# Synergisms Between Nuclear Hydrogen, Renewable Electricity, and Coal Liquefaction

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*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: HIPES: MIT Nov06

# Abstract: Synergisms Between Nuclear Hydrogen, Renewable Electricity, and Coal Liquefaction

Different hydrogen production methods have different characteristics. The defining characteristics of hydrogen from nuclear systems are: (1) centralized, large-scale production, (2) co-production of hydrogen and oxygen, and (3) availability of low-cost heat.

Those characteristics may enable the large scale use of renewable electricity by providing a low-cost method to provide backup electricity when the sun does not shine and the wind does not blow. Centralized nuclear hydrogen couples with large-scale underground storage of hydrogen and oxygen. That combination potentially enables the development of low-cost methods to produce intermediate and peak electrical power. The use of hydrogen and oxygen in power conversion systems potentially results in much lower costs for intermediate and peak electricity production than power conversion systems that use hydrogen and air.

In the context of coal liquefaction, coal liquefaction plants require large inputs of hydrogen, oxygen, and heat. The inputs match the outputs of nuclear hydrogen production. Coal liquefaction with nuclear hydrogen avoids greenhouse gas releases in the production of liquid fuels. For traditional coal liquefaction plants, more greenhouse gases are released in the production of liquid fuels than in the burning of liquid fuels.

# Nuclear Hydrogen Synergisms

- **Nuclear hydrogen ($H_2$) synergies are applications where the characteristics of nuclear-$H_2$ systems combined with the user needs result in <u>economic savings relative to other methods to produce $H_2$</u>**
  - **WIN — WIN**
- **The <u>extra value</u> for nuclear $H_2$ in these markets is a result of one or more characteristics of nuclear $H_2$ relative to other $H_2$ production technologies**
  - **Co-production of $H_2$ and oxygen (Fossil systems only produce $H_2$)**
  - **Centralized large-scale production**
  - **Availability of heat**

# Nuclear Hydrogen For Peak Electricity Production

## An Enabling Technology for Renewable Electricity

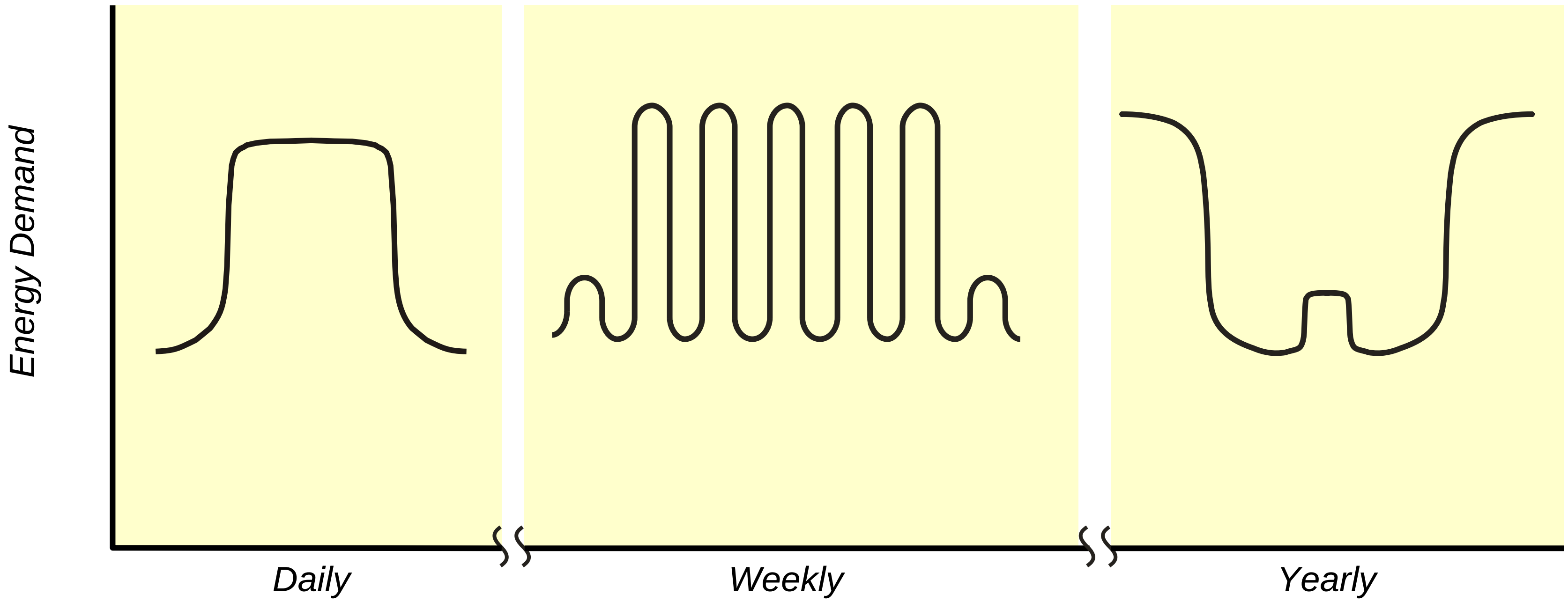
# The Challenge

## Characteristics of the Electricity and $H_2$ Markets

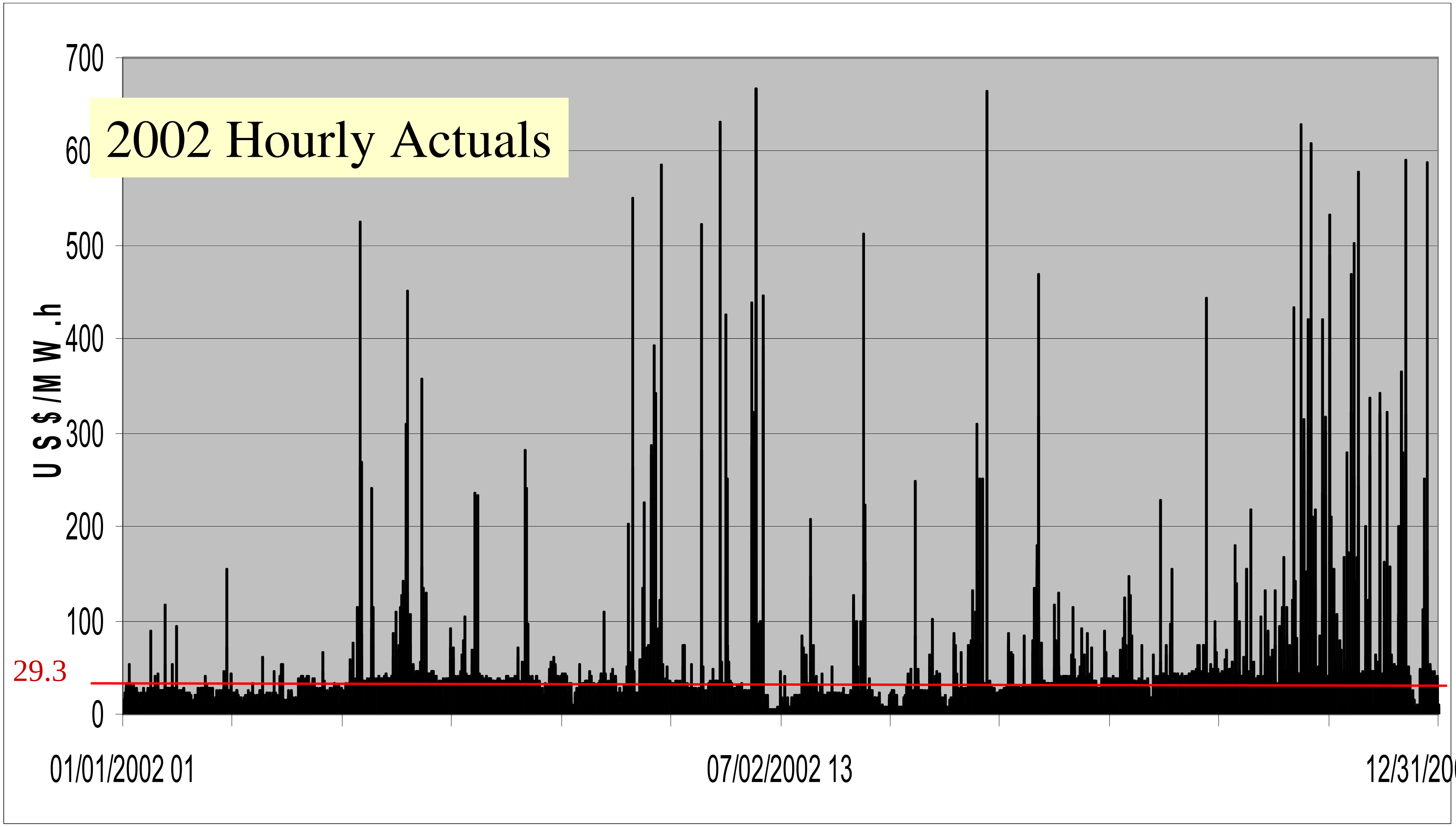
## Characteristics of Energy Sources

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

(A Large-Scale $H_2$ Economy Will Have Similar Characteristics)



# The Price (and Cost) of Electricity at Times of Peak Demand is High






[Alberta Power Pool (US$/MW-h)]

# Different Electricity Sources Have Different Economic Characteristics

| Energy Source | Capital Cost | Operating Cost |
|---|---|---|
| Nuclear | High | Low |
| Renewables | High | Low |
| Fossil | Low | High |

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

# Hydrogen Production Options

- **Near term: Electrolysis**
  - **Base-load**
  - **Night-time and weekend**
- **Longer term (Nuclear or Solar)**
  - **High-temperature electrolysis**
  - **Hybrid**
  - **Thermochemical**

**Norsk Atmospheric Electrolyser**

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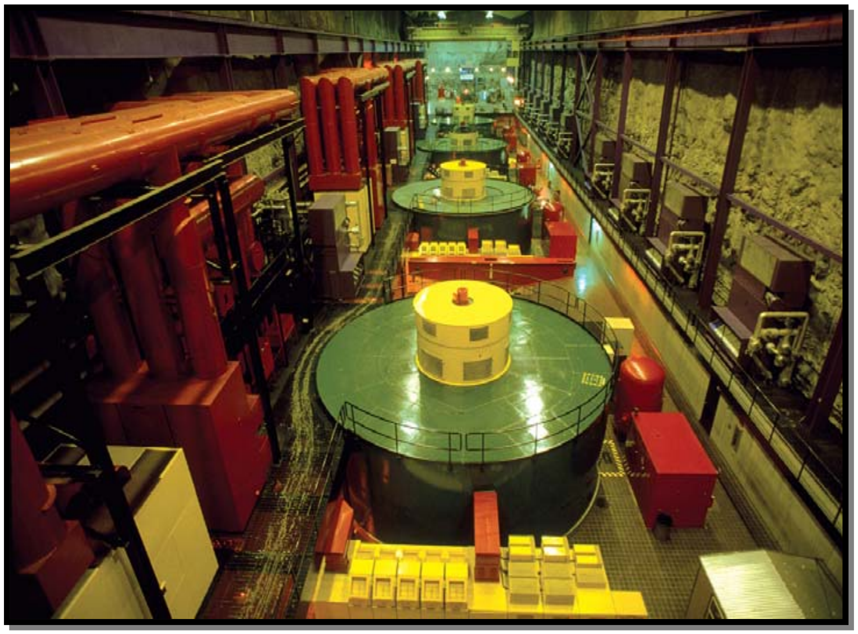
**"Base-Load" Operations are Required for Low-Cost Nuclear and Renewable Hydrogen**

# Large-Scale Renewable Electric Production May Not Be Viable Without Electricity Storage

- **Large-scale electric renewables (>10% of electricity) requires delivery of electricity when needed**
- **There are windless days, cloudy days, and night**
- **Backup power is expensive**

# Limited Electricity Storage Options — < 1 Day Capacity: Not Match Renewable Need



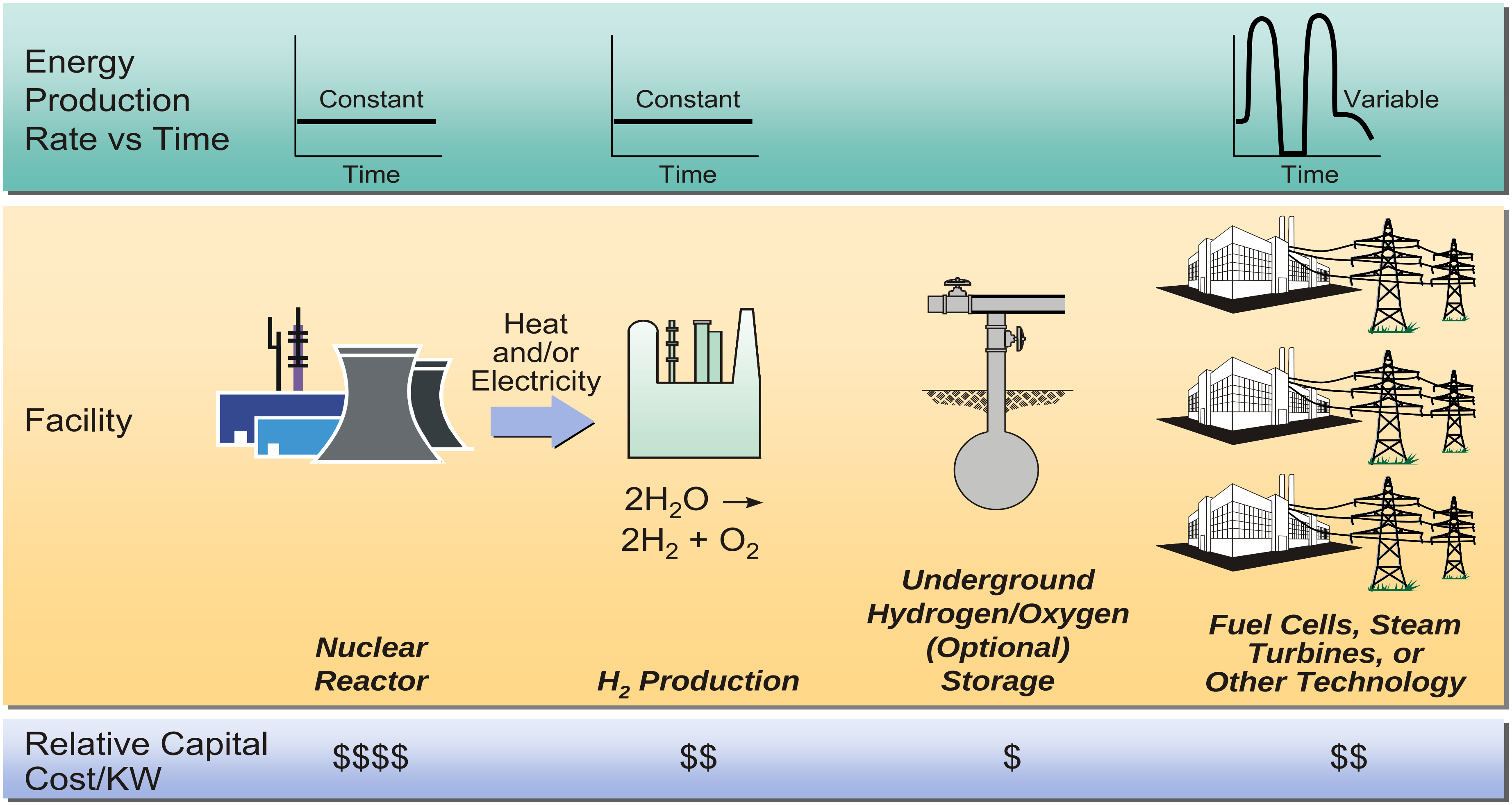
- **Hydro Pump Storage**
  - Storage for hours (Water volume)
  - Example: TVA Raccoon Mountain →
    - 1530 MW(e)
- **Compressed Air Energy System**
- **Flow Batteries**

# A Potential Solution To Produce Lower-Cost Peak Electricity

# The Hydrogen Intermediate and Peal Electrical System (HIPES)

# Hydrogen Intermediate And Peak Electrical System to Meet Variable Electrical Loads

(A Daily, Weekly, and Seasonal Solution to the Renewable Electrical Storage Problem

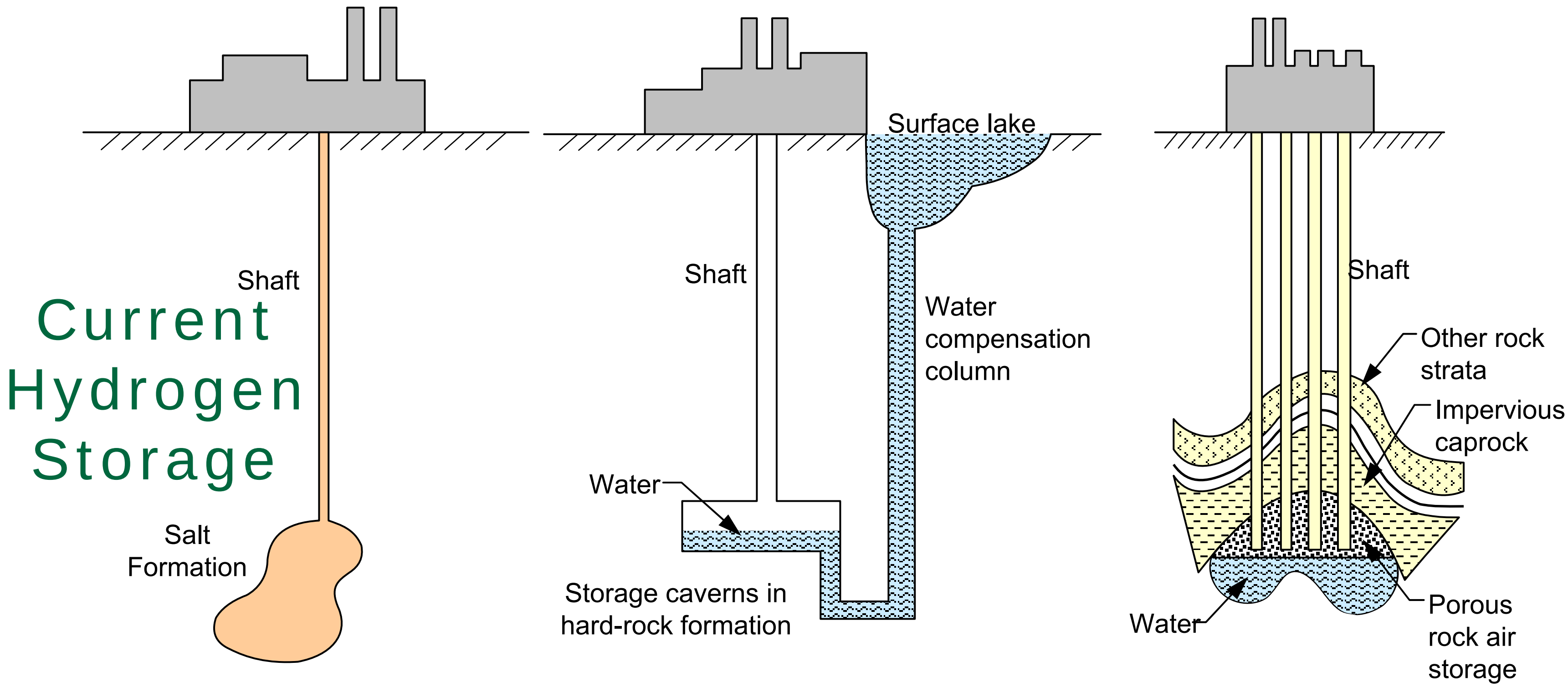


# Hydrogen Production Options

- **Near term: Electrolysis**
  - **Base-load or night-time electricity**
- **Longer term (Nuclear or Solar)**
  - **High-temperature electrolysis**
  - **Hybrid**
  - **Thermochemical**

**Norsk Atmospheric Electrolyser**

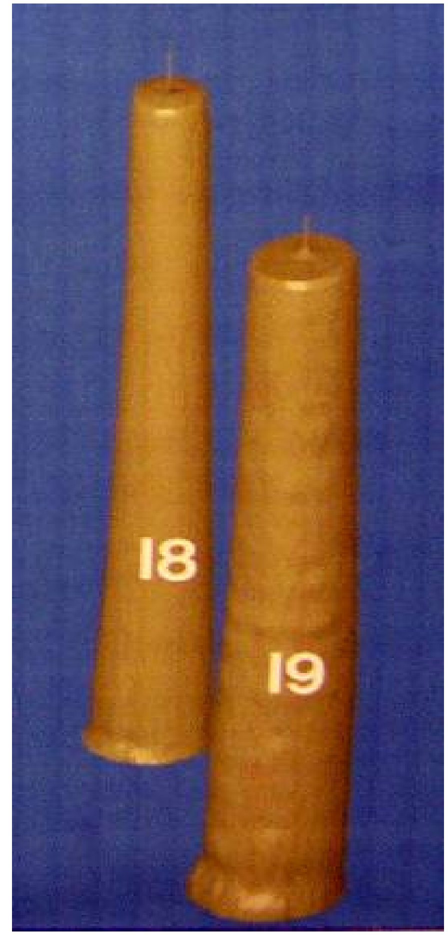
# Hydrogen (Like Natural Gas) Is Stored Underground




U.S. Natural-Gas Storage Volume Equals 1/3 Annual Consumption

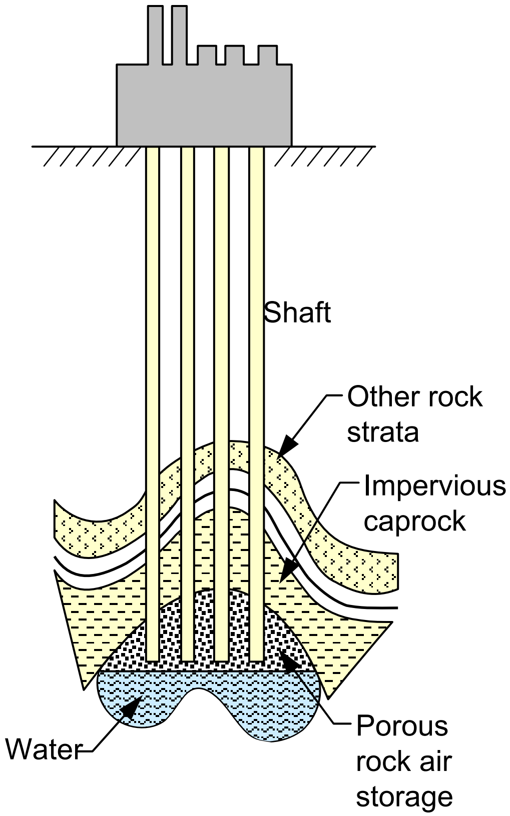
# Large-Scale Hydrogen Storage Is Inexpensive

- **Commercial technology in salt**
- **Not currently commercial in other geologies**
- **Based on natural-gas storage technology**
- **<u>Small-scale $H_2$ storage is expensive</u>**




**Chevron-Phillips Clemens Terminal**
**(160’ X 1,000’ Cylinder Salt Cavern)**

# Underground Bulk $H_2$ Storage Cost 1/100 of Other Technologies (Same Technology Used for Natural Gas)




## Constraints*

**Economics demands high-volume $H_2$ storage**

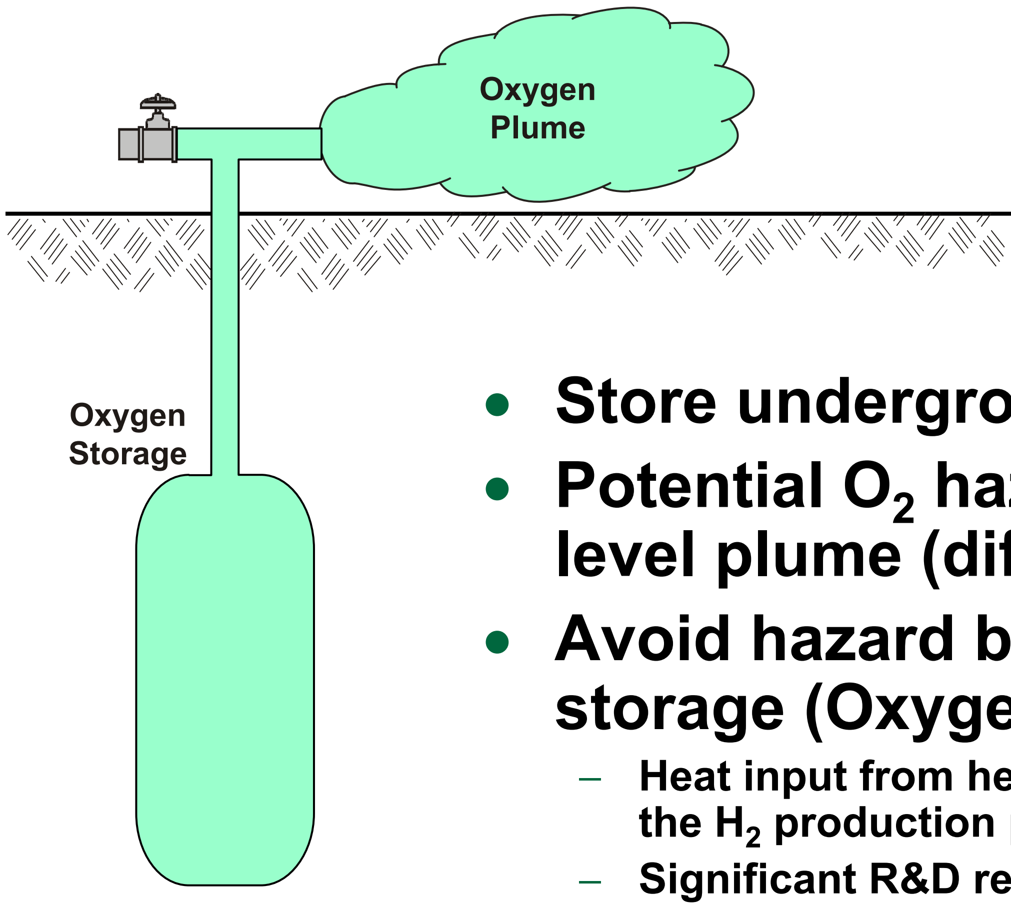
**$>10^{10}$ $ft^3$/facility**

**Capital Cost: \$0.80-1.60/kg $H_2$**

**Centralized $H_2$ production avoids $H_2$ collection costs**

*Based on Natural Gas Experience

# Oxygen Storage Minimizes HIPES Costs Per kW(e); But, It Creates Challenges




- **Store underground like $H_2$**
- **Potential $O_2$ hazard is a ground-level plume (difficult to transport)**
- **Avoid hazard by heating $O_2$ before storage (Oxygen rises if it escapes)**
  - **Heat input from heat source or inefficiencies in the $H_2$ production process**
  - **Significant R&D required**
- **Other options**

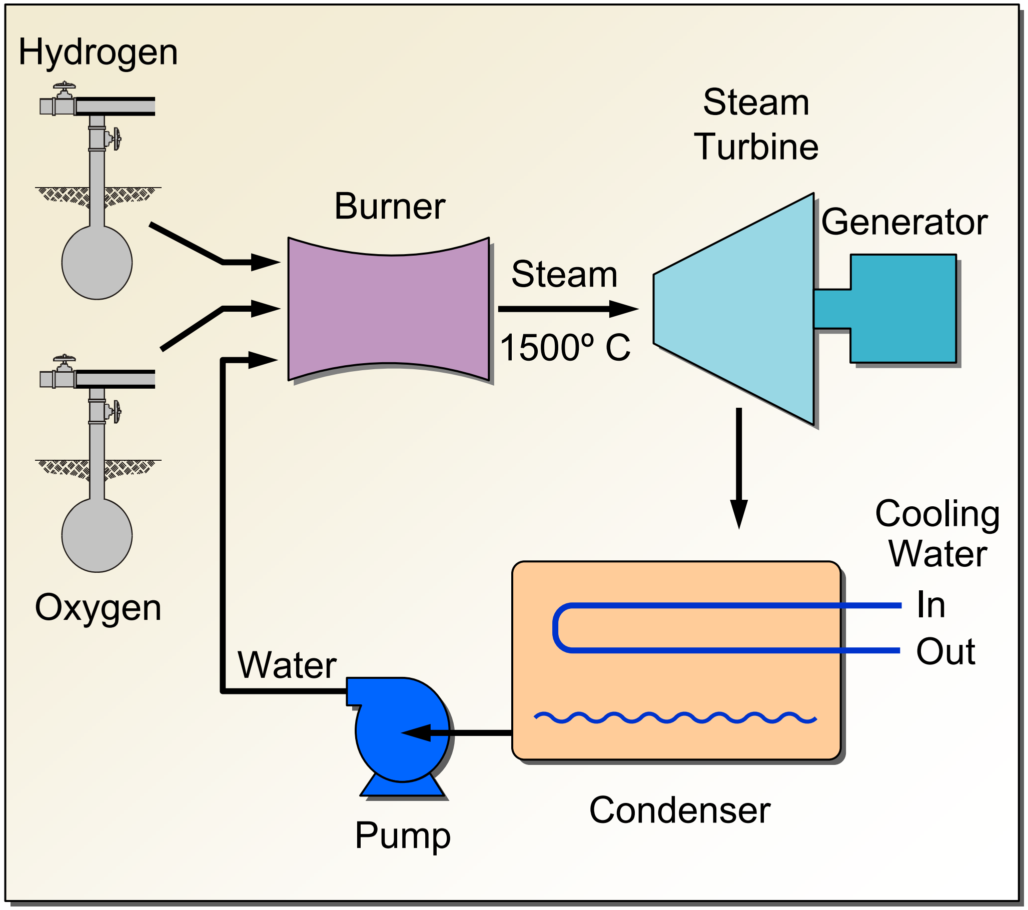
# HIPES Requires Low-Cost Efficient Conversion of $H_2$ and $O_2$ to Electricity

- **Hydrogen production systems operate at high load factors to minimize $H_2$ production costs**
- **Storage is cheap**
- **Hydrogen-to-electricity systems operate a <u>limited number of hours per year</u>**
  - **Require low capital costs per kW(e)**
  - **Require high efficiency**
- **Multiple options based on $H_2$ and $O_2$ feed**
  - **Steam turbines**
  - **Fuel cells**

# HIPES Steam Turbine For Electricity*

(Low-Cost Conversion of $H_2$ and $O_2$ to Electricity)

- **Nuclear $H_2$ "extra value" synergies**
  - **$H_2$ and $O_2$ available**
  - **Size**
- **High-temperature steam cycle**
  - **$H_2 + O_2 \rightarrow$ Water**
- **Low cost**
  - **No boiler**
  - **High-efficiency (70%)**

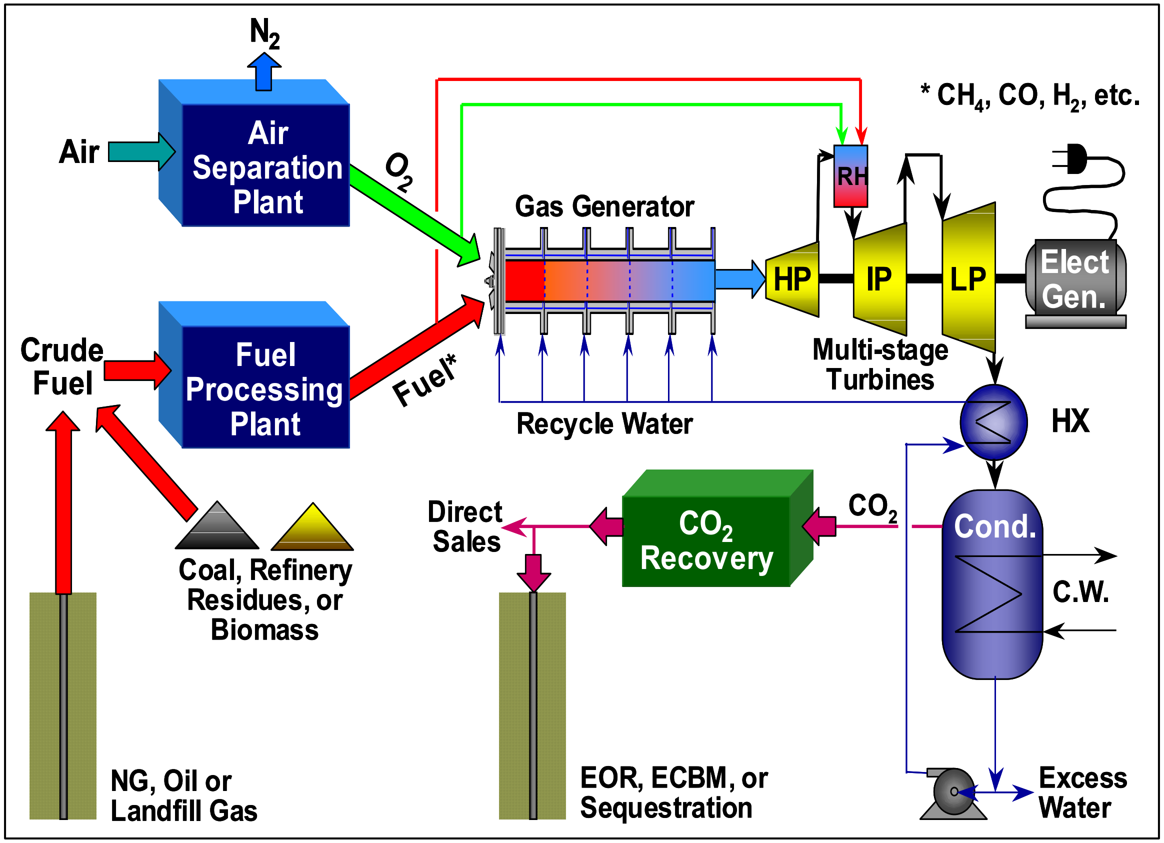





*20 MW(t) natural gas + $O_2 \rightarrow$ Electricity demonstration underway by Clean Energy Systems

# *Clean Energy Systems* Is Developing a Natural-Gas/Oxygen System

## Technology Applicable to HIPES; Technology Being Developed for Advanced Fossil Fuel Plants




20 MW(t) CES Combustor

Courtesy of Clean Energy Systems (CES)

# Hydrogen to Electricity Options

## HIPES

- New system
- Feed: $H_2$ and $O_2$
- Major Components (Low capital cost)
  - Combustor
  - Steam turbine
  - Electric generator
- Efficiency: 70%

## Combined Cycle

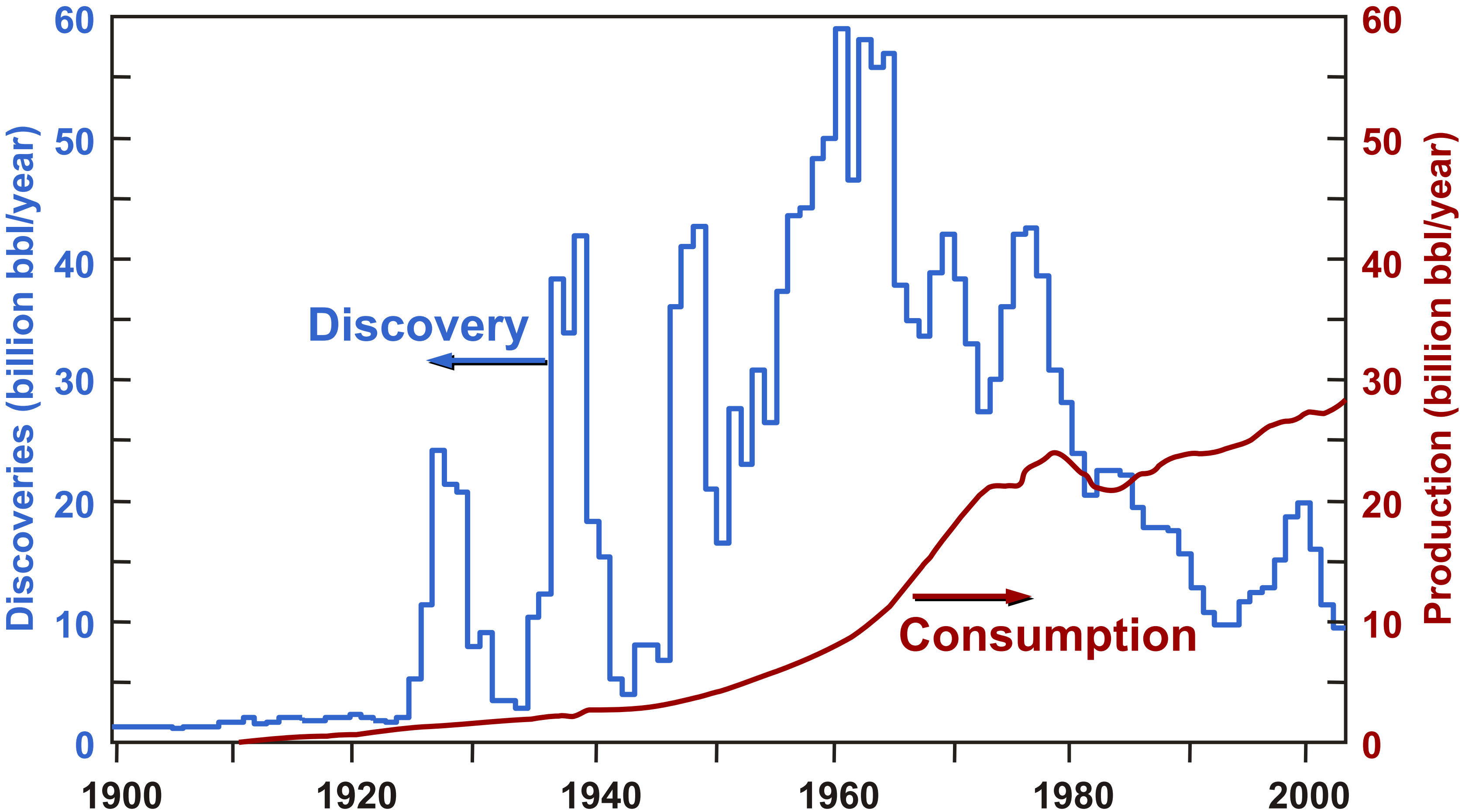
- Commercial (Natural-gas electric plant)
- Feed: $H_2$ and air
- Major Components
  - Combustor
  - Gas turbine
  - Steam boiler
  - Steam turbine
  - Electric generator
- Efficiency: 54%

# HIPES May Enable Large-Scale Renewable Electricity

- **Addresses the renewable electricity challenge: economic backup power when needed**
- **HIPES matches nuclear $H_2$ characteristics**
  - **$H_2$ and $O_2$**
  - **Large scale to match storage characteristics**
    - **No collection of $H_2$ from dispersed sources**
    - **No long-distance transport of $O_2$**
  - **Heat**
- **Grid electricity-electrolysis variants of HIPES increase the demand for base-load electricity**
  - **Other challenges**

# Nuclear Hydrogen For Fossil Liquid-Fuels Production

# The Age of Oil for Fuels is Closing




OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Oil and Gas J.; Feb. 21, 2005

UT-BATTELLE

05-021

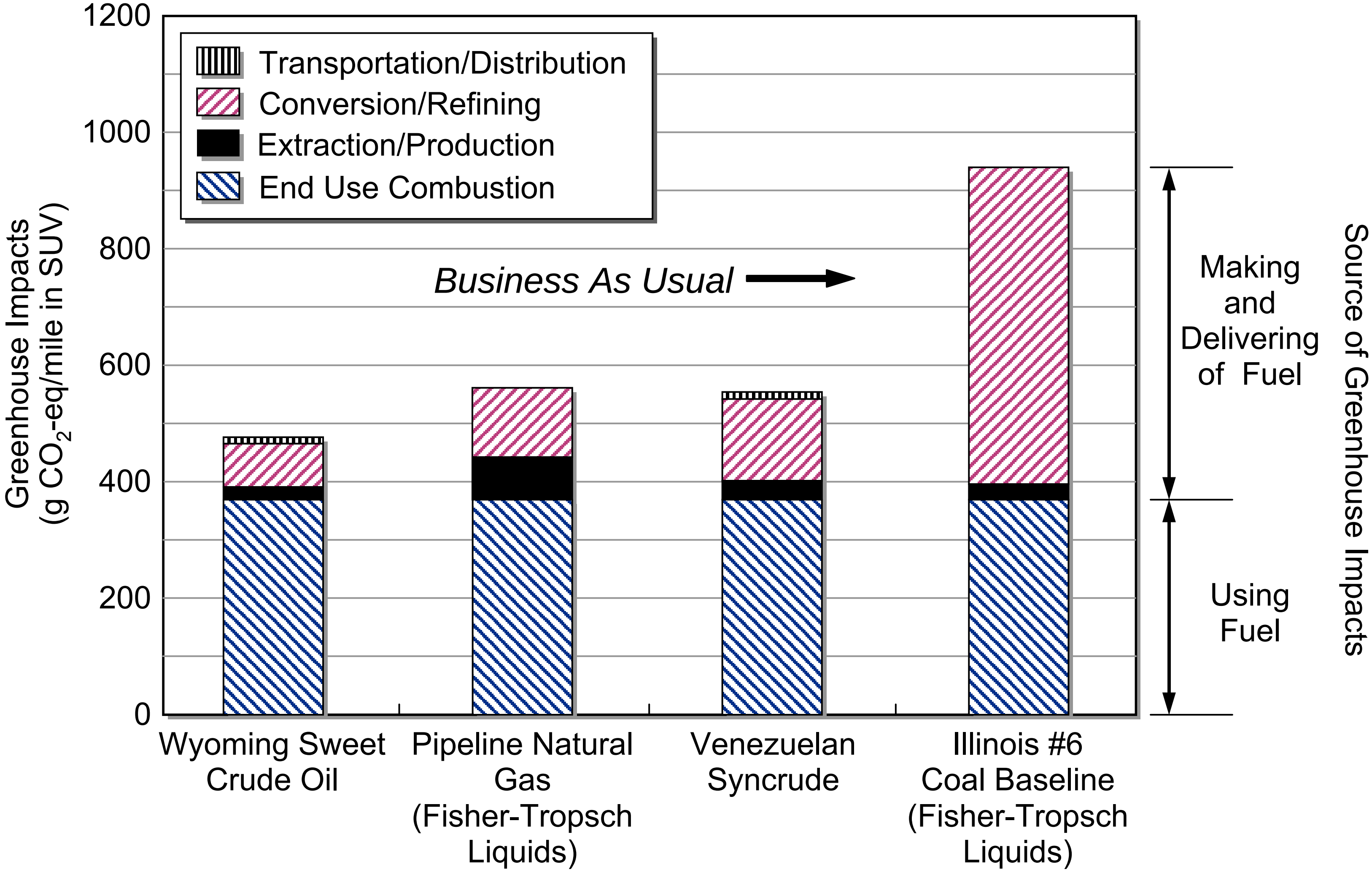
# Conventional Futures: Liquid Fuels From Heavy Oils and Tar Sands

**(Fossil Input: Low $H_2$-to-Carbon Ratio Feed)**

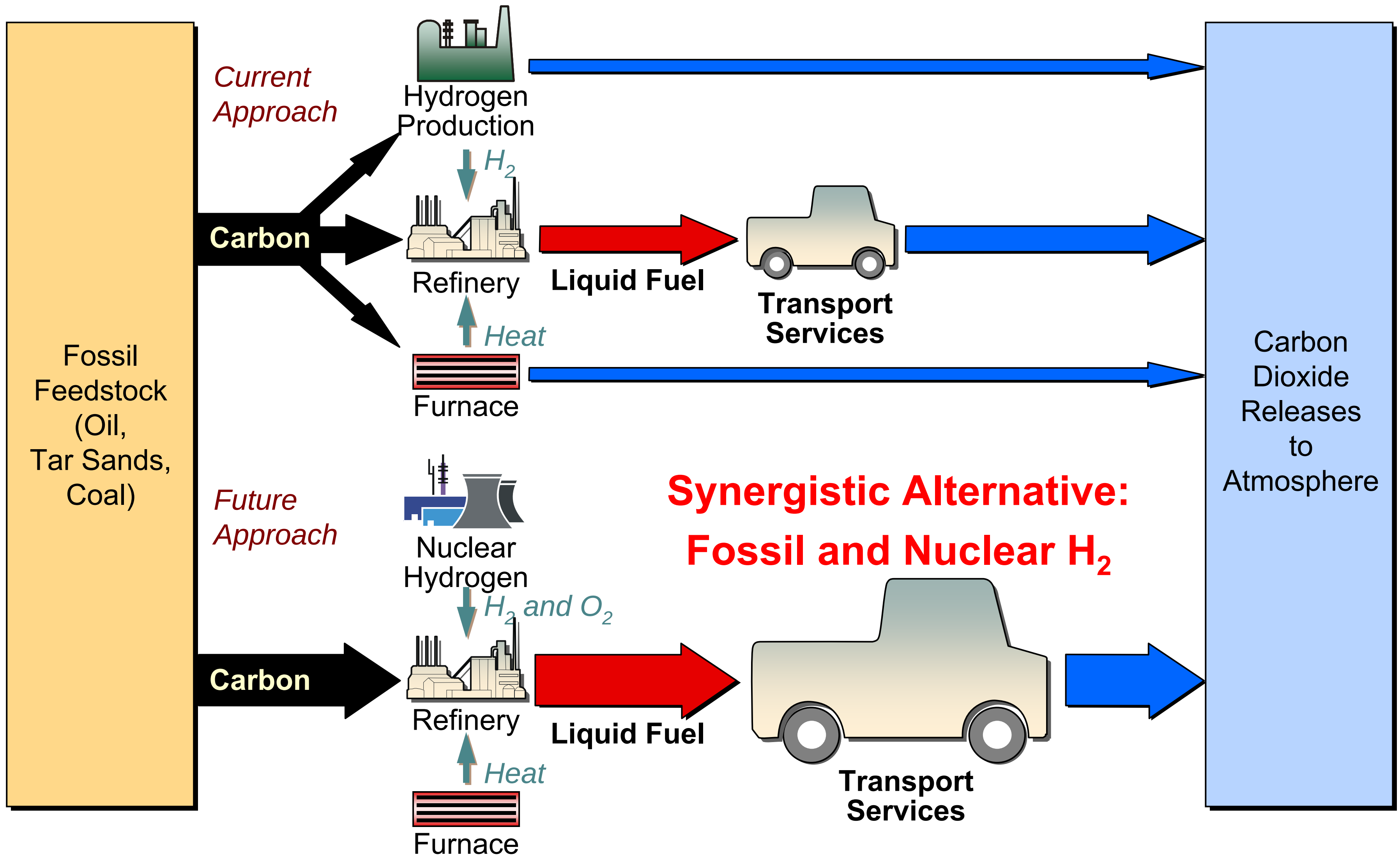
Syncrude Canada Ltd.
Tar Sands Operations


- **Liquid fuels have a high $H_2$-to-carbon ratio**
- **Tar sands and heavy oils are converted to liquid fuels by:**
  - **Addition of $H_2$**
  - **Removal of carbon with carbon dioxide ultimately sent to the atmosphere**
- **Implies major increases in greenhouse gas releases ($CO_2$) per vehicle mile**

# Conventional Futures Imply Increasing Greenhouse Emissions per Mile Traveled



# Nuclear Hydrogen can Increase Liquid Fuel per Unit of Feedstock and Reduce Emissions

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**Hydrogen sources: nuclear, renewables, and coal with carbon dioxide sequestration**

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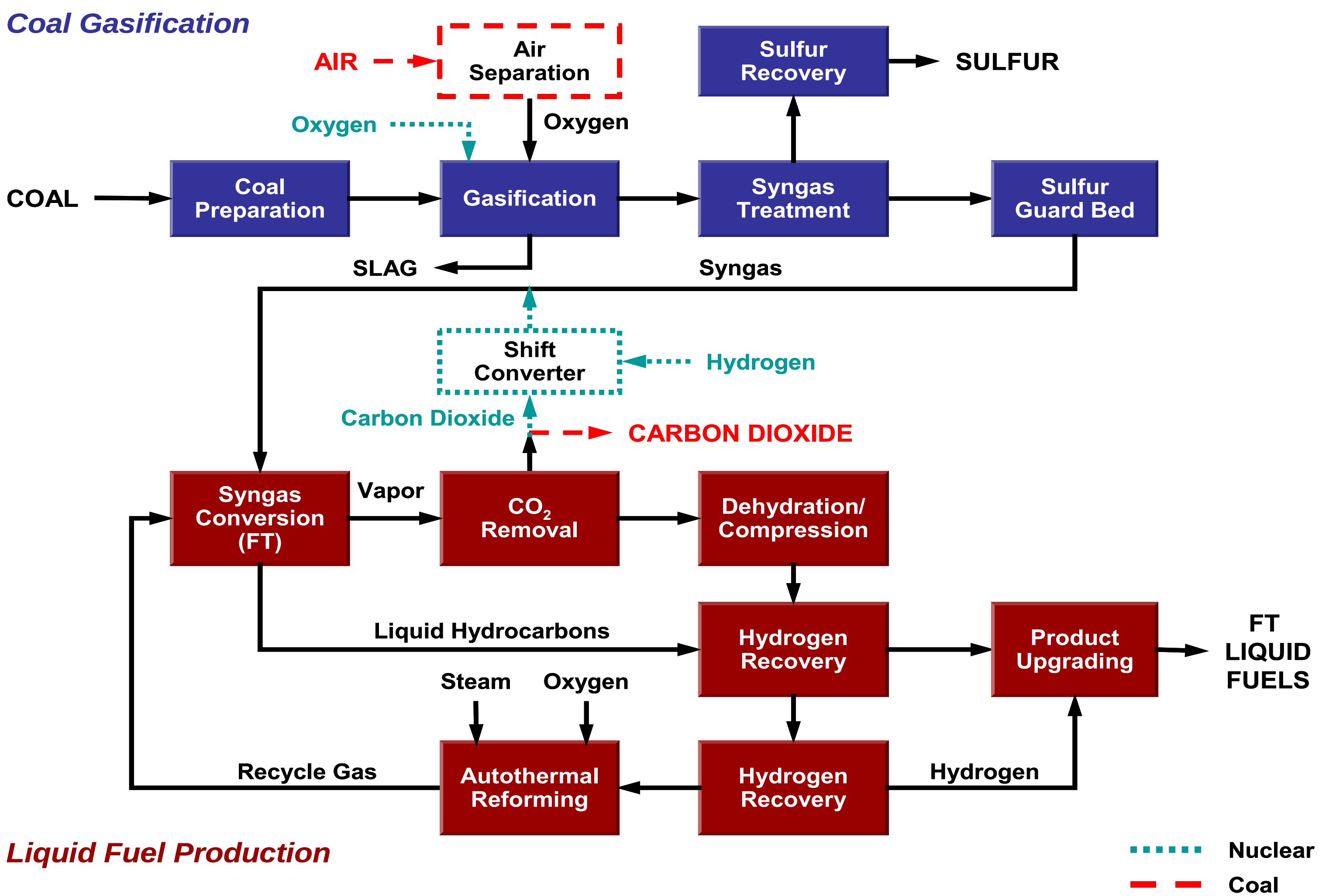
05-074

# Coal Liquefaction Needs Match Nuclear Hydrogen Capabilities

- **Centralized inputs to coal liquefaction plant match centralized nuclear $H_2$ plant outputs**
  - **Hydrogen**
  - **Oxygen**
  - **Heat**
- **Nuclear $H_2$ can eliminate greenhouse gas releases from the coal liquefaction process**
  - **Cut total greenhouse gas releases from liquid fuel <u>production and consumption</u> in half per vehicle mile**
- **Nuclear energy replaces coal as an energy source for process energy and $H_2$ demands**

# Fischer-Tropsch (FT) Liquid Fuels



# Conclusions

- **The initial markets for nuclear $H_2$ will likely be where nuclear $H_2$ provides "added value"**
- **Synergy: Hydrogen Intermediate and Peak Electrical System**
  - **Nuclear outputs ($H_2$, $O_2$, and heat) match HIPES needs**
  - **Entire system is owned by the electric utility**
    - **No separation of $H_2$ producer from user**
    - **Utilities familiar with nuclear operations**
- **Synergy: Liquid fuels from coal**
  - **Nuclear outputs ($H_2$, $O_2$, and heat) match coal liquefaction inputs**
  - **Avoids massive greenhouse impacts of coal liquefaction**
- **Need to develop technologies to take advantage of potential synergisms**

# Added Information

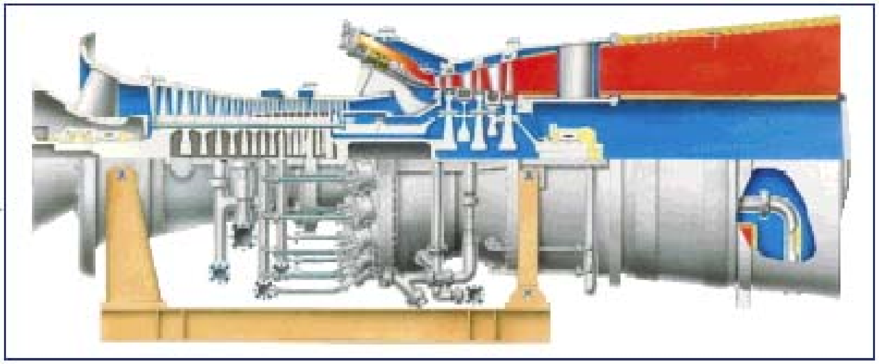
# Biography:  Charles Forsberg

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. Charles 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 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.

# Fossil Fuels Are Used To Match Electricity Demand With Production

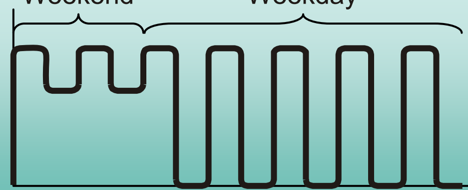
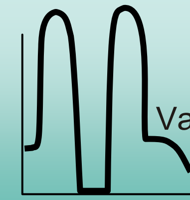
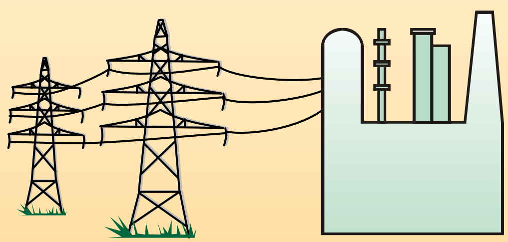
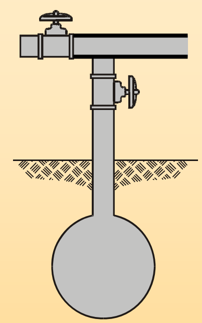
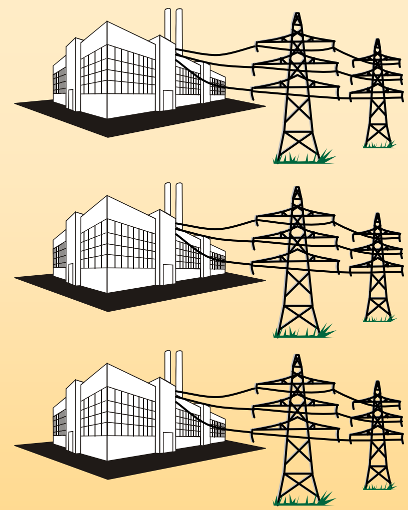
- **Fossil fuels are <u>cheap to store</u> (coal piles, oil tanks, etc.)**

- **Systems to convert fossil-fuels to electricity have relatively <u>low capital costs</u>**



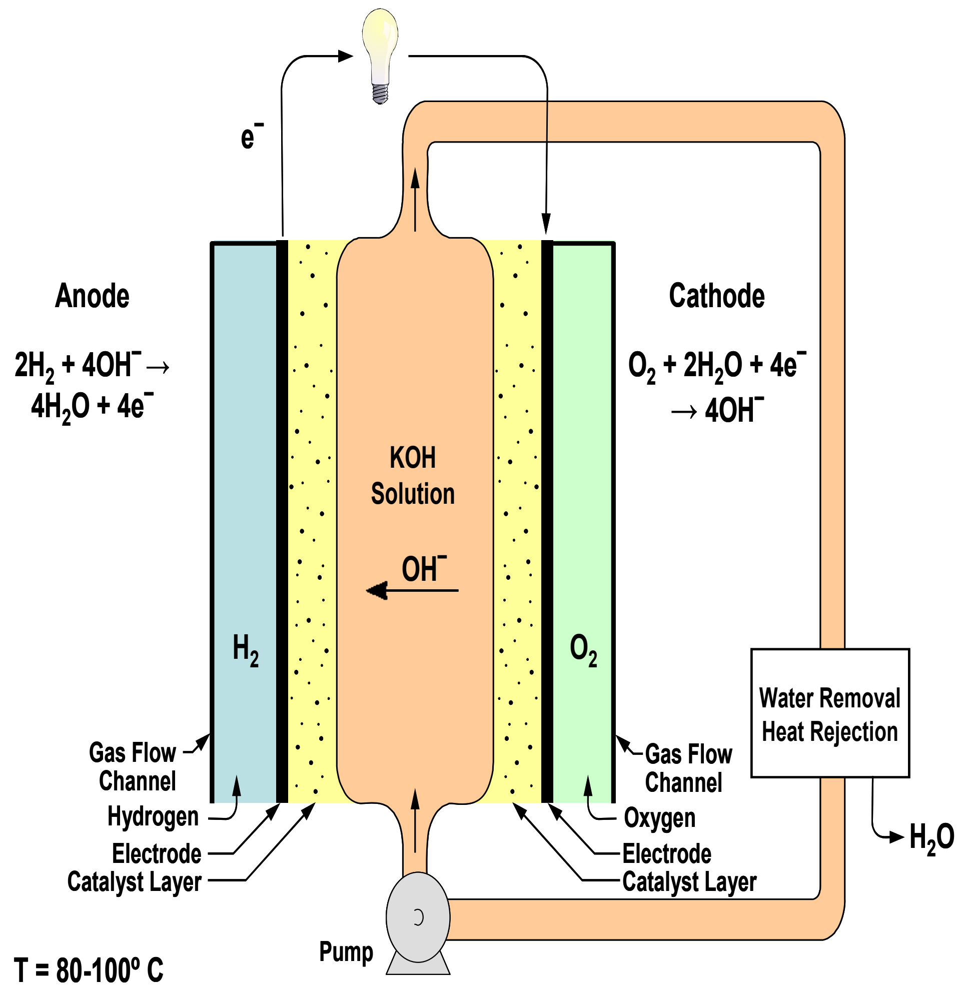
- **If fossil fuel consumption is limited, what alternatives have fossil-fuel-electrical system characteristics ?**

# HIPES: Grid Electricity and Electrolysis

| | *H₂ Production* | *Underground Hydrogen/Oxygen (Optional) Storage* | *Fuel Cells, Steam Turbines, or Other Technology* |
|---|---|---|---|
| Energy Production Rate vs Time |   | |   |
| Facility | Electrolyzer Complex  $2H_2O \rightarrow 2H_2 + O_2$ |  |  |
| Relative Capital Cost/kW | $$$ | $ | $$ |

# HIPES Fuel Cell for Electricity

- **Reduced fuel cell cost and higher efficiency by using $O_2$ rather than air**
  - **Oxygen electrode limits performance**
  - **Liquid electrolyte for active cooling at high power densities**
  - **Potential for ~70% efficiency**
- **NASA shuttle uses alkaline oxygen-hydrogen fuel cells**




***Alkaline Fuel Cell***

04-096

# Fuel Cells Are Being Developed

- **Alkaline fuel cells are a potential replacements for gas turbines**
- **Cenergie developing industrial stationary alkaline fuel cell systems**
- **GE developing an alternative industrial stationary solid-oxide fuel cell / electrolyzer system**
- **Potential for combined electrolysis-fuel cell system**
  - **Fuel cell output >> electrolysis capacity**
  - **Oxygen (rather than air) reduces cost and boosts efficiency**


***Cenergie alkaline-fuel-cell stack***