The Nuclear-Hydrogen Renewables Economy

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Components of the Nuclear-Hydrogen Renewables Economy

Biomass, Hydrogen, and Liquid Fuels

Wind, Hydrogen, and Electricity

Hydrogen and Nuclear Energy

Biomass, Hydrogen, and Liquid Fuels

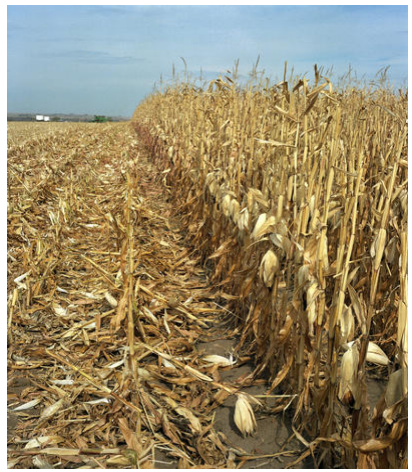
Corn

Corn to Fuel Ethanol

The Biotech Revolution Is Creating A New Fuel-Ethanol Industry

Sugar (Sugarcane, Sugar Beets, etc.)

Sugar → Ethanol (Traditional Technology)



Starch (Corn, Barley, etc.)

Starch + Enzyme → Sugar → Ethanol

Process Has Been Used for Millennia

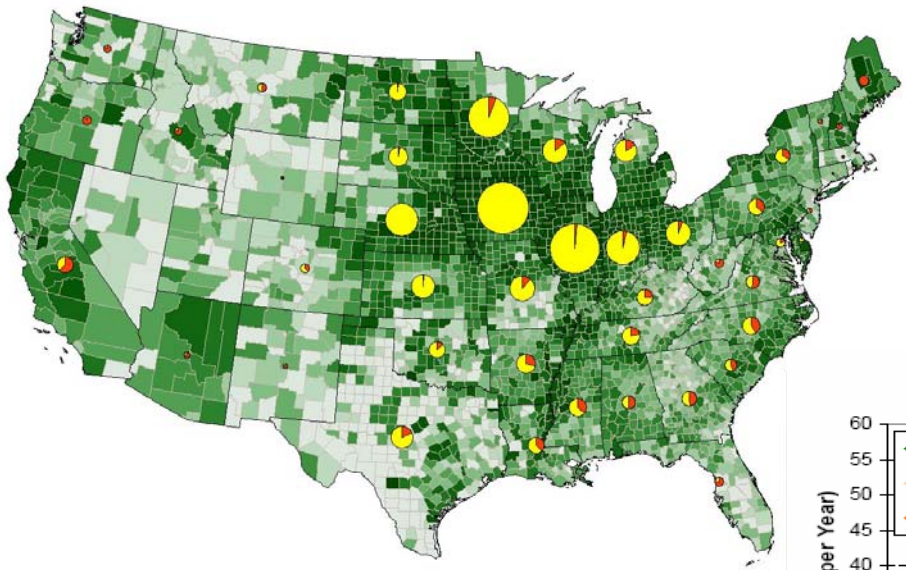
New Low-Cost Enzymes for Rapid Starch-to-Sugar Conversion (Corn-to-Ethanol Boom)

Cellulose (Trees, Agricultural Waste, Etc.)

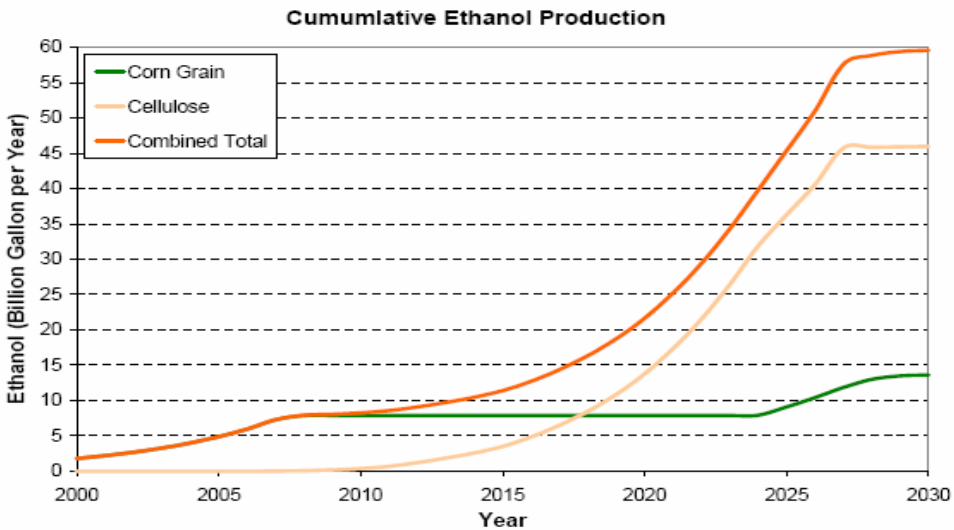
Cellulose + Enzyme → Sugar → Ethanol

Enzyme Costs Dropping Rapidly; Precommercial Plants Operating

Potential Distribution and Scale-up of Ethanol-Refining Capacity



- Corn: Limited supply
- Cellulose: Larger supply

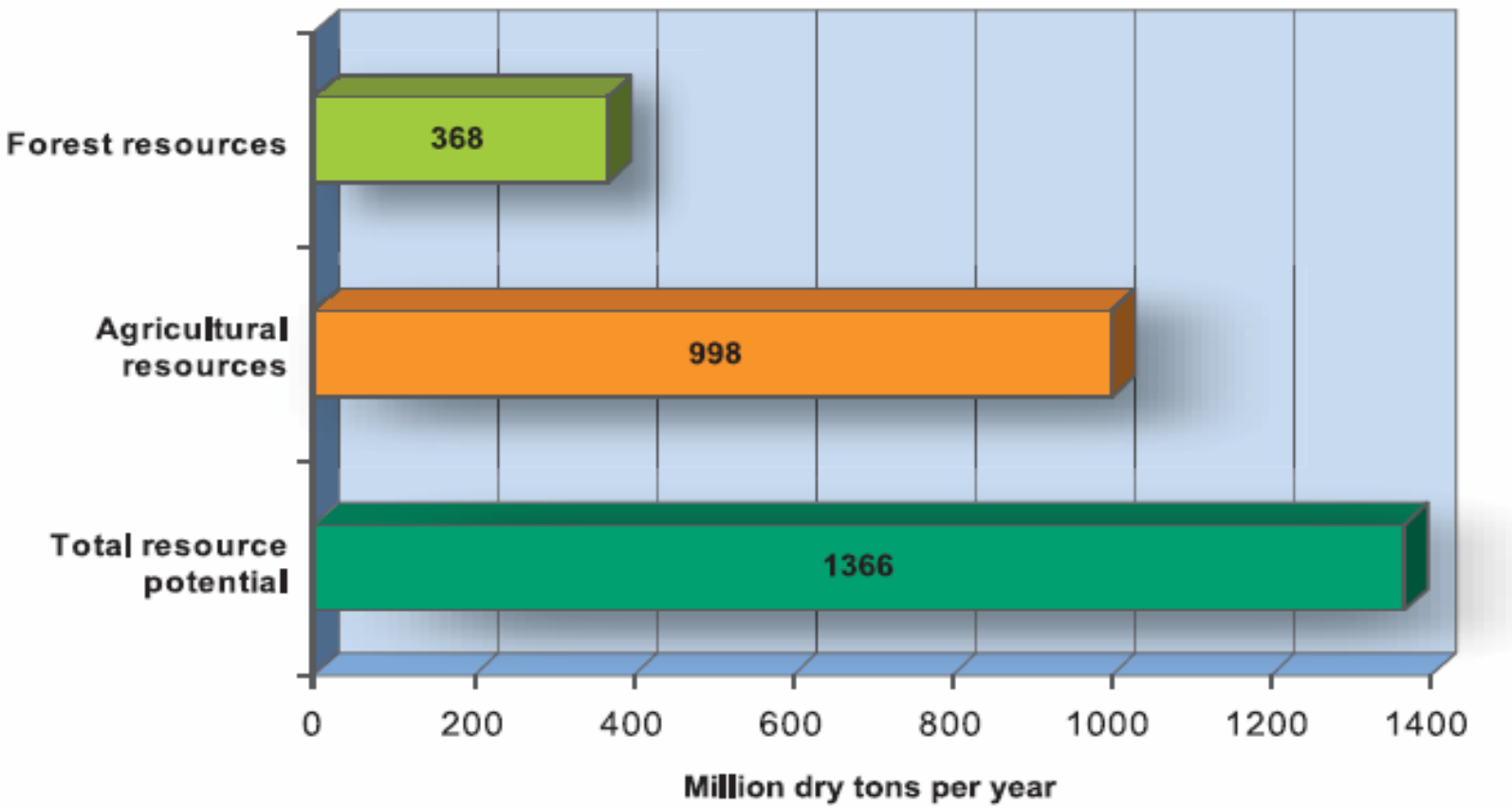


Source: NREL – Bob Wooley

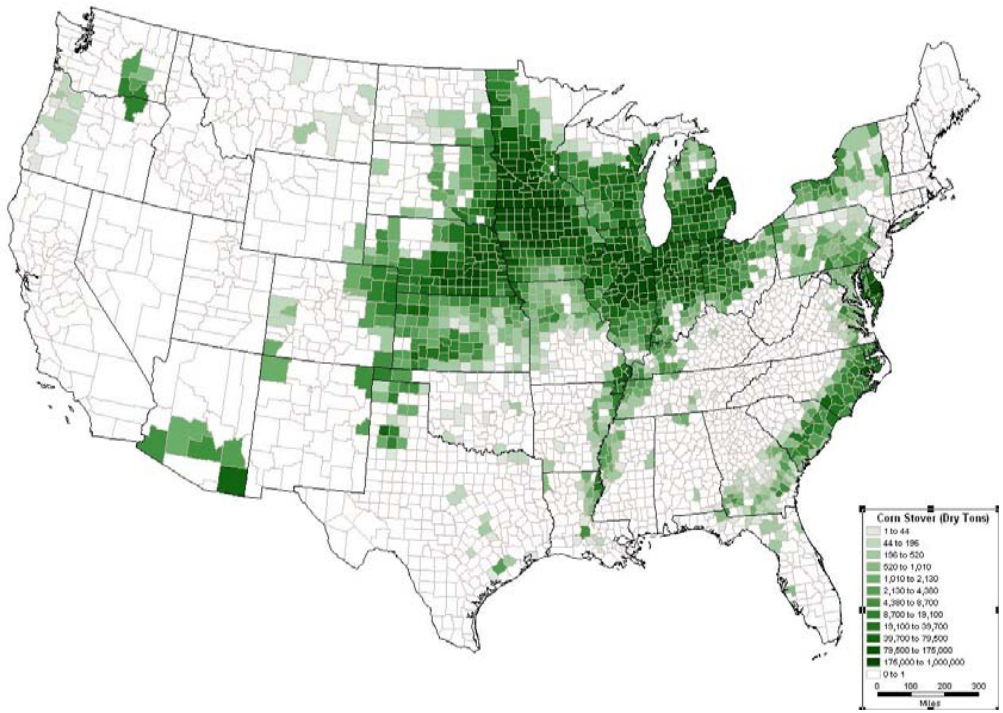
Cellulose is the Primary Biomass on Earth

Economic Conversion of Low-Cost Cellulose to Fuel Ethanol Implies a Liquid-Fuel Revolution

Biomass Ethanol Could Meet 30% of Our Liquid Fuel Demand by 2030



The Largest Available Cellulose Source is Corn Stover

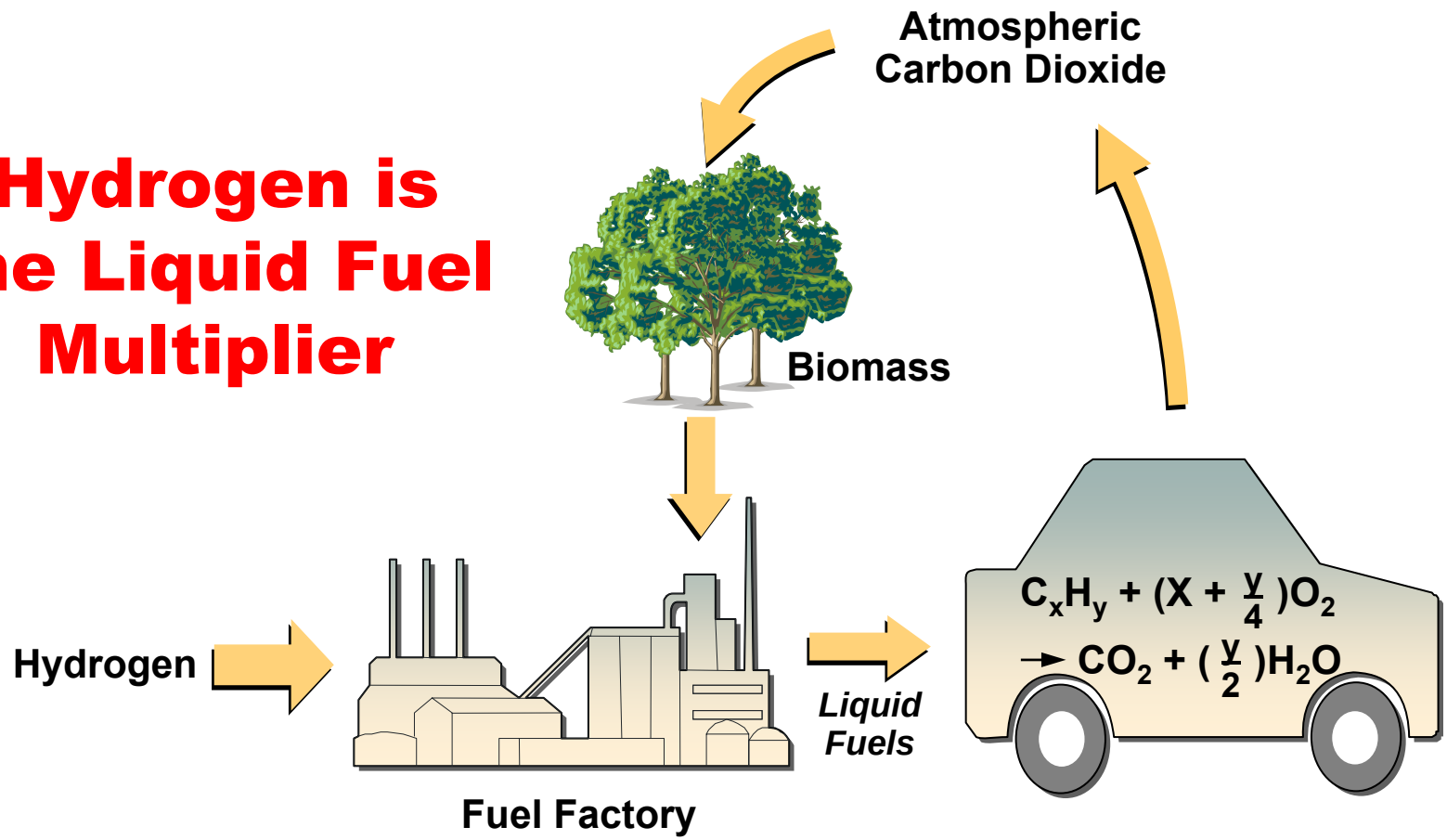


The Problem: Not Enough Biomass

- Only one-third of the world's liquid fuel demand could be met with biomass to ethanol
- Ethanol production: A good start
  - Biomass → Ethanol + Carbon Dioxide + Residues
  - <u>Biomass is used by yeast as a fuel</u>
- The longer-term hydrogen alternative
  - Biomass + H_2 → Hydrocarbon liquid Fuels + Water
  - Hydrocarbon liquid fuels: Gasoline, diesel, and jet fuel
  - Hydrogen serves two functions
    - Energy source to operate the process
    - Hydrogenation of biomass to high-energy hydrocarbons
  - <u>Increase the energy value of the liquid fuel by a factor of 3 to 4 per unit of biomass</u>

Conclusion I: Biomass and Hydrogen can Create Abundant Greenhouse-Neutral Liquid Fuels

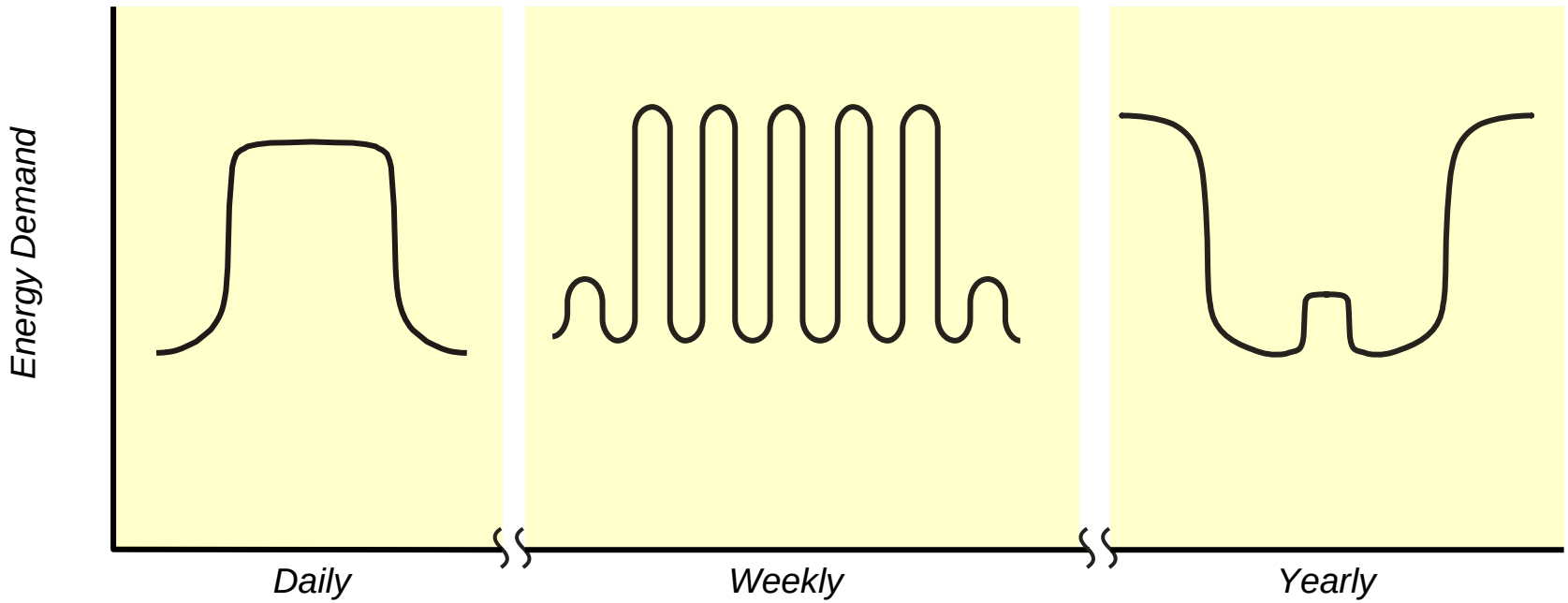
Hydrogen is the Liquid Fuel Multiplier



Wind, Hydrogen, and Electricity

The Challenge of Electricity Production: Matching Production with Demand

Electricity Demand Varies with Time of Day, Weekly, and Seasonally



Different Electricity Sources have Different Characteristics

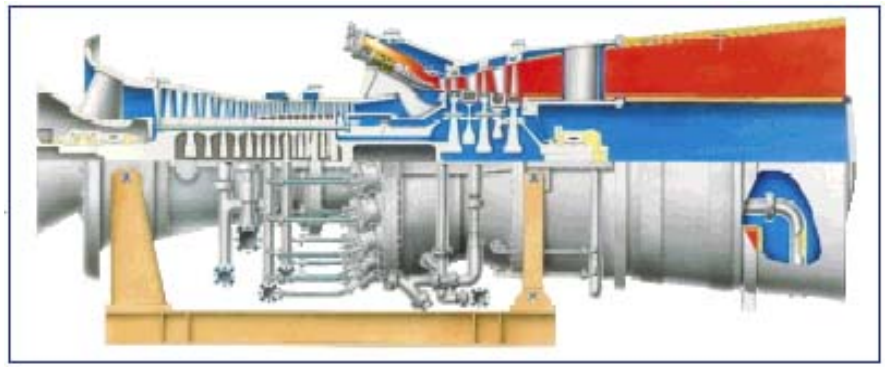
Electricity Source	Capital Cost	Operating Cost
Nuclear and Renewables	High	Low
Fossil	Low	High

"Base-Load" Operations are Required for Low-Cost Nuclear and Renewable Electricity

Fossil Fuels are Used Today to Match Electricity Demand with Production

- Fossil fuels are <u>inexpensive to store</u> (coal piles, oil tanks, etc.)

- Fossil fuel-to-electricity systems have relatively <u>low capital costs</u>



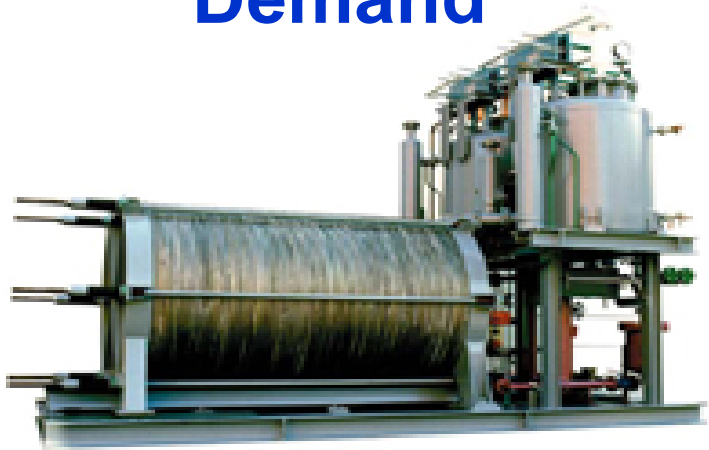
- If fossil-fuel consumption is limited (greenhouse, etc), what alternatives have the fossil fuel characteristics: (1) inexpensive fuel storage and (2) low capital costs?

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

- Renewable electricity production does not match electric demand
- Backup power is expensive and depends upon fossil fuels
- Viability of large scale renewable electricity (>10% of electricity) depends upon finding low-cost electricity storage technologies

Hydrogen Intermediate and Peak Electric System (HIPES)

Using Hydrogen to Match Electricity Production with Demand

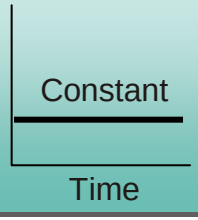
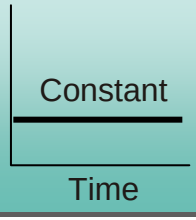
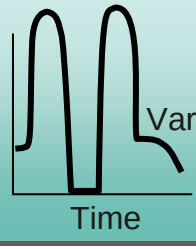
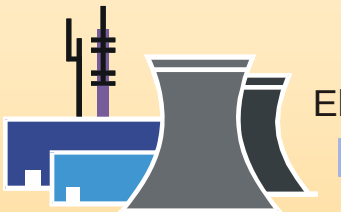
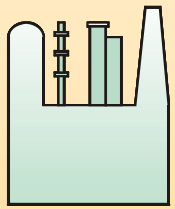
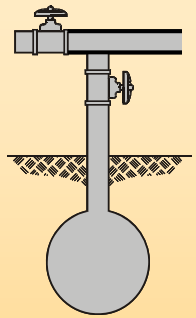
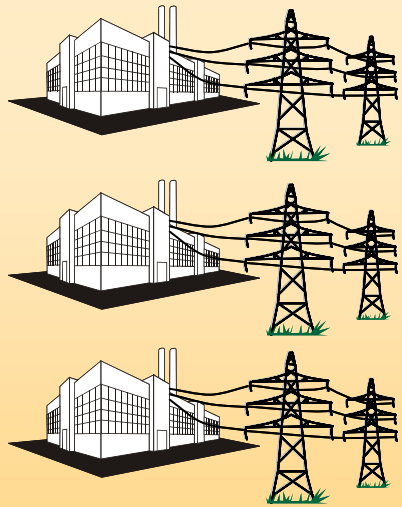


Electricity Storage Requirements for a Non-Fossil Electrical System

- Store days or weeks of electricity demand
  - Address weekly and seasonal mismatches in production with demand
  - Address multiday “no-wind” or “no-sun” electricity production shortfalls
- Storage capacity sized independently of the electricity production capacity

HIPES: Nuclear Version

(Other Centralized Systems Such as Solar Power Towers Have Similar Characteristics)

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	$$$$	$$	$	$$

Hydrogen Production Options

- Near term
  - Electrolysis
    - (Water + electricity → 2 H_2+ O_2)
  - Electricity supply options
    - Base-load electricity
    - Low-cost off-peak electricity
- Longer term
  - High-temperature electrolysis
    - Steam + Electricity → 2H_2+ O_2
  - Hybrid cycles
    - Water + Heat + Electricity → 2H_2+ O_2
  - Thermochemical cycles
    - Water + Heat → 2H_2+ O_2

Norsk Atmospheric Electrolyser

One Low-Cost Bulk Hydrogen Storage Technology Exists

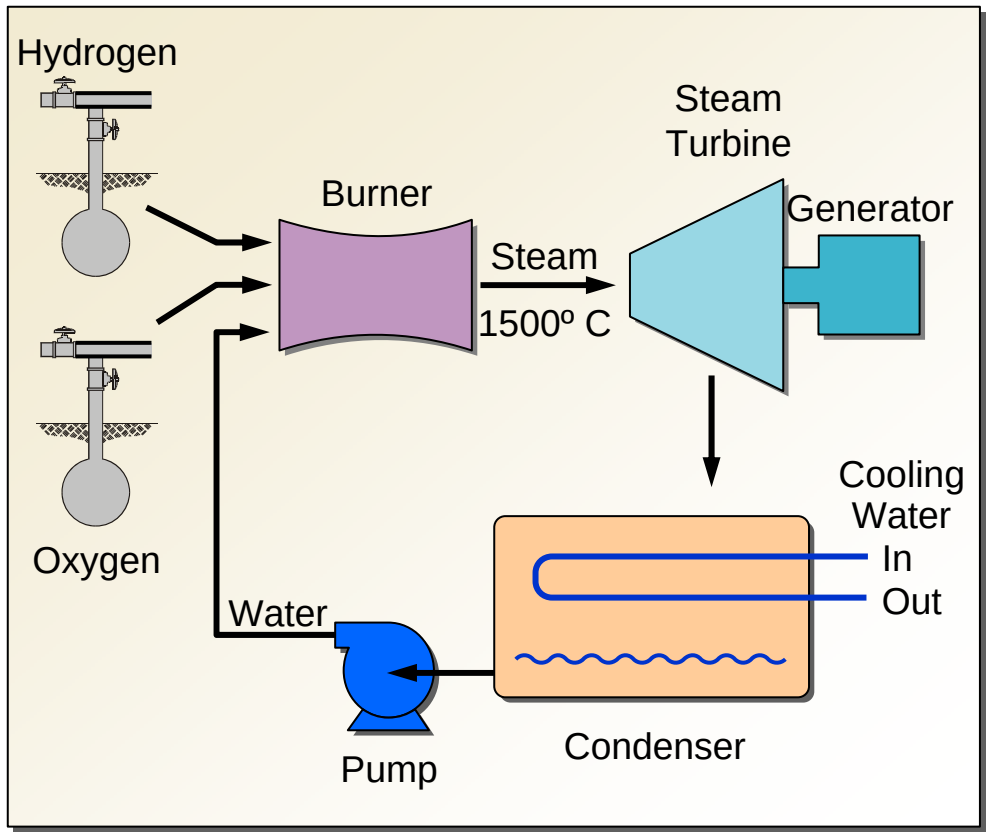
- Underground storage
- Chevron Phillips H_2 Clemens Terminal →
  - 160 x 1000 ft cylinder salt cavern
- Used by the natural gas industry to store one-third of a year's supply of natural gas in the fall

Same Storage Technology for Oxygen

Special Steam Turbines Convert Hydrogen and Oxygen to Electricity

(Used limited number of hours per year so must have low capital cost)

- **High-temperature steam cycle**
  - **$2H_2 + O_2 \rightarrow$ Steam**
  - **Unique characteristic of hydrogen as a fuel and oxygen as the oxidizer**
- **Low cost**
  - **No boiler**
  - **No air with 80% N_2**
  - **High efficiency (70%)**



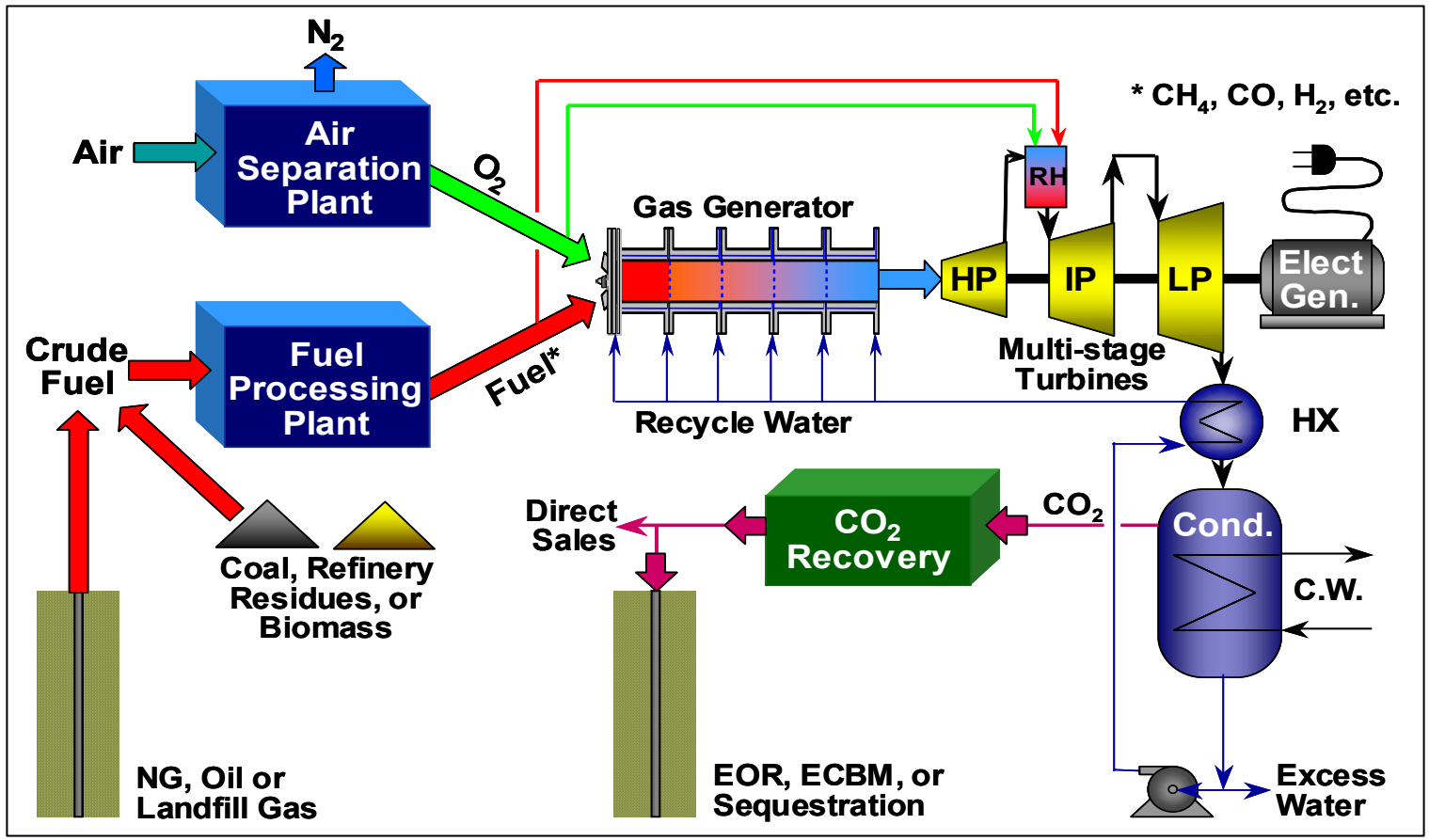
Oxy-Fuel Combustors Are Being Developed

- Japan: $2H_2 + O_2$
- U.S.: Natural gas-O_2
- Clean Energy Systems test unit
  - Natural gas and oxygen
  - 20 MW(t)
  - Pressures from 2.07 to 10.34 MPa
  - Combustion chamber temperature: 1760ºC
  - Turbine technology limits performance

Courtesy of Clean Energy Systems (CES)

CES is Developing a Natural Gas–Oxygen Electric System

(Higher Efficiency and Pure CO_2 Stream)



Courtesy of Clean Energy Systems (CES)

Kimberlina Oxy-Fuel Power Plant Test Facility

(Courtesy of Clean Energy Systems, Inc.)

Gas Generator/Turbo-Generator Test

Steam Turbine and Generator (Powered by Steam/CO_2)

Using Hydrogen and Oxygen Enables Low-Cost High-Efficiency Systems

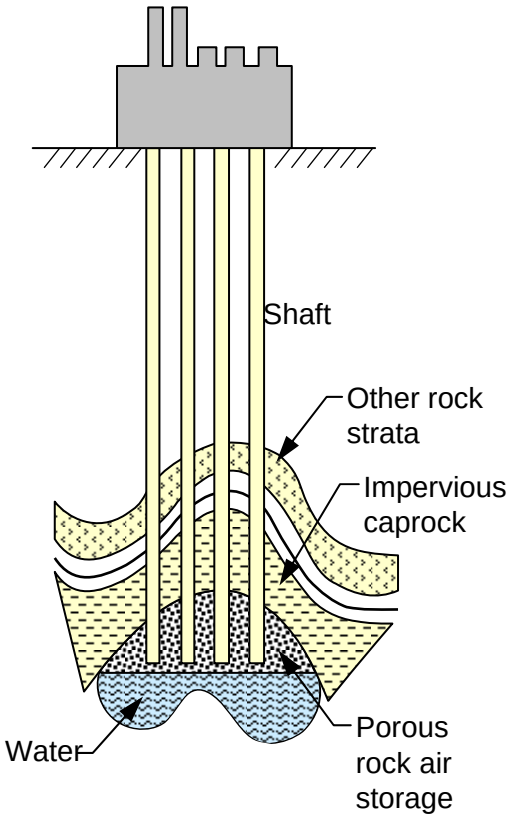
HIPES

- New system
- Feed: H_2 and O_2
- Major components (low capital cost)
  - Combustor
  - Steam turbine
  - Electric generator
- Efficiency: 70%
- Low capital cost relative to other technologies

Combined Cycle

- Commercial
  - Natural-gas electric plant
- Feed: H_2 and air (80% N_2)
  - High volume nitrogen flows
- Major components
  - Combustor
  - Gas turbine (80% N_2 Flow)
  - Steam boiler (80% N_2 Flow)
  - Steam turbine
  - Electric generator
- Efficiency: 54%

Conclusion II: Hydrogen Storage May Enable Renewable Electricity Use



Need for stored "electricity"

<u>Stored hydrogen replaces piles of coal and tanks of oil</u>

Storage costs are low (<10%) compared with H_2 costs

Hydrogen may be the enabling technology for large-scale use of renewable electricity

*Commercial in salt;
Not a commercial H_2 technology in other geologies

Hydrogen and Nuclear Energy

Hydrogen Production, Storage, and Transport are Centralized Technologies

+

A Primary Energy Source (Nuclear, Fossil, etc.) is Required to Make Hydrogen

↓

Nuclear Energy (a Centralized Energy Source) Matches the Hydrogen Production Requirements

There is Only One Low-Cost Hydrogen Storage Technology: Underground

- Storage is required
- Low-cost storage is possible only on a large scale
- Centralized hydrogen storage favors centralized hydrogen production to avoid H_2 transport collection costs

Hydrogen Collection and Distribution are Different than for Electricity

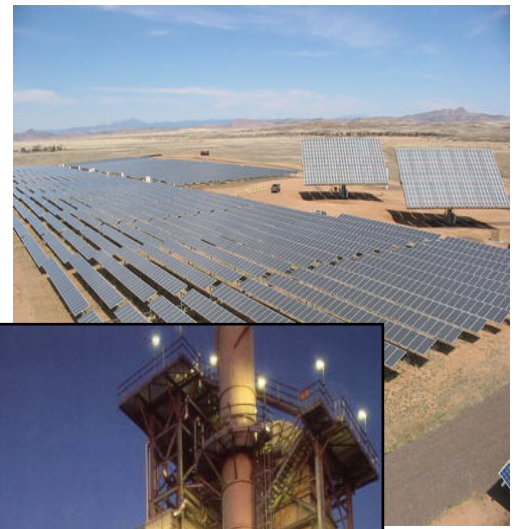
- Electricity transport
  - Two-way systems with transformers
  - Highly efficient methods to change voltage (electrical pressure)
- Hydrogen transport is similar to natural gas
  - Hydrogen transmits one way: high to low pressure
  - Large economics of scale associated with hydrogen compression
  - Favors centralized hydrogen production, storage, and transport

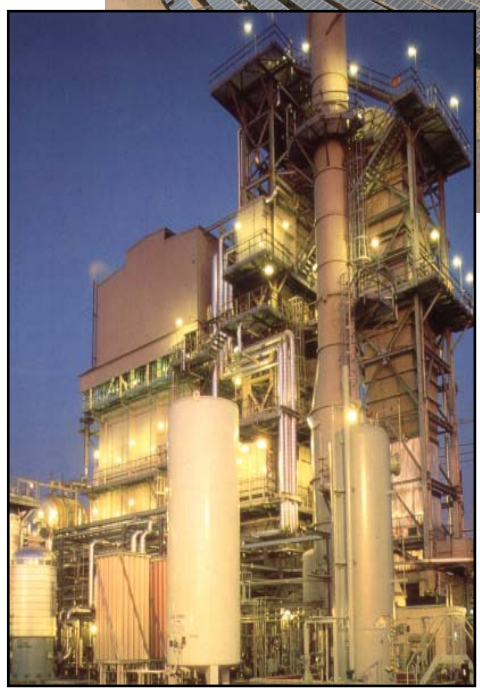
Hydrogen Gas Compression Favors Large Centralized Facilities

- Hydrogen gas compression is a major cost and required for:
  - Production
  - Storage
  - Transport
- Compressor design characteristics strongly favor large systems
  - Gas properties determine compressor design
  - Hydrogen is the lightest gas with the most extreme properties
  - Small hydrogen compressors are inefficient and expensive per unit of compression
- Hydrogen properties drive the technology toward large sizes

Hydrogen Production Favors High-Capacity Systems

- Many factors favor large systems
  - Hydrogen leakage
  - Hydrogen compression
  - Safety systems
- Economics of Scale
  - Electricity (Electrons):
    - Multiple production methods (wind, nuclear, coal, etc.)
    - Electricity production cost vary by a factor of 3
    - Plant sizes vary by over 3 orders of magnitude
  - Hydrogen (Atoms):
    - Large economics of scale
    - Chemical industry experience





Economics have Driven the Largest Natural Gas-to-Hydrogen Plant Outputs to Match Three 1000-MW(e) Nuclear Power Plants

Browns Ferry Nuclear Power Plant (Courtesy of TVA)

*Natural gas-to-H_2 plant with total output from four trains of $15.6 \cdot 10^6$ m^3/day

Nuclear Energy is the Non-Greenhouse Option that Matches Hydrogen Production Characteristics

Characteristic	Nuclear Energy	Hydrogen Production
Economic Size	Large	Large
Staff	Highly Skilled	Highly Skilled
Capital Investment	Large	Large

Conclusion III: Nuclear Energy Characteristics Match Hydrogen Production Needs

Strong Incentives for Centralized Hydrogen Production Independent of the Energy or Hydrogen-Production Technology

Conclusions

Hydrogen Can Extend Biomass Resources to Meet Liquid Fuel Needs

Hydrogen May Enable the Use of Renewable Electric Systems by Solving the Electric Storage Challenge

Hydrogen Production, Storage, and Transport are Large-Scale Technologies that Couple to Nuclear Energy

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. After working for Bechtel Corporation, he joined the staff of Oak Ridge National Laboratory, where he is presently the Senior Reactor Technical Advisor. Dr. Forsberg has been awarded 10 patents and has published over 200 papers in advanced energy systems, waste management, and hydrogen futures.