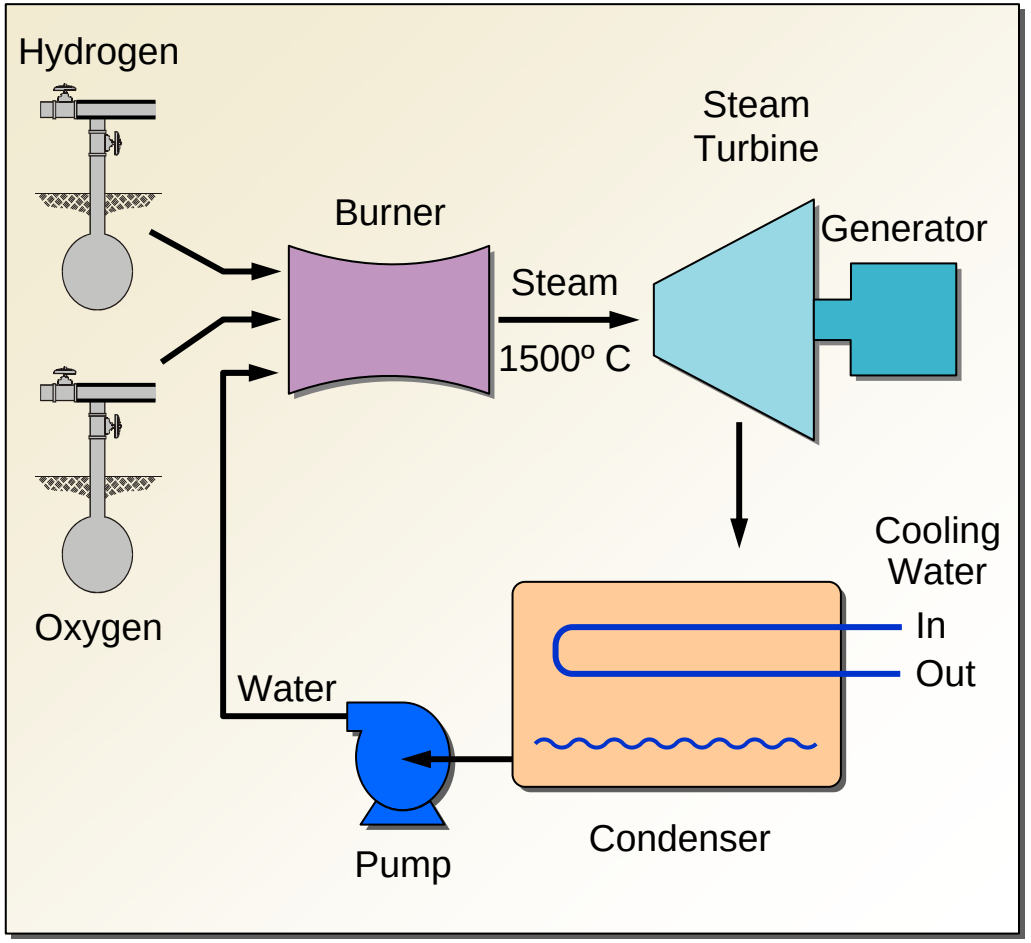


Use Same Technology for Oxygen Storage

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**



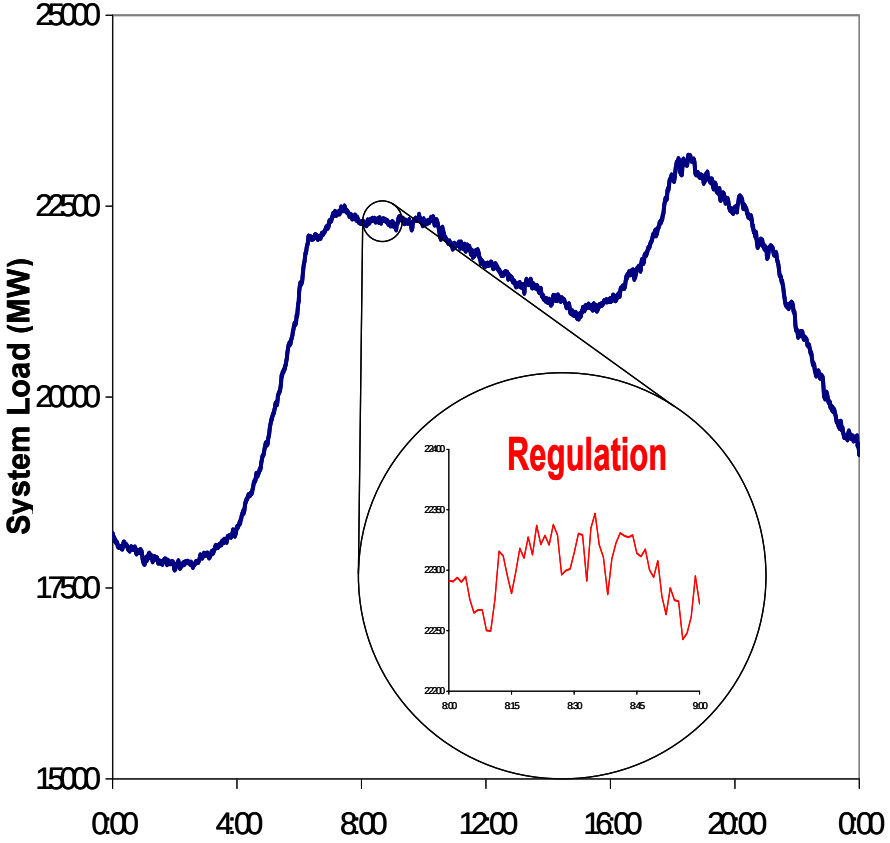
Oxy-Fuel Combustors Are Being Developed for Advanced Fossil Plants

- **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)

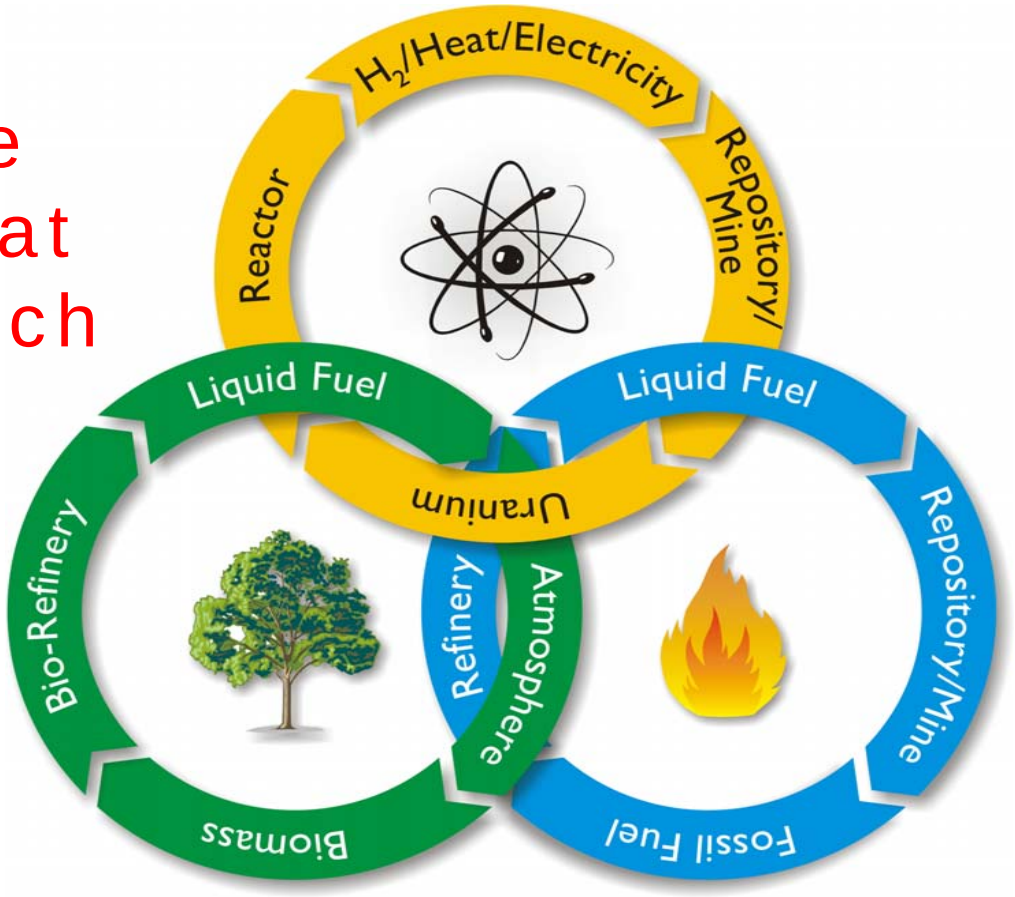
HIPES may Enable Large-Scale Nuclear-Renewable Electricity

- **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 Research

Goals Determine Requirements That Determine Research Needs



New Requirements for Sustainable Nuclear Combined Cycles

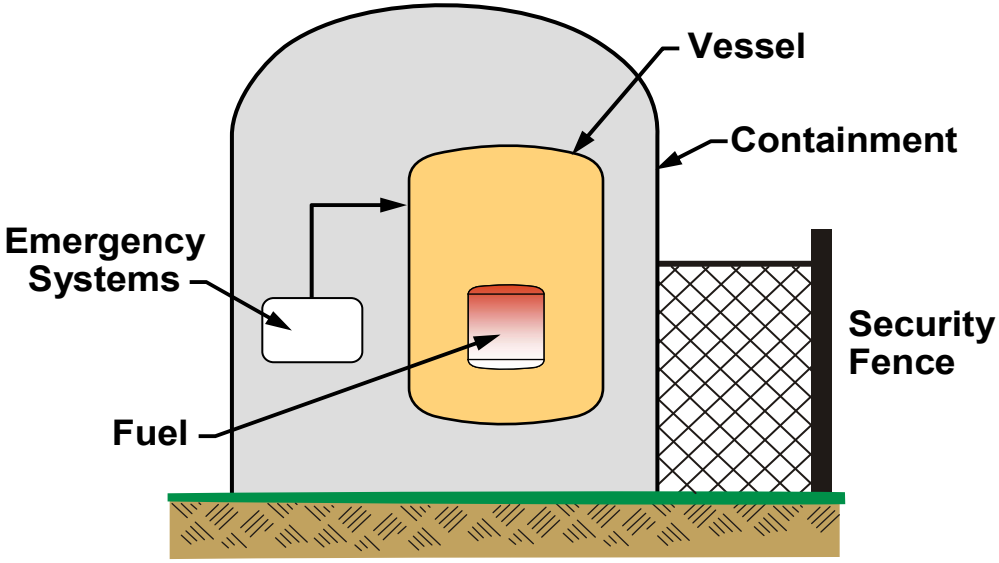
Nuclear Fossil Renwables Fuel Cycles

- **Need for smaller reactors (600-MW(t))**
  - **Underground refining heat demand per acre limits reactor size**
  - **Cost of biomass transport limits transport distances and thus the size of reactor**
  - **Peak-power unit size limited**
- **Economics of small reactors require changes in nuclear technologies**
  - **Site security costs must be controlled**
  - **Safety systems must be simplified**

Combined Cycles may Require Alternative Nuclear Reactor Designs

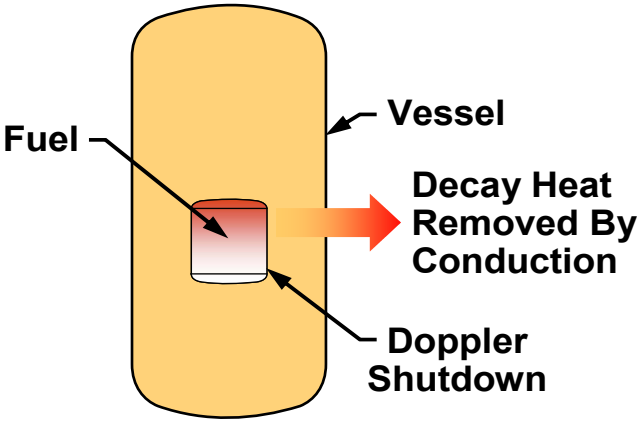
Goal: Lower Costs with Limits on the Size of Operating Crews and Security Forces

Traditional



Nuclear Systems Protects Fuel and Public

"Fuel-Based" Advanced System



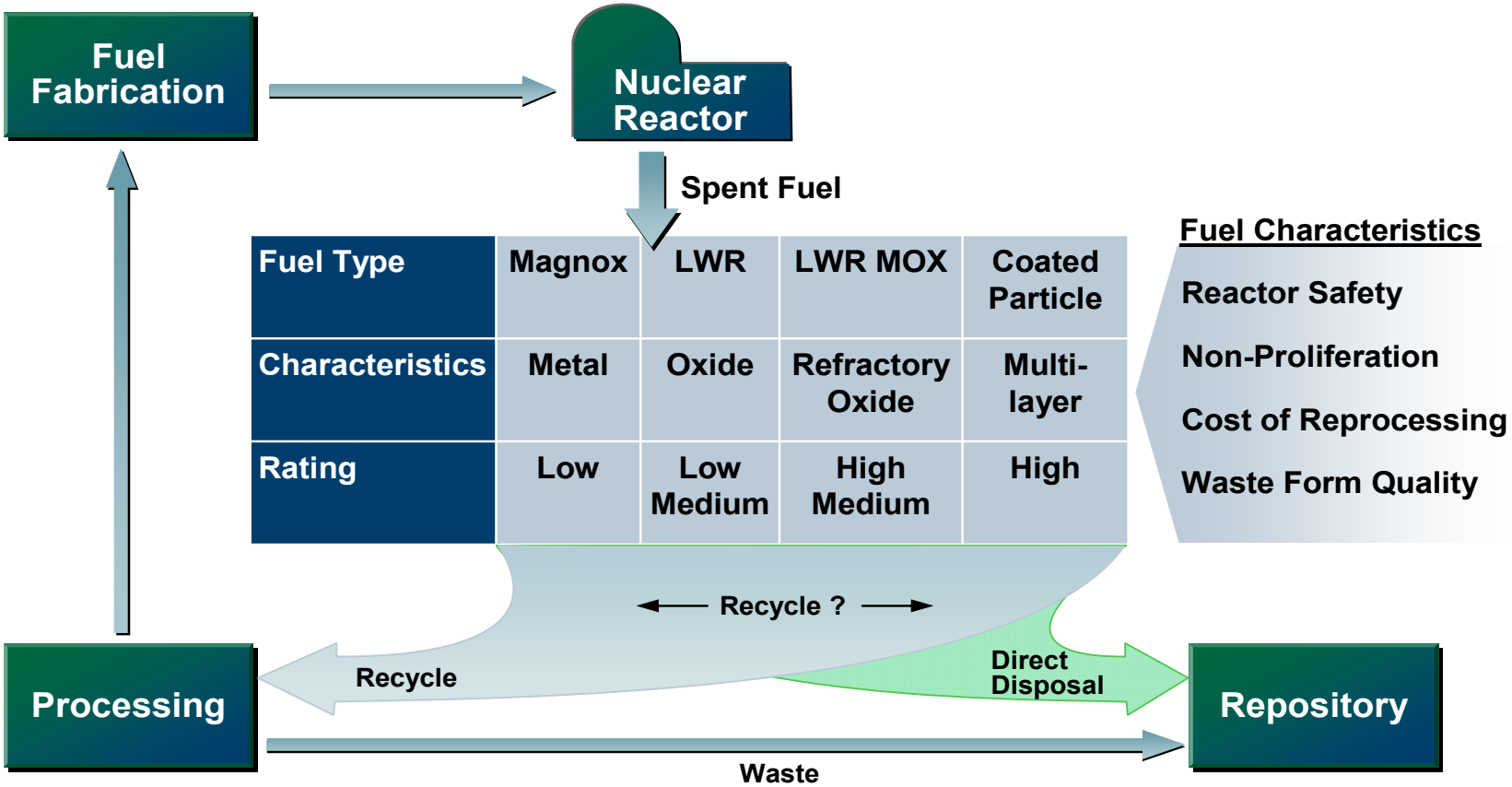
Fuel Protects Nuclear System and Public

Goal: "Indestructable" Fuel

"Indestructible" or "Abuse-Resistant" Fuel May Be Needed for Nuclear-Fossil-Renewable Fuel Cycles

- **Desired characteristics**
  - **High-temperature capabilities for accidents**
  - **No significant radionuclide dispersion under extreme conditions**
    - **Fire**
    - **Assault resistant (shock waves, etc.)**
    - **Crushing**
  - **Proliferation resistant (Low enrichment, high-burnup, difficult to process)**
- **Goals imply fuels with large inert component fractions to meet multiple requirements**
  - **Coated particle**
  - **Cermets**

Alternative Nuclear Reactor Designs may Imply Alternative Fuel Cycles



Fuel Type	Magnox	LWR	LWR MOX	Coated Particle
Characteristics	Metal	Oxide	Refractory Oxide	Multi-layer
Rating	Low	Low Medium	High Medium	High

"Abuse-Resistant" Fuel Characteristics with High Processing Cost May Favor Direct Disposal

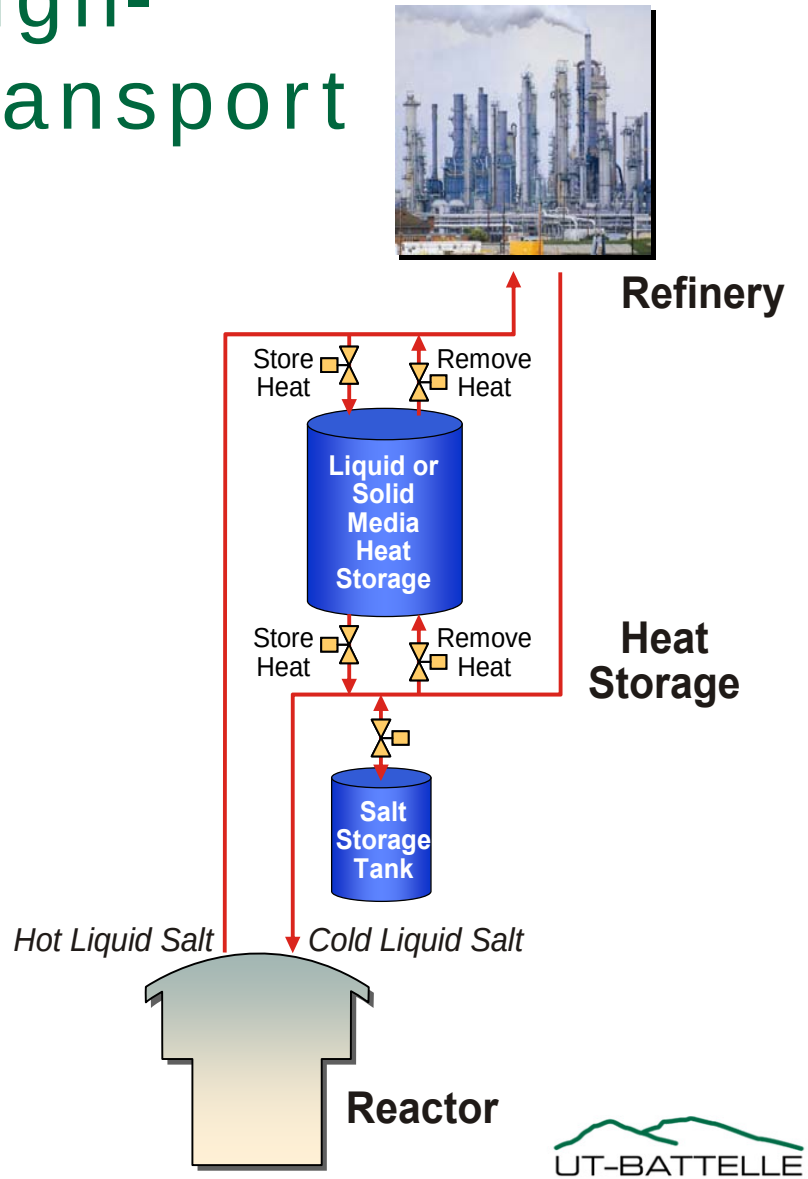
New Requirements for Sustainable Nuclear Combined Cycles

Nuclear Fossil Biomass Renewable Fuel Cycles

- **Need for high-temperature reactors**
  - **Underground refining**
  - **Biomass processing**
  - **Hydrogen production**
- **Requirements**
  - **Most applications meet with ~700°C reactor**
  - **Some applications may require higher temperatures**

Combined Cycles Require Long-Distance High-Temperature Heat Transport

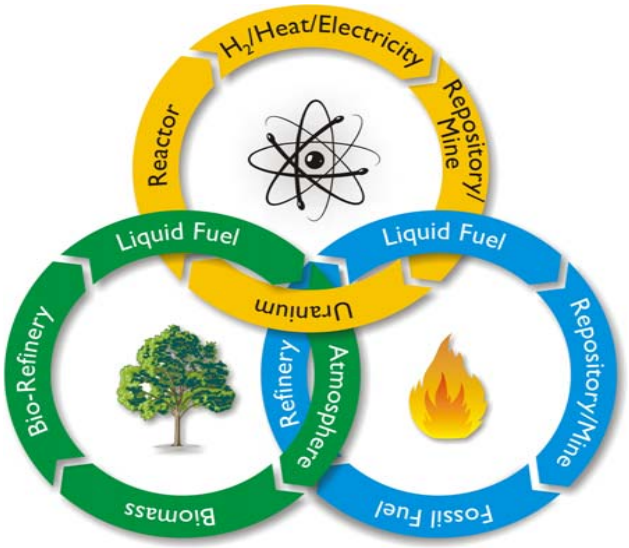
- Multiple nuclear high-temperature heat applications
  - Underground refining
  - Hydrogen production
  - Biomass processing
- No commercial heat transfer fluids above 600°C for kilometer-long heat transfer
- Multiple candidates in the laboratory
  - Fluoride salts
  - Chloride salts
  - Etc.



Non-Nuclear Research Challenges for Specific Nuclear-Fossil-Renewable Combined Cycles

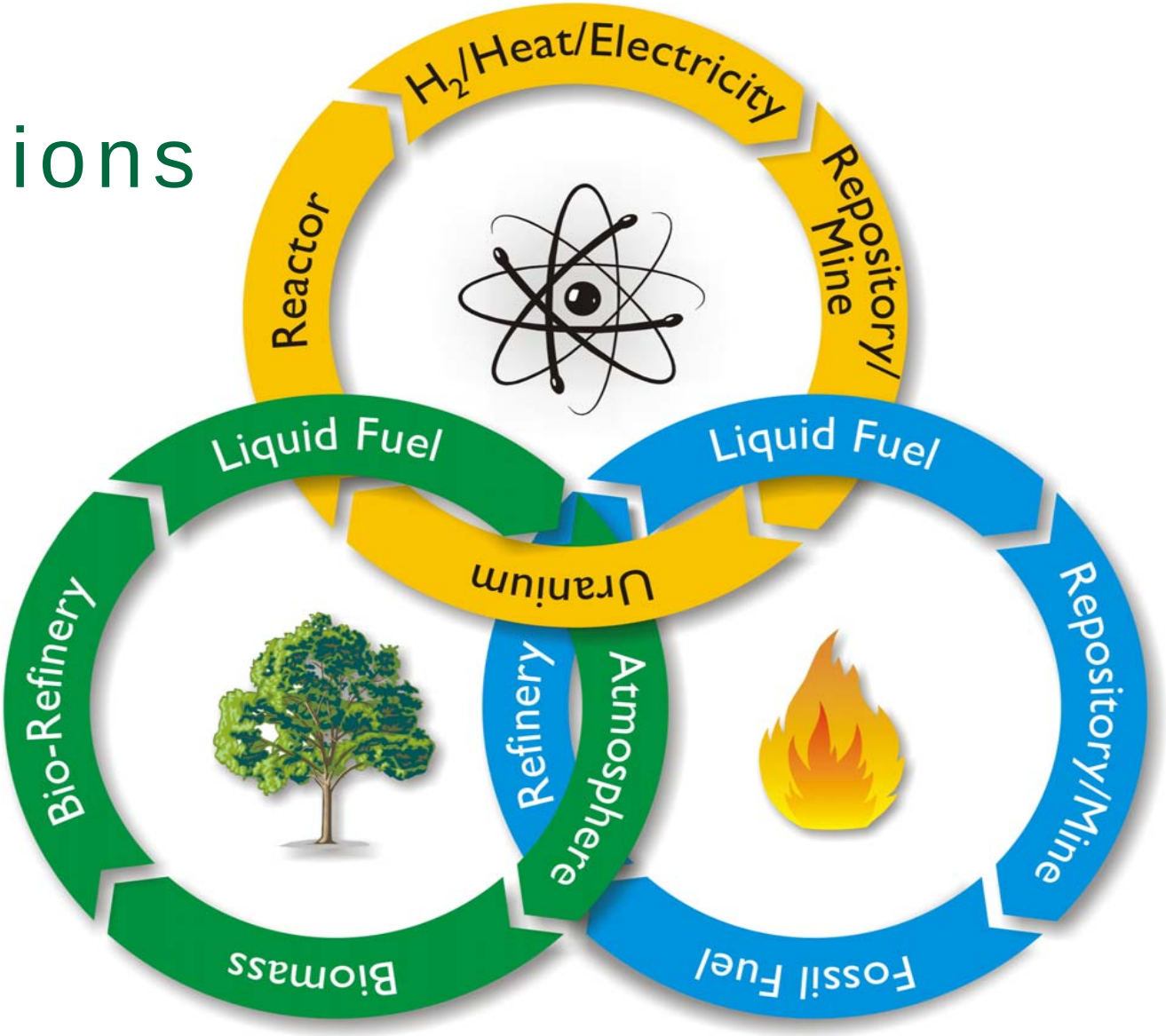
- **Nuclear-Biomass to Liquid Fuels**
  - **Hydro cracking of lignin biomass to gasoline**
  - **Direct hydrogenation of cellulosic feedstock to hydrocarbons gasoline and diesel**
- **Underground Refining**
  - **High-temperature heat-transfer loops**
- **Nuclear-Renewable Peak Electricity**
  - **Underground oxygen storage**
  - **Hydrogen production**

Conclusions



- **Sustainability goals**
  - **No oil consumption**
  - **No climate change**
- **Sustainability will require integration of fossil, biomass, and nuclear fuel cycles**
- **Combined fossil, renewable, nuclear fuel cycles create requirements for nuclear reactors**
- **Sustainability may require reactors with "abuse-resistant" fuels**
- **Non-nuclear supporting technologies must also be developed**

Questions


H_2/Heat/Electricity
Reactor
Repository/ Mine
Liquid Fuel
Liquid Fuel
Uranium
Bio-Refinery
Refinery
Atmosphere
Repository/Mine
Biomass
Fossil Fuel

Backup Slides

Backup Slides

Backup Slides

—Abstract—

Combining Nuclear, Renewable, and Fossil Fuel Cycles for Sustainability: Implications for Research

Charles W. Forsberg; Oak Ridge National Laboratory; Tel: (865) 574-6783; E-mail: forsbergcw@ornl.gov

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, 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 without moving it from the original underground deposits. This would significantly reduce greenhouse gas releases per vehicle mile by eliminating most of the greenhouse gas releases from producing and converting fossil fuels into transport fuels. Underground refining requires high-temperature heat that could be provided by high-temperature nuclear reactors.

Biomass fuel cycles. The use of biomass for production of liquid fuels and chemicals avoids the release of greenhouse gases. However, U.S. 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.

Renewable electric fuel cycles. The central challenge of renewable electricity is the need to provide electricity when the sun does not shine and the wind does not blow. One strategy is the production of oxygen and hydrogen using nuclear energy, storing these gases underground, and using these gases to produce peak electricity in a special steam cycle where the oxygen and hydrogen are combined to directly produce high-pressure steam. The low-cost gas storage combined with a low-cost method to convert it to electricity may provide the backup for larger scale use of renewable electricity

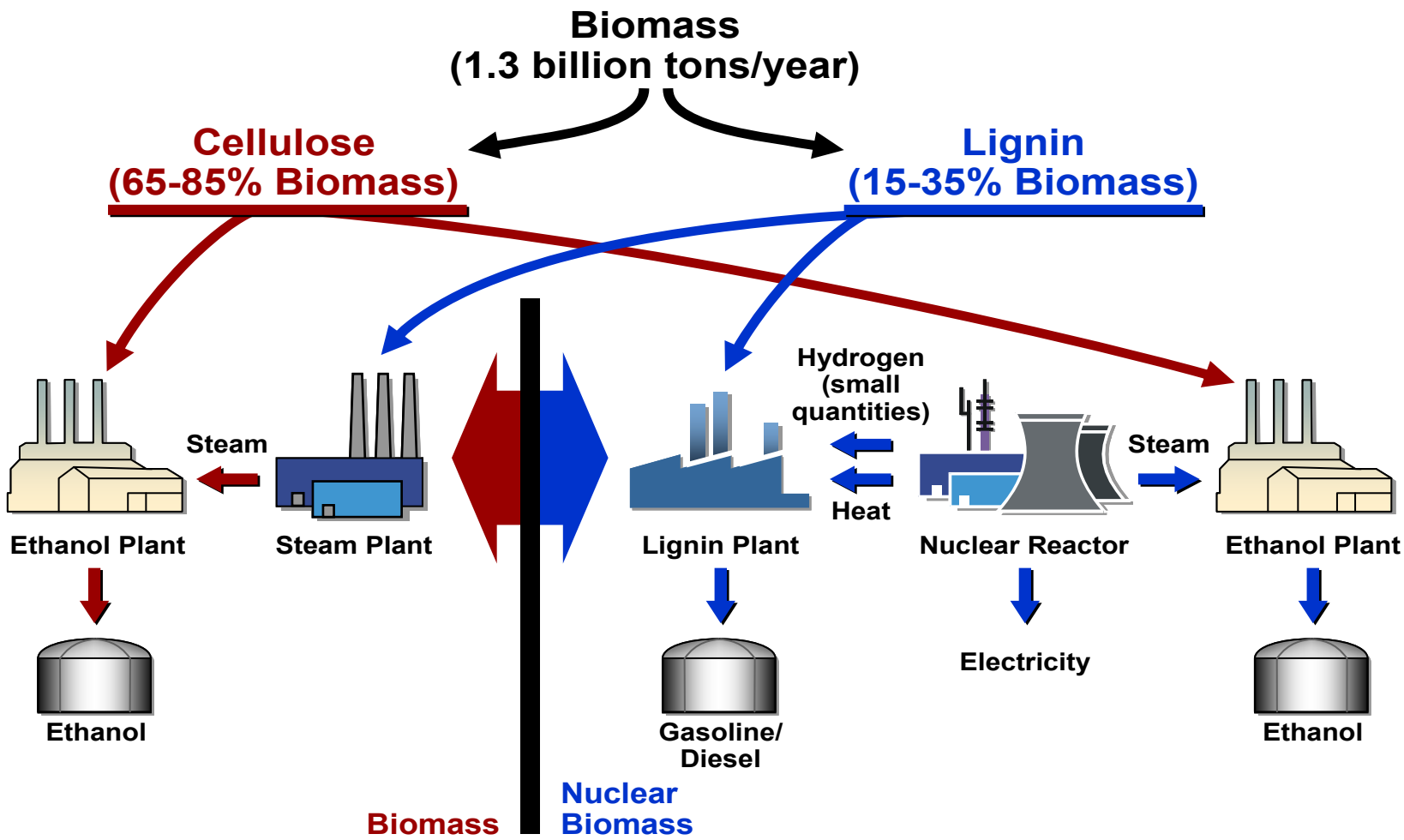
Nuclear fuel cycles. For many of these applications, smaller reactors are required. If such reactors are to be economic, a different design approach is required. The size of the reactor security and operating staff must be reduced as must the capital costs. One strategy is the development of “indestructible” or “abuse resistant” fuel. In traditional nuclear reactors, various nuclear systems protect the fuel against damage and protect the public. The alternative strategy is to develop fuels to protect the reactor system and the public. In effect, the safety and security requirements become part of the fuel rather than primarily systems in the reactor.

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.

Cellulose to Ethanol and Diesel

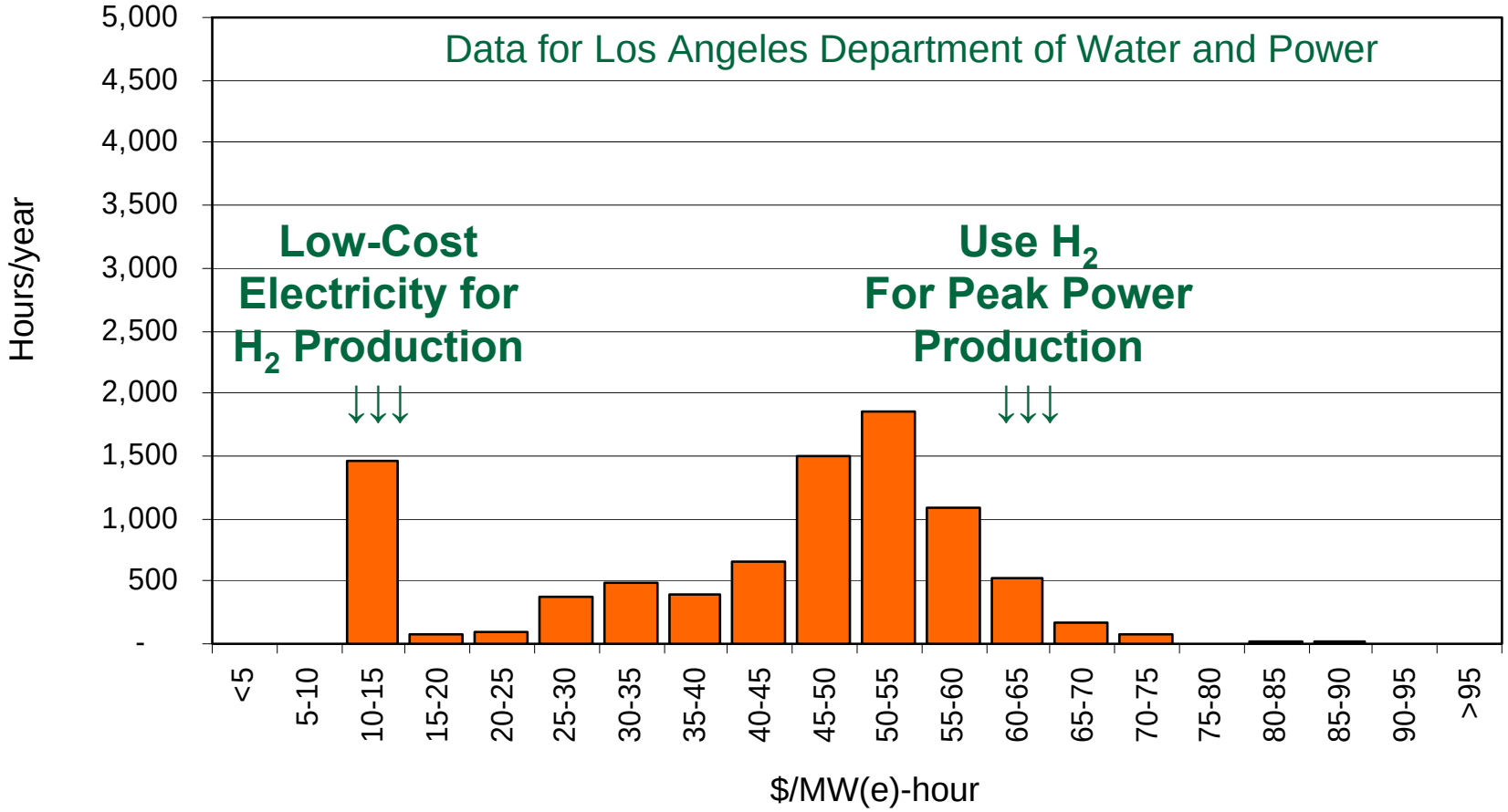
One Midterm Option with High Economic Potential



50% Increase Liquid Fuel/Unit Biomass

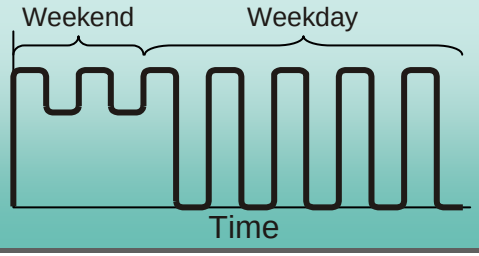
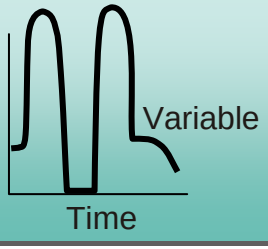
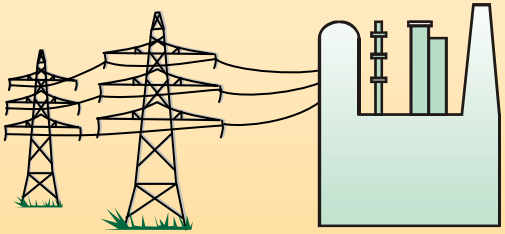
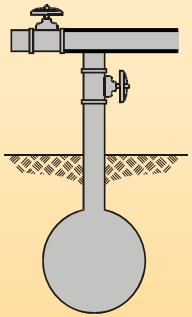
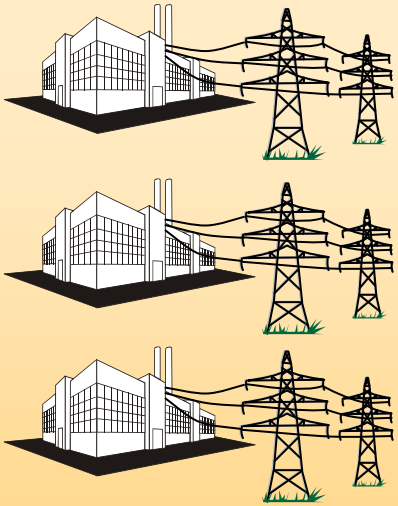
HIPES Economics Is Based on Variable Electricity Prices

Price vs Hours/Year in Each Price Range



FY 2004 FERC Marginal Price

HIPES: Grid Electricity and Electrolysis

Energy Production Rate vs Time			
Facility	Electrolyzer Complex  $2H_2O \rightarrow 2H_2 + O_2$		
	H_2 Production	***Underground Hydrogen/Oxygen (Optional) Storage***	***Fuel Cells, Steam Turbines, or Other Technology***
Relative Capital Cost/kW	$$$	$	$$

Potential Requirements for Combined-Cycle Small-Reactor Fuel

Property	Basis	Technical Fuel Implication
High-Temperature	Prevent accident releases	Refractory
Chemical Resistant	Prevent accident releases	Multilayer resistance to oxidation and reduction
Stress resistance	Avoid structural failure	Encapsulated fuel; matrix for stress
Shock resistant	Accident and assault	Encapsulated fuel with inert matrix to withstand shock damage to fuel

Comparison of Traditional Nuclear Fuels and "Abuse-Resistant" Fuels

Property	Traditional Fuel (Magnox, LWR)	Abuse-Resistant Fuel (Coated Particle, etc.)
Fuel Fraction	65–95%	<10%
Reactor Safety	Reactor systems protect fuel	Fuel is the safety system
Reprocessing	Simple	Fuel designed to be indestructible
Security and Nonproliferation	Not a design consideration	Intrinsic resistance to abuse

Abuse-resistant fuel properties make such fuel:
(1) expensive to recycle and (2) an excellent waste form