# Innovative Energy Sources: The Post-Fossil World


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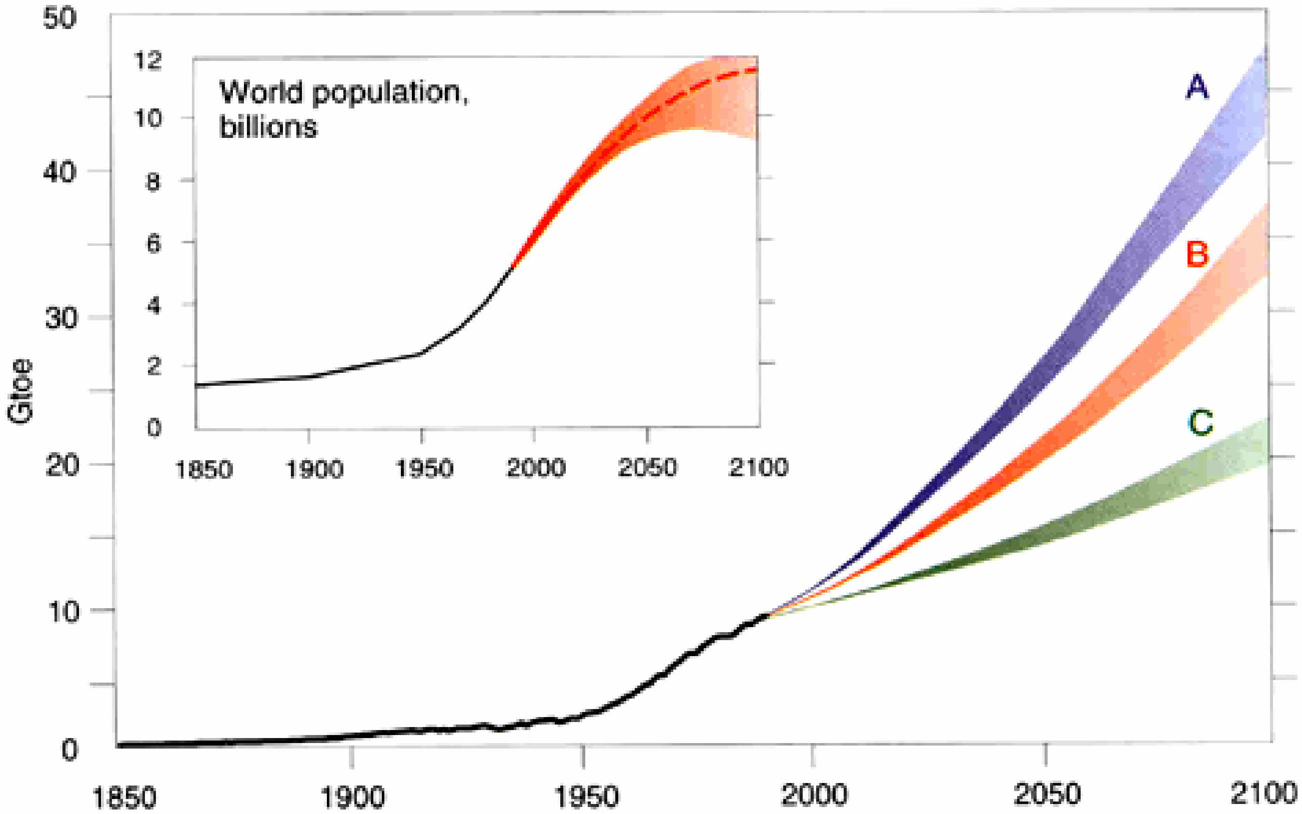
# Overview

- The Energy Challenge
- Replacing the Fossil-Fuel Combined Energy and Energy Storage System
- Nuclear-Biomass Liquid-Fuel Futures
- Hydrogen Futures
    - Hydrogen for Materials Production
    - Hydrogen for Peak Electricity Production
- Demand Side Energy Storage: Plug-in Hybrid Electric Vehicles

# The Energy Challenge

# World Electricity

## 2 Billion people have no access to electricity or to any energy network




A : High growth (Income, energy, technology)

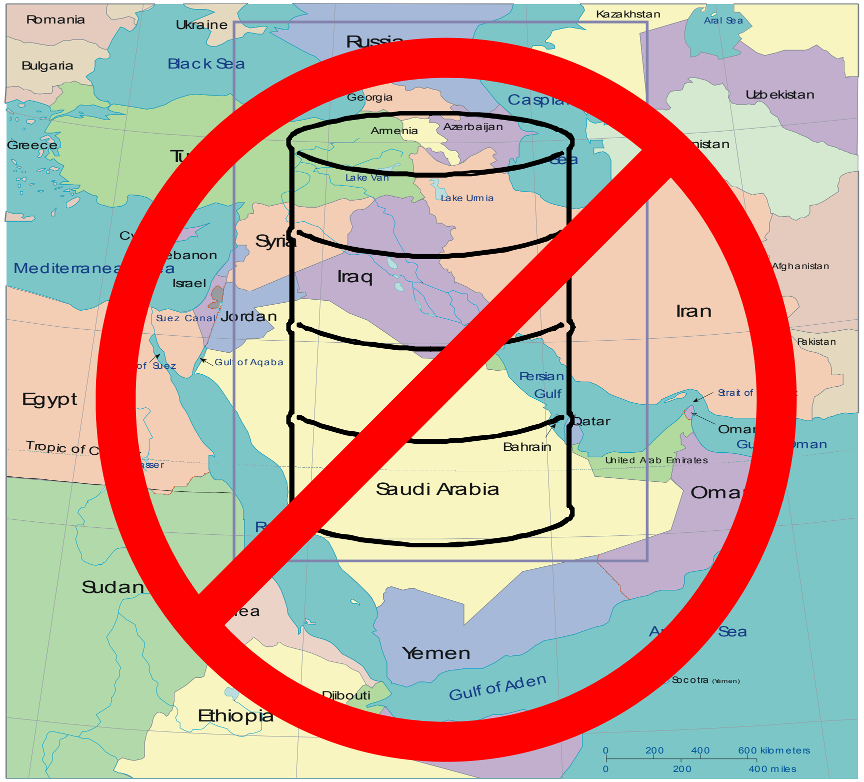
B : Modest growth

C : Ecologically driven growth

## Liquid Fuels and Heating Demand Following a Similar Trends

# Energy Futures May Be Determined By Two Sustainability Goals

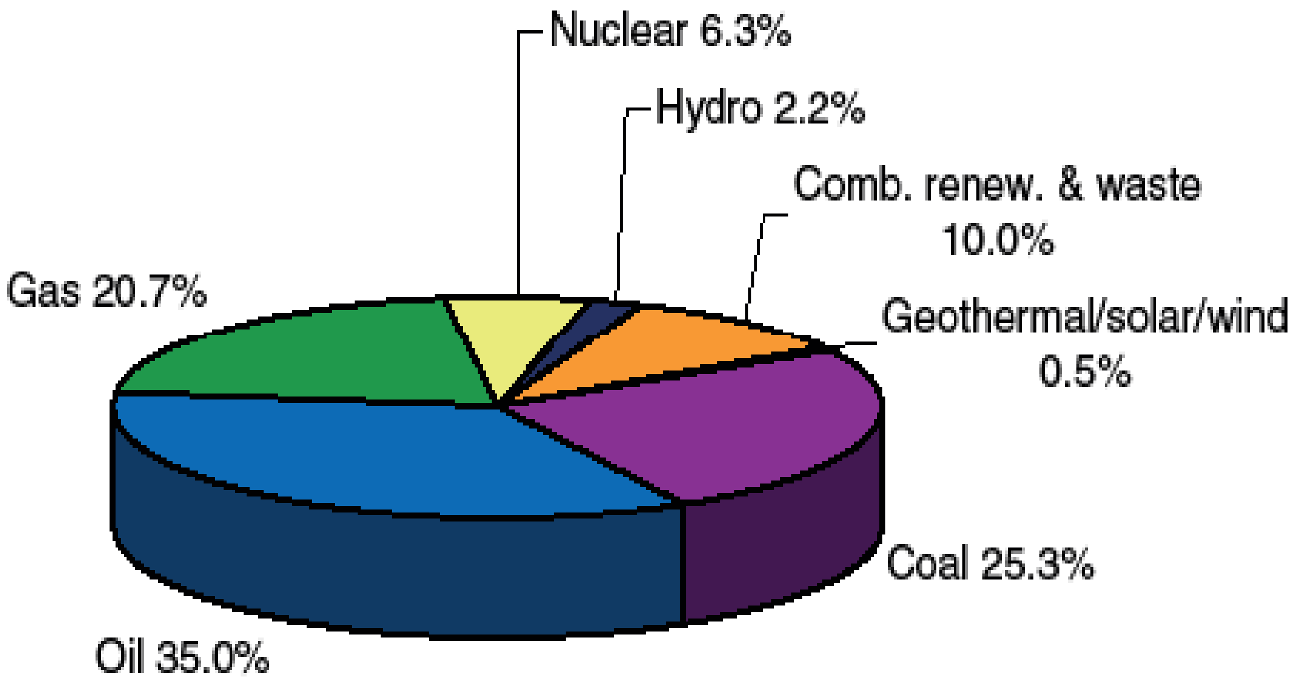
**No Imported Crude Oil**




**No Climate Change**

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

# A Massive Challenge If Fossil Fuel Use Is Limited to Prevent Climate Change

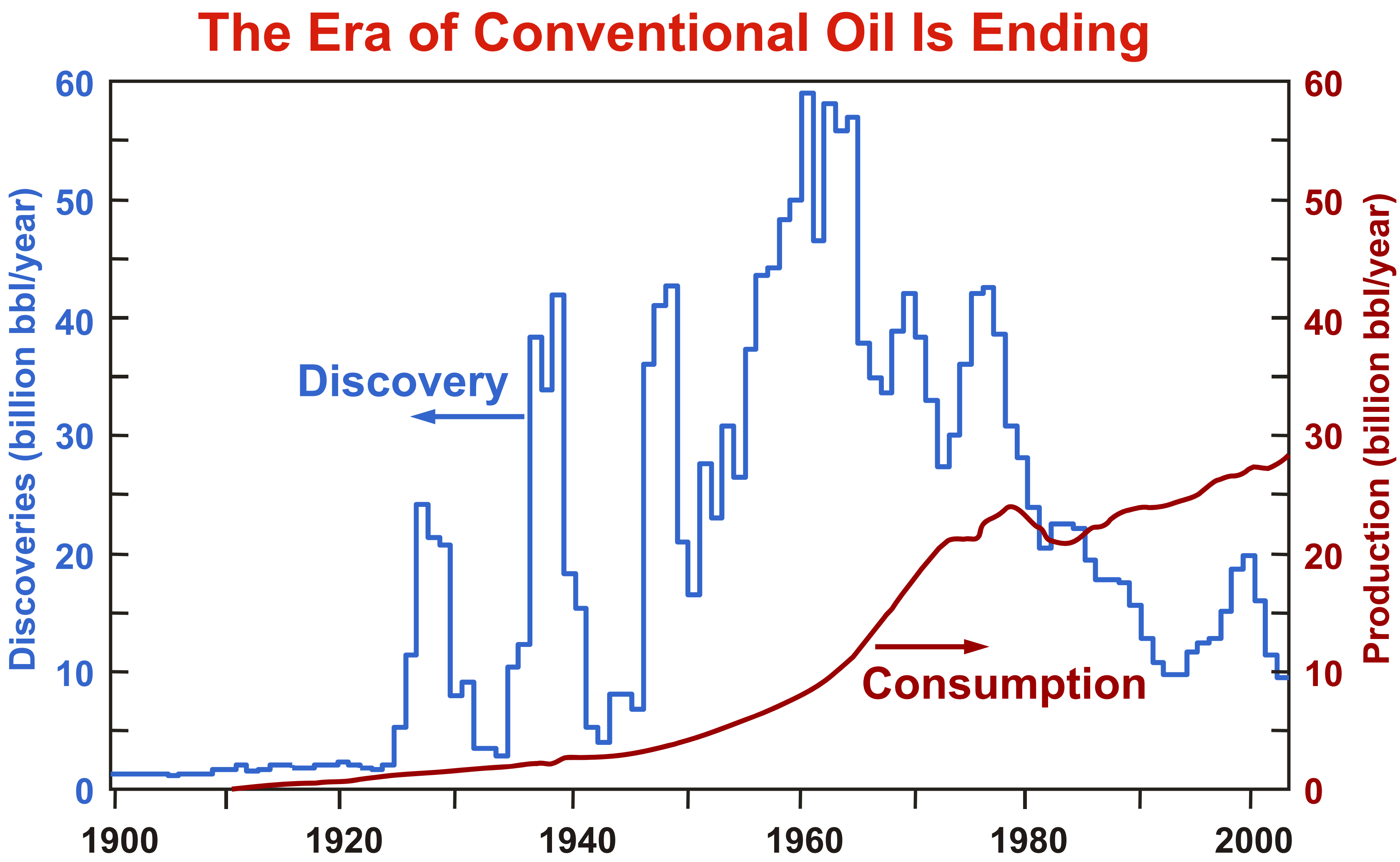



**Fossil Fuels are 80% of the Total**
**Oil Is The Largest Energy Source**

**11 434 Mtoe**

Share of total primary energy supply in 2005: OECD/IEA 2007; http://www.iea,org/statist/index.htm

# World Oil Discoveries Are Down and World Oil Consumption Is Up

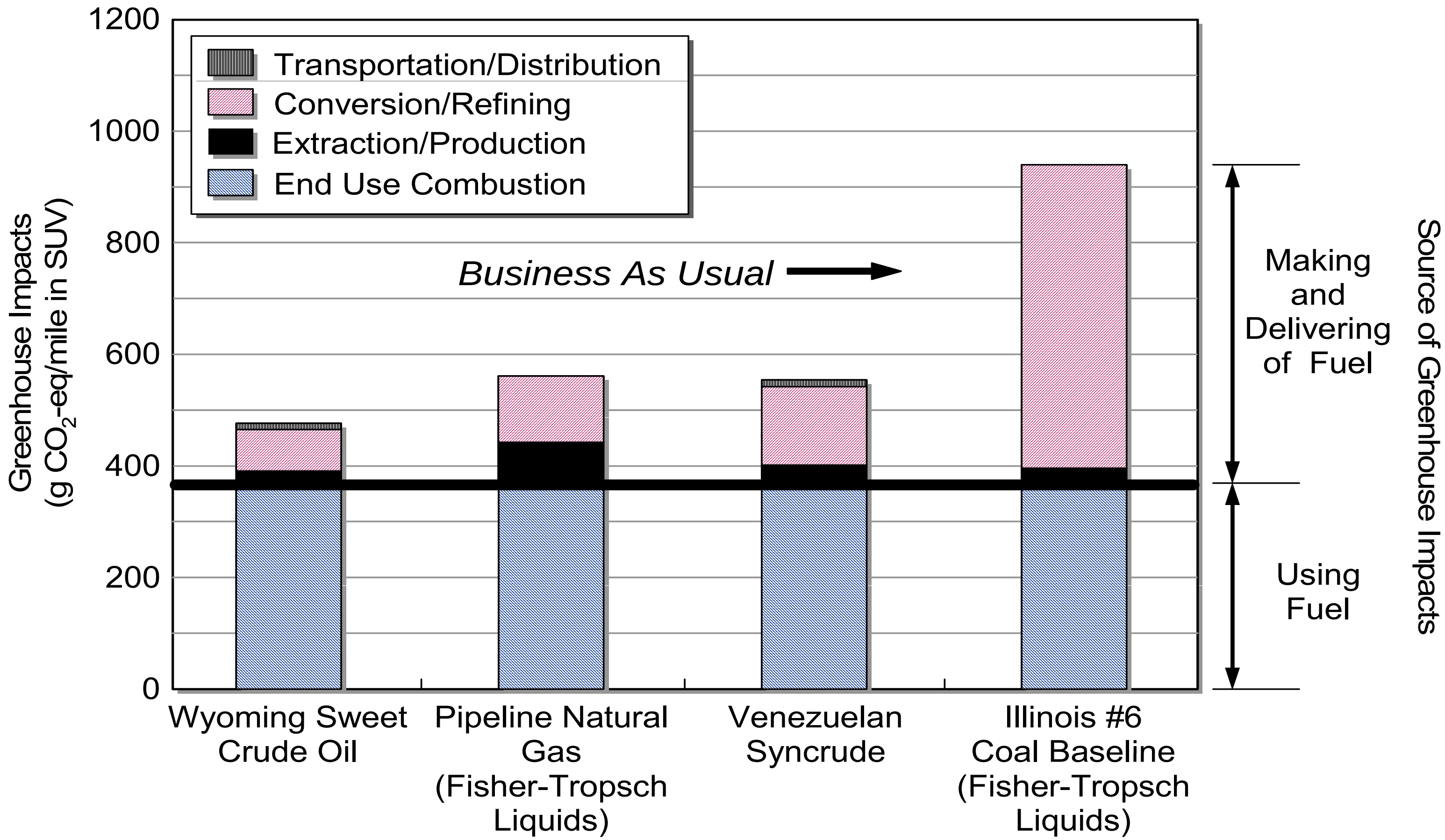





Oil and Gas J.; Feb. 21, 2005; Most projections indicate one to two decades of large swings in oil prices in the transition off of oil

# Liquid Fuels Production Is Accelerating Greenhouse-Gas Emissions

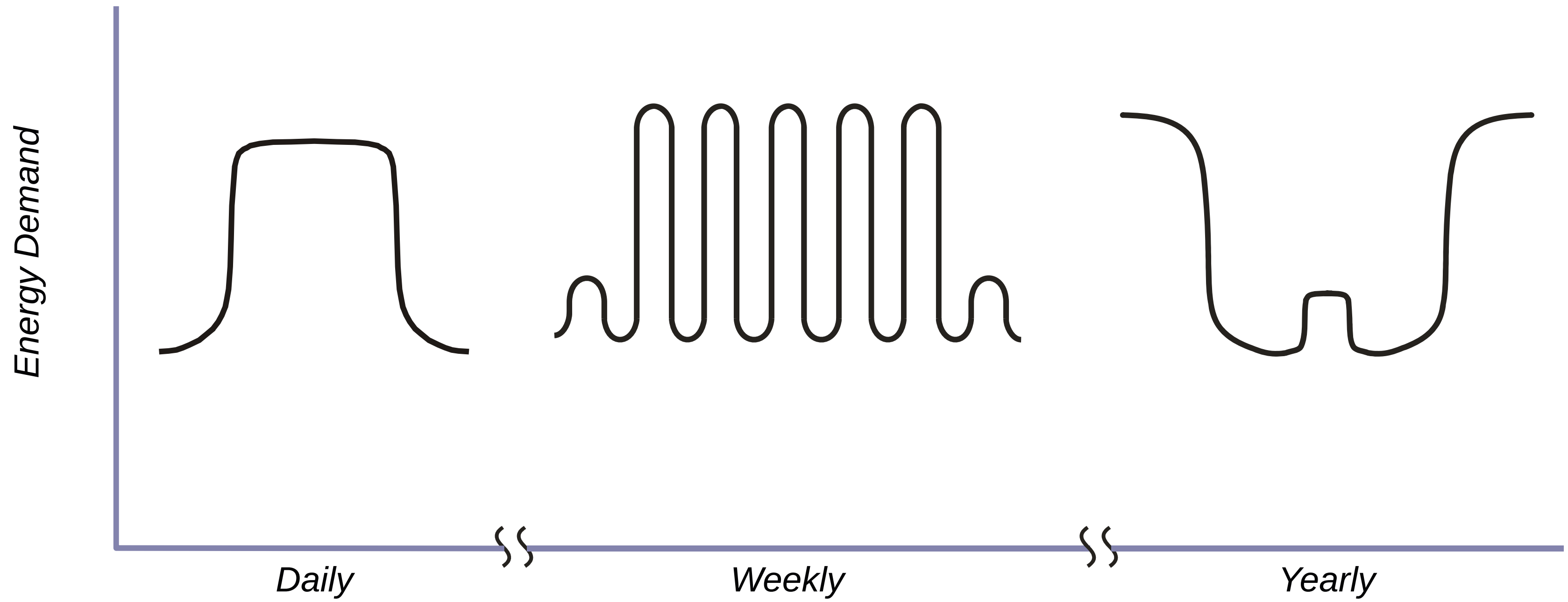
## Greenhouse Gas Impacts Per Liter of Fuel Are Going Up



# Replacing the Fossil-Fuel Combined Energy and Energy Storage System

**Finding New Energy Sources is Half the Problem, Must Also Find Energy Storage Solutions**

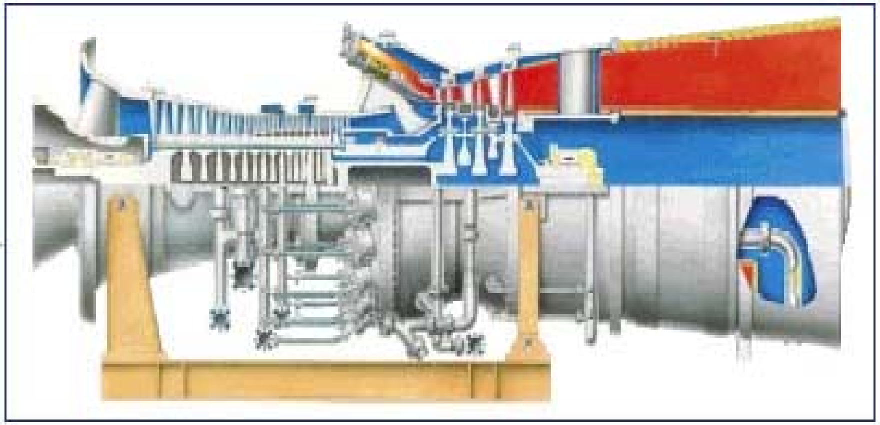
# Electricity Demand Varies with Time of Day, Weekly, and Seasonally




**Seasonal Swings in Liquid Fuels and Heating Demand**

# Fossil Fuels are Used Today to Match Energy Demand with Production

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



- If fossil-fuel consumption is limited by greenhouse or cost constraints, what replaces the storage functions of fossil fuels?

# Large-Scale Renewable Energy Production Does Not Match Demand

- Energy when the wind blows and the sun shines
- Does not match needs
- Backup power is expensive and depends upon fossil fuels
  - Today: stored oil and natural gas
  - Not viable backup energy sources if greenhouse gas constraints (Carbon-dioxide sequestration only viable with base-load power plants)

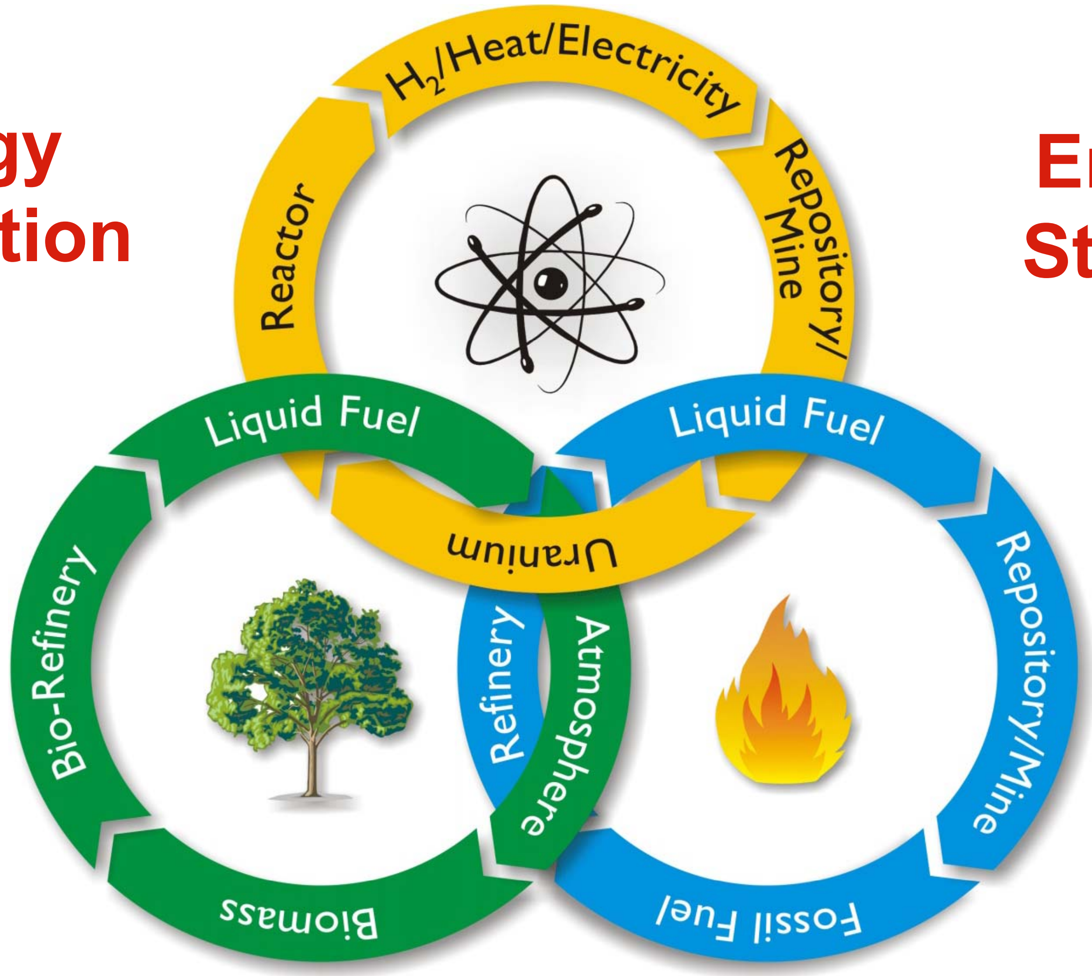
# Nuclear Energy, Fossil Fuels with Carbon Sequestration, and Fusion (If it Works) Do Not Match Energy Needs

- High-capital-cost low-operating-cost energy sources
- Economics depends upon demand for base-load electricity
- Production does not match demand

# Replacement of Fossil Fuels Requires Rethinking Energy Systems

**Energy Production**

**Energy Storage**



# Nuclear-Hydro Electricity

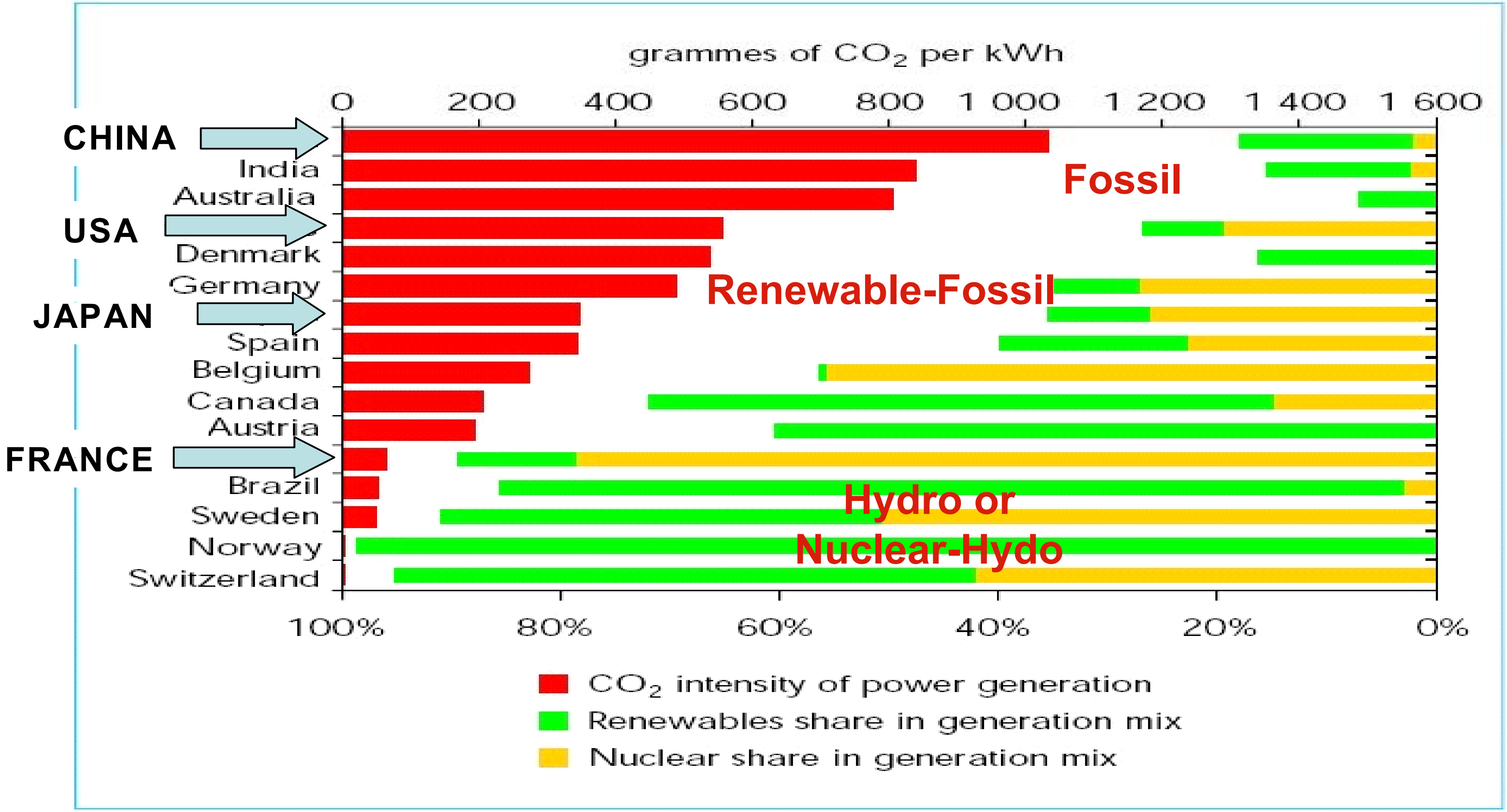
**The Only Existing Large-Scale Low-Carbon Hybrid-Energy Production and Storage System**

**Base-Load Nuclear Electricity**

**Energy Storage With Variable Output Hydropower**

# Low-Carbon Electricity with Base-Load Nuclear and Storable Hydroelectricity

***$CO_2$ emissions per kWh and shares of nuclear power and renewables in selected countries (2004)***




***But, Only A Few Countries Have Sufficient Hydro***

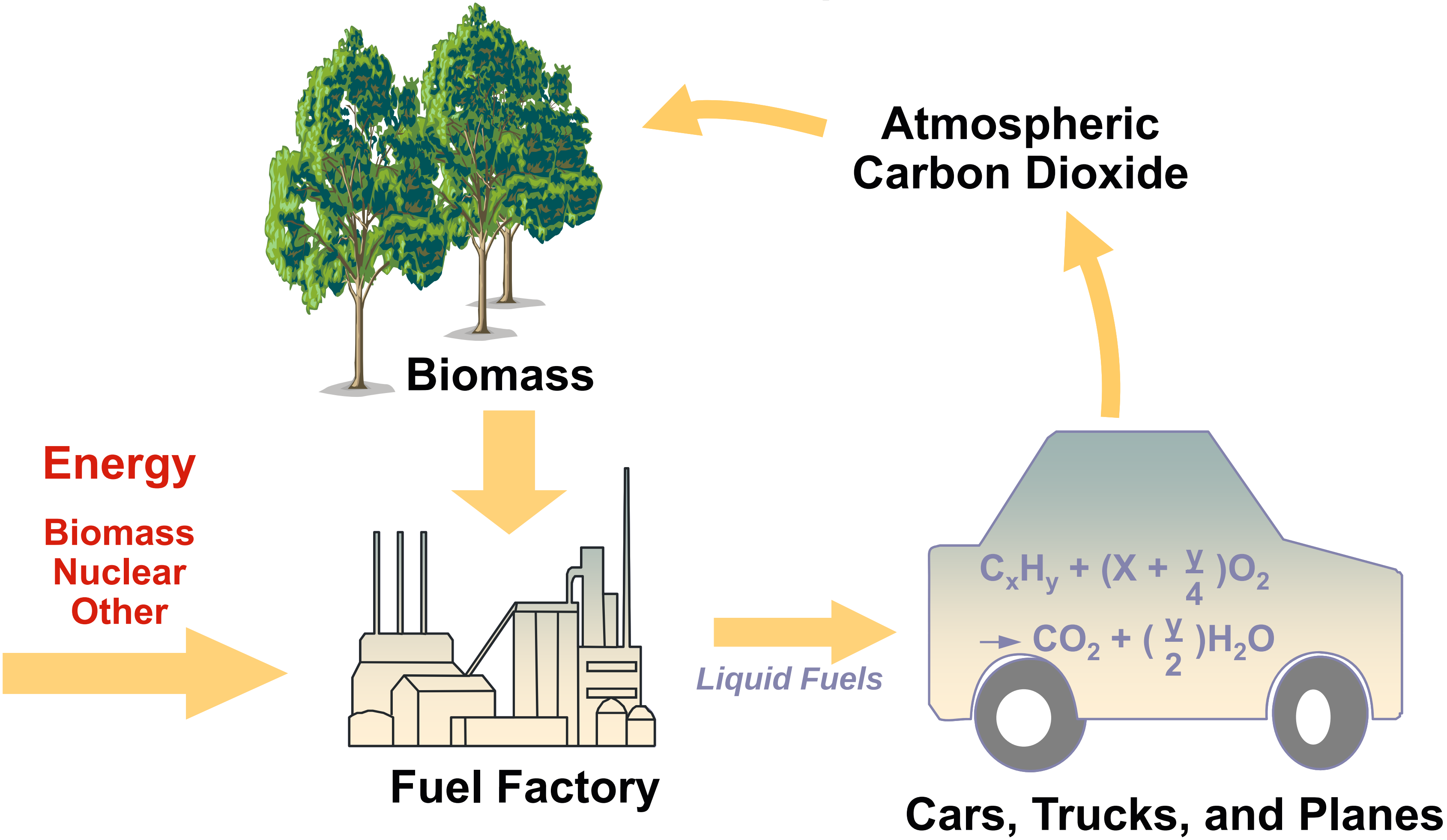
# New Hybrid-Energy Systems Required To Replace Fossil Fuel Energy Sources and Storage

**Nuclear Biomass Liquid-Fuel Systems**
**Hydrogen Futures**
**Demand-Side Energy Storage**

# Nuclear-Biomass Liquid-Fuel Futures

## Low-Carbon Liquid Fuels for Energy and Energy Storage

# Biomass Can Be A Source of Low-Carbon Liquid Fuels



# Biomass: Worldwide Resources Measured in Billions of Tons per Year

**Without Significantly Impacting Food, Fiber, and Timber**

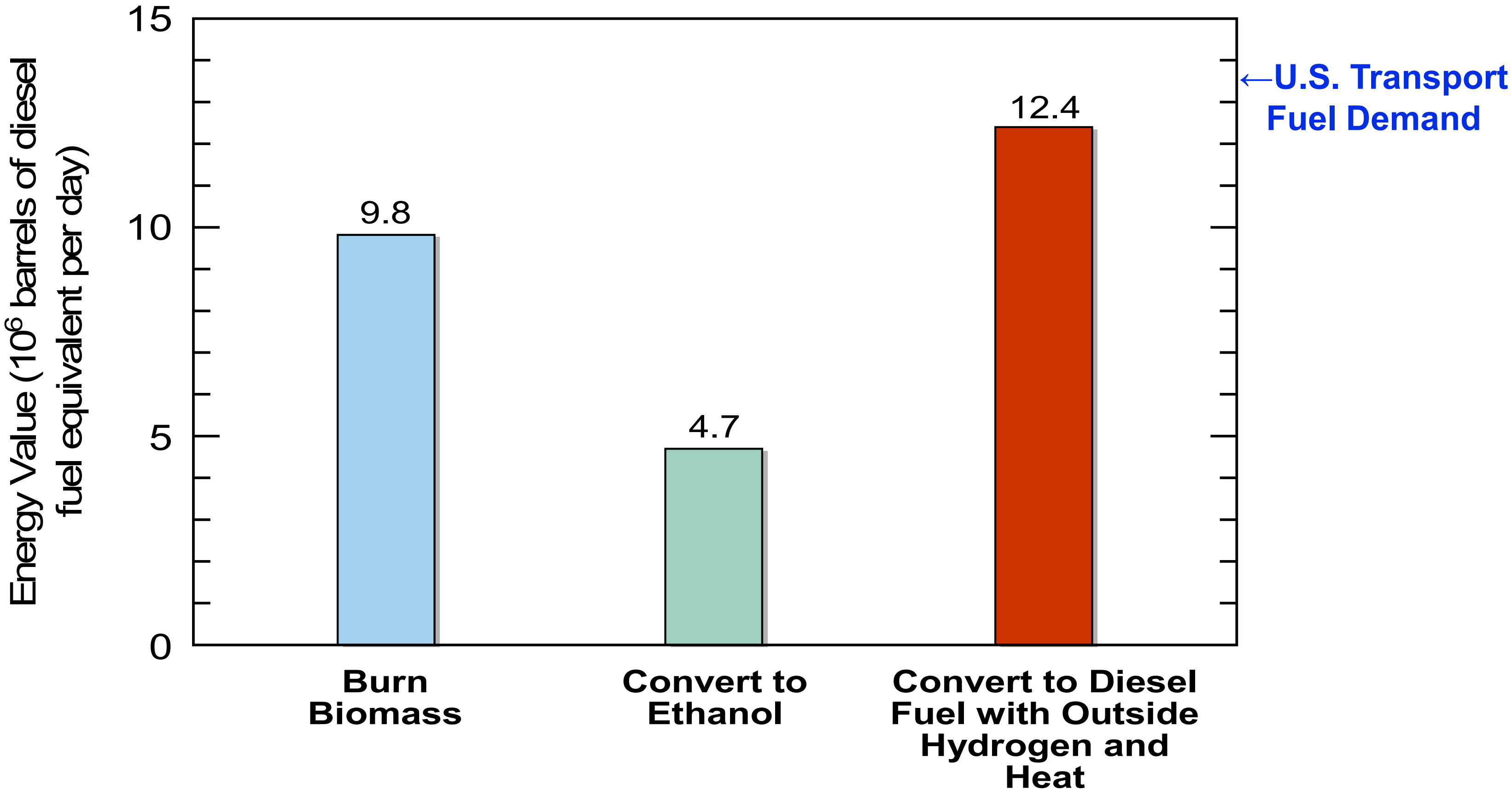



# Chemical Engineers Can Convert Any Carbon Source into Diesel



- But the less it looks Like diesel, the more energy and hydrogen it takes to convert a feedstock to diesel
- Chemical plants require constant energy input (long transition times to steady state).
- Natural gas is the primary energy source for chemical plants

# Biomass Conversion to Liquid Fuel Requires Energy




**Energy Value of 1.3 Billion Tons/year of U.S. Renewable Biomass Measured in Equivalent Barrels of Diesel Fuel per Day**

# Biomass Liquid Fuel Potential Depends Upon the Energy Source For Biomass-to-Liquid Fuels Plants

- Biomass is a limited resource
- Nuclear hydrogen and heat increases liquid fuels per ton of biomass by a factor of three
- Option makes biomass potentially a worldwide liquid fuel replacement for oil

**Algae**

# Hydrogen Futures

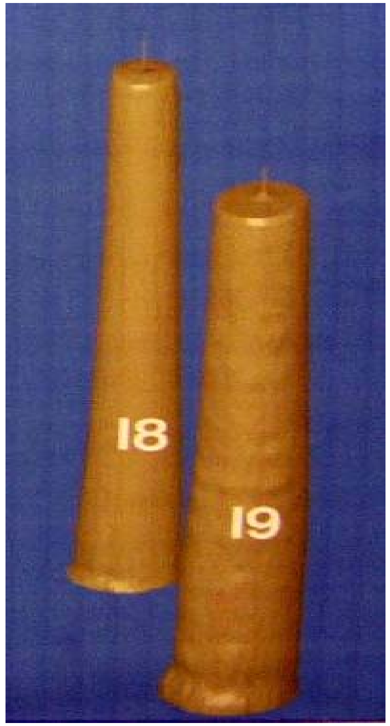
## A Storable Energy Carrier

**Hydrogen: An Intrinsically Large-Scale Technology**
**Electricity: Not Intrinsically a Large-Scale Technology**

# Hydrogen Future Characteristics

- **Electricity: Movement of Electrons**
  - Does not require large centralized production facilities
  - Not storable on a GW-year scale
- **Hydrogen: Movement of Atoms**
  - $H_2$ properties favor large-scale centralized systems
  - Storable on a GW-year scale
- **Three Unique Hydrogen Markets**
  - Liquid transport fuels production
  - Materials production
  - Peak electricity

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




- Underground storage is the only cheap hydrogen storage technology—but only on a large scale
- Technology
  - Underground storage in multiple geologies
  - Used for natural gas (~400 existing facilities in U.S.)
  - Existing hydrogen storage technology
- *Centralized hydrogen storage favors centralized hydrogen production to avoid transport costs*

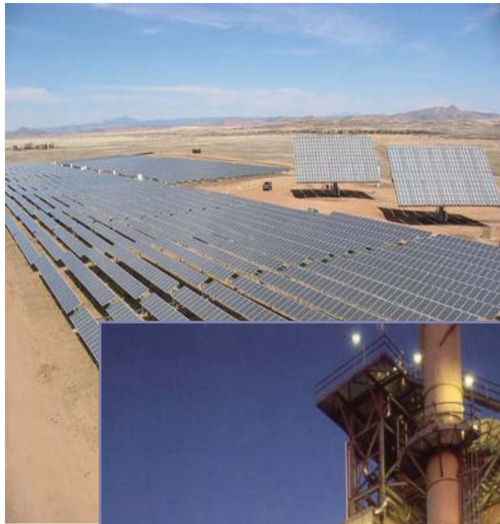
- ←Chevron Phillips↑ Clemens Terminal-$H_2$
- 160 x 1000 ft cylinder salt cavern

# Hydrogen Collection and Distribution are Different than for Electricity

- Electricity transport
  - Two-way systems with transformers
  - Efficient methods to change voltage
- Hydrogen transport is similar to natural gas
  - Hydrogen transmits one way: high to low pressure
  - Large economics of scale associated with hydrogen compression
- **$H_2$ transport characteristics favor centralized production, storage, and distribution**


# Hydrogen Production Favors High-Capacity Centralized Systems

- $H_2$ properties create major problems in small systems
  - $H_2$ leakage (surface to volume effect)
  - Inefficient $H_2$ compression
- Economics of Scale
  - Electricity (<u>Electrons</u>):
    - Multiple production methods (wind, nuclear, coal, etc.)
    - Plant sizes vary by over 3 orders of magnitude
    - Electricity costs vary by a factor of 3
    - Not intrinsically a large-scale technology
  - Hydrogen (<u>Atoms</u>):
    - 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 • $10^6$ $m^3$/day

# Nuclear Energy and Centralized Solar Systems Match $H_2$ Production Needs

**Could Hydrogen Production be the Long-Term Future of Nuclear Power?**

# Hydrogen for Materials Production

## Iron, Cement, and Other Materials

# Hydrogen Can Replace Carbon For Materials Production

- We use massive quantities of materials: steel, concrete, etc.
- The earth is made of oxides and carbonates, not metals or cement
- **Fossil fuels are the chemical reducing agents to convert oxides and carbonates to useful materials**

# The Chemistry of Materials Production

## (Example: Steel Production)

- Oxidized raw material (iron ore) + Carbon (coal, oil or natural gas) → Partly refined material (pig iron) + Carbon dioxide ↑

- Partly refined material (pig iron) + Added Processing → Steel

# The Chemistry of Materials Production Is Switching to Hydrogen

- Carbon (coal, oil or natural gas) + Oxygen + Water → Hydrogen + Carbon dioxide ↑
- Oxidized raw material (iron ore) + Hydrogen → Steel + Water
- Hydrogen is used for 4% of iron production to produce high-purity iron

**Hydrogen Can Be the Chemical Reducing Agent That Our Physical World Is Built On**

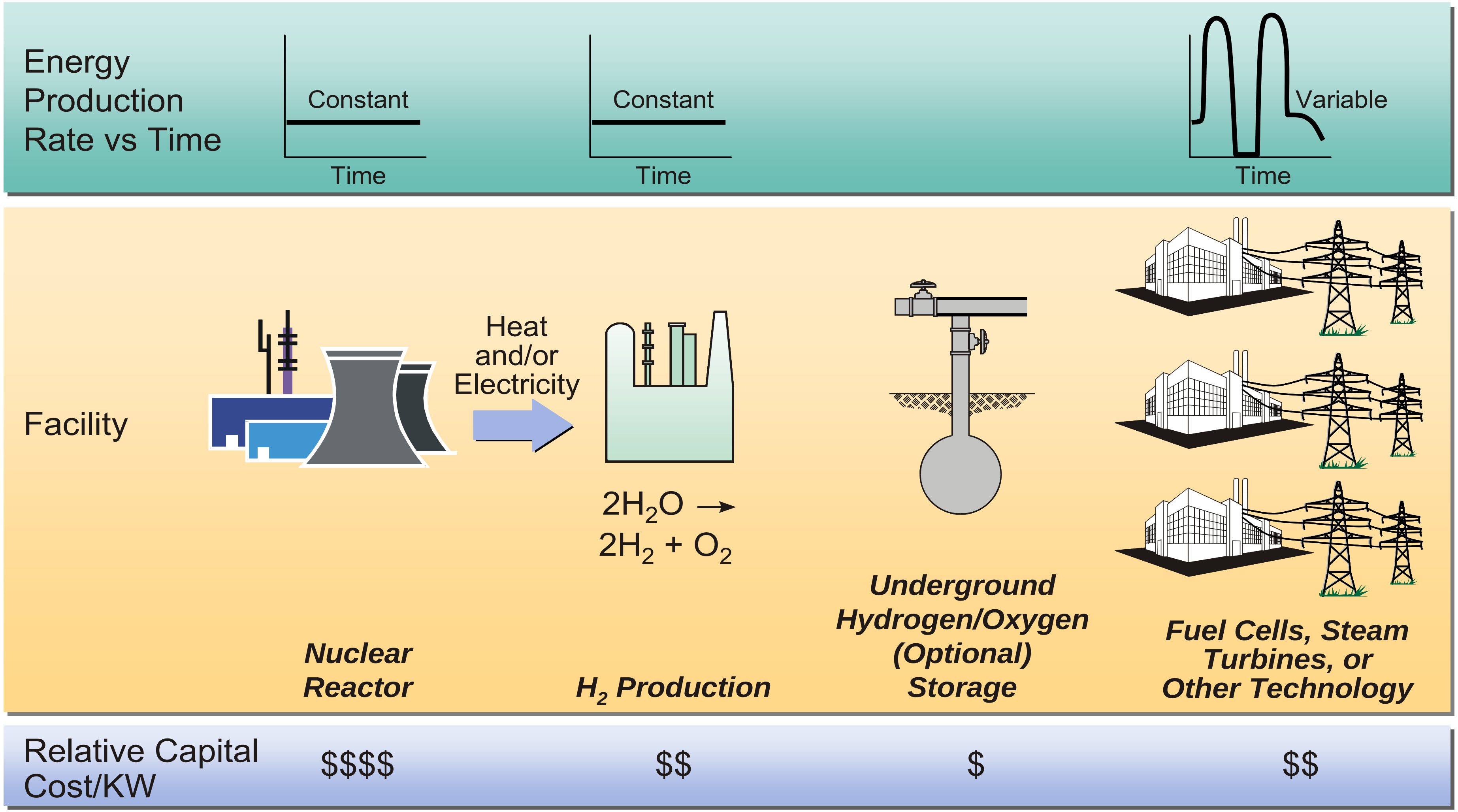
# Hydrogen for Peak Electricity Production

## Multiple Technology Options

# Potential for Electric Renewables

- There is no theoretical reason why solar cells could not be cheap
- Impacts
  - Highly variable renewable power output
  - Massive increase in peak power demand when the wind does not blow or the sun does not shine
- Renewable viability depends upon solving daily, weekly and seasonal electricity storage

# Hydrogen Intermediate and Peak Electric System (HIPES)



# Non-Fossil Methods Convert Water Into Hydrogen and Oxygen

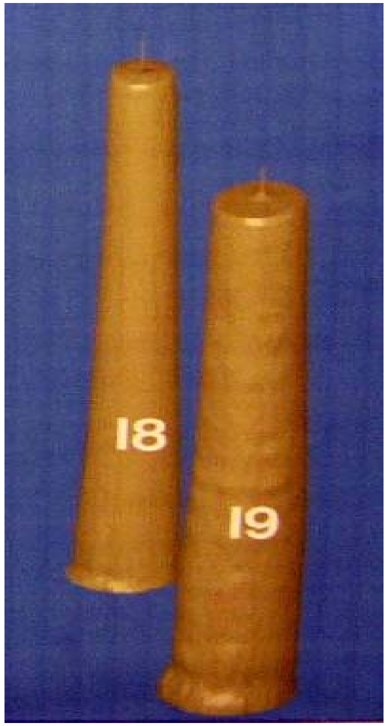
- Fossil-fuel hydrogen methods produce hydrogen but not oxygen
- Low-carbon hydrogen production
  - Electrolysis (Current)
  - High-temperature electrolysis
  - Hybrid
  - Thermochemical (Heat input)

**Norsk Atmospheric Electrolyser**

**Nuclear and Centralized Solar Hydrogen Characteristics: Hydrogen, Oxygen, Heat, and Centralized Delivery**

# HIPES Is Based on Low-Cost Underground $H_2$ and $O_2$ Storage

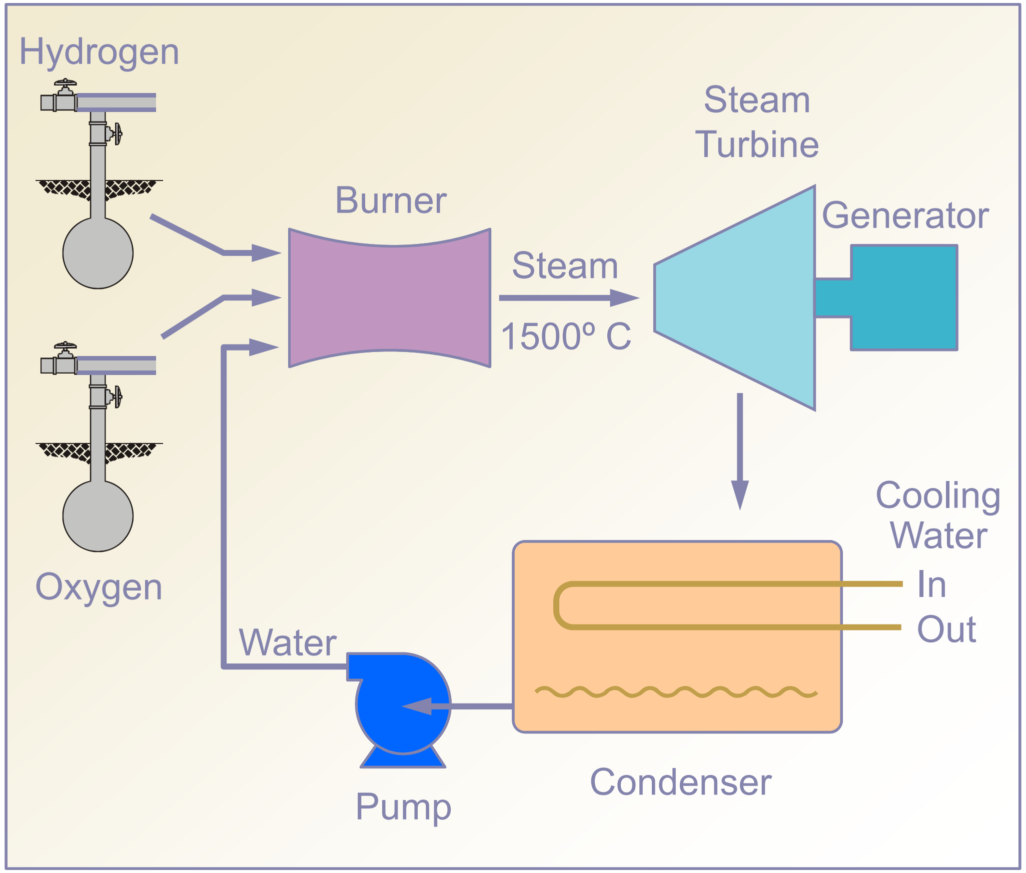
- Technology status
  - Hydrogen storage commercial
  - Oxygen storage not commercial
- $H_2/O_2$ storage enables low-cost efficient peak power production




- ←Chevron Phillips↑ Clemens Terminal-$H_2$
- 160 x 1000 ft cylinder salt cavern

# Low-Cost High-Efficiency Methods Are Being Developed to Convert $O_2/H_2$ to Electricity

- 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




Alternative: Hydrogen/Oxygen Fuel Cell

# Oxy-Hydrogen Combustor Replaces Steam Boiler: Lower Cost & Higher Efficiency

## But Requires Hydrogen and Oxygen As Feed

**Oxy-Hydrogen Combustor to Produce Steam**

**Coal Boiler to Produce Steam**

# Demand Side: Plug-In Hybrid Electric Vehicles (PHEVs)

**Demand Side Option To Address Variable Daily, Weekly and Seasonally Energy Demand**

**Cars / Light Trucks: The Biggest Energy Users**

# PHEVs: Recharge Batteries from the Electric Grid Plus Use of Gasoline

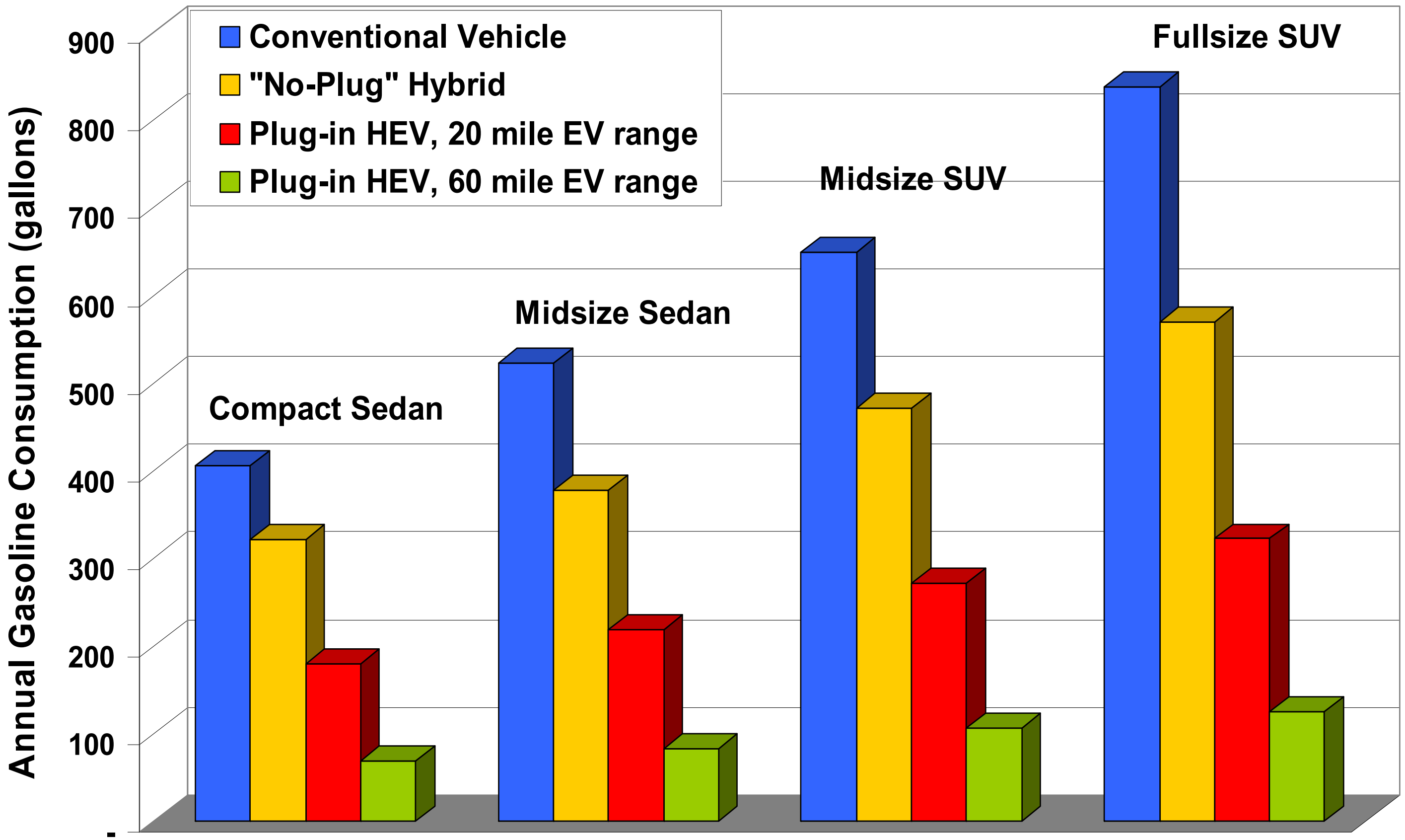
- Electric car limitations
  - Limited range
  - Recharge time (Gasoline/Diesel refueling rate is ~10 MW)
- Plug-in hybrid electric vehicle
  - Electric drive for short trips
  - Recharge battery overnight to avoid rapid recharge requirement
  - Hybrid engine with gasoline or diesel engine for longer trips
- Connects cars and light trucks to the electrical grid

Courtesy of the Electric Power Research Institute

# PHEVs: Annual Gasoline Consumption

## Substituting Electricity for Liquid Fuels

### U.S. Average Driving Cycle




Courtesy of the Electric Power Research Institute

# Plug-In Hybrid Electric Vehicles: Dual Energy Demand System

- Duel fuel use
  - Electricity
  - Gasoline
- With energy pricing, capability to move demand between electricity and gasoline
  - Electricity and gasoline do not have the same weekly and seasonal demands
  - Demand side option to address energy storage challenge

# Conclusions

- Future energy systems are likely to be more diverse and driven by two challenges (no fossil monoculture)
  - Low-carbon energy production
  - Energy storage for days, weeks, and months
- New energy / storage systems required
  - Combined nuclear-bio and nuclear-renewable systems
  - Requires thinking beyond energy production
- Hydrogen futures
  - The primary incentive for a hydrogen economy is the ability to store energy
  - The physics of hydrogen supports large-scale systems
  - Uses: Liquid fuels, peak electricity, and materials production
- The grand challenge—Addressing energy production and energy storage

# Backup Slides

# Biography and References

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 and the American Association for the Advancement of Science. Dr. Forsberg is the 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 10 patents and has published over 200 papers.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## —Abstract—

# Innovative Energy Sources: The Post Fossil World

**Charles Forsberg**

We live in a monoculture energy world based on fossil fuels that provides energy and a method to store energy. Coal piles, oil tanks, and natural gas caverns allow our energy demand to swing each day, each week, and over the seasons. The depletion of oil reserves and the challenge of climate change imply we are entering the end of the age of fossil fuels. While the newspapers provide headlines of new energy sources, the silence is deafening on how to replace the storage function of fossil fuels that matches energy production with energy consumption. Nuclear energy and electricity from fossil fuels with carbon dioxide sequestration both provide energy at a constant rate. Renewable energy consumption depends upon when the wind blows and the sun shines. None of these or any combination matches energy production with energy demand. Innovative energy sources and systems are required that meet both characteristics of fossil fuels: energy sources and energy storage.

The solutions will require combining energy sources in different ways. Today, countries such as Sweden combine base-load nuclear with hydro for carbon-free electricity—but most of the world does not have sufficient hydro for this option. However, there are new options on the horizon. Biomass can be converted to storable liquids; however, biomass is limited. Nuclear biomass systems that use nuclear heat and hydrogen can boost the liquids fuel production per ton of biomass by a factor of three—sufficient to meet world liquid fuel demand. Hydrogen can be stored at low cost for months in underground caverns. The technical characteristics of hydrogen make it a highly centralized technology that will likely couple to centralized nuclear and solar production systems. Hydrogen then becomes the feedstock for materials production, peak electricity production, and liquid fuels production. On the demand side, there are a few technologies that can address weekly and seasonal changes in energy demand—most noteworthy is the plug-in hybrid vehicle.

The grand energy challenge may not be finding ways to produce energy. It may instead be ways to produce energy and store that energy to meet our variable energy demands.

# Today's Methods For Peak Electricity Production

| Requirement | Hydro | Fossil |
|---|---|---|
| **Energy Storage** | Lake behind dam | Oil tank or natural gas |
| **Electricity Production** | Hydro-turbine | Gas turbine |
| **Limitation** | Hydro sites (water storage) | Climate change |

Carbon dioxide sequestration likely to be prohibitively expensive for fossil peak power units that operate a few hours per day