Economic Implications of Peak vs Base-Load Electricity Costs on Nuclear Hydrogen Systems

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Abstract

Electricity demand varies daily, weekly, and seasonally. The cost and price of electricity to meet the peak demands can be an order of magnitude greater or more than the cost and price of electricity at times of minimum demand. Nuclear systems are capital intensive, with low operating costs relative to those for most other methods used to produce electricity; thus, nuclear energy is most competitive in the production of base-load electricity (i.e., that part of the electricity demand that is constant throughout the year). Nuclear energy is generally not competitive for the production of intermediate and peak electricity, where the power plant operates for only a fraction of the year. Two nuclear hydrogen technologies (hydrogen produced using the energy from a nuclear reactor) have the potential to "convert" peak electricity demand into "base-load" demand and thus expand the markets in which nuclear energy is competitive.

The production of hydrogen by electrolysis for industrial markets at times of low electricity demand can significantly increase the base-load demand for electricity. Alternatively, the Hydrogen Intermediate and Peak Electrical System (HIPES) may enable nuclear hydrogen to be used to economically meet peak electrical demands and further expand the market for nuclear energy. HIPES would use off-peak electricity or dedicated nuclear hydrogen plants to produce hydrogen and oxygen that is stored and then used in hydrogen–oxygen steam cycles or fuel cells to produce peak electricity. If electrolysis is used, the off-peak electricity to hydrogen to peak electricity efficiency is ~50%.

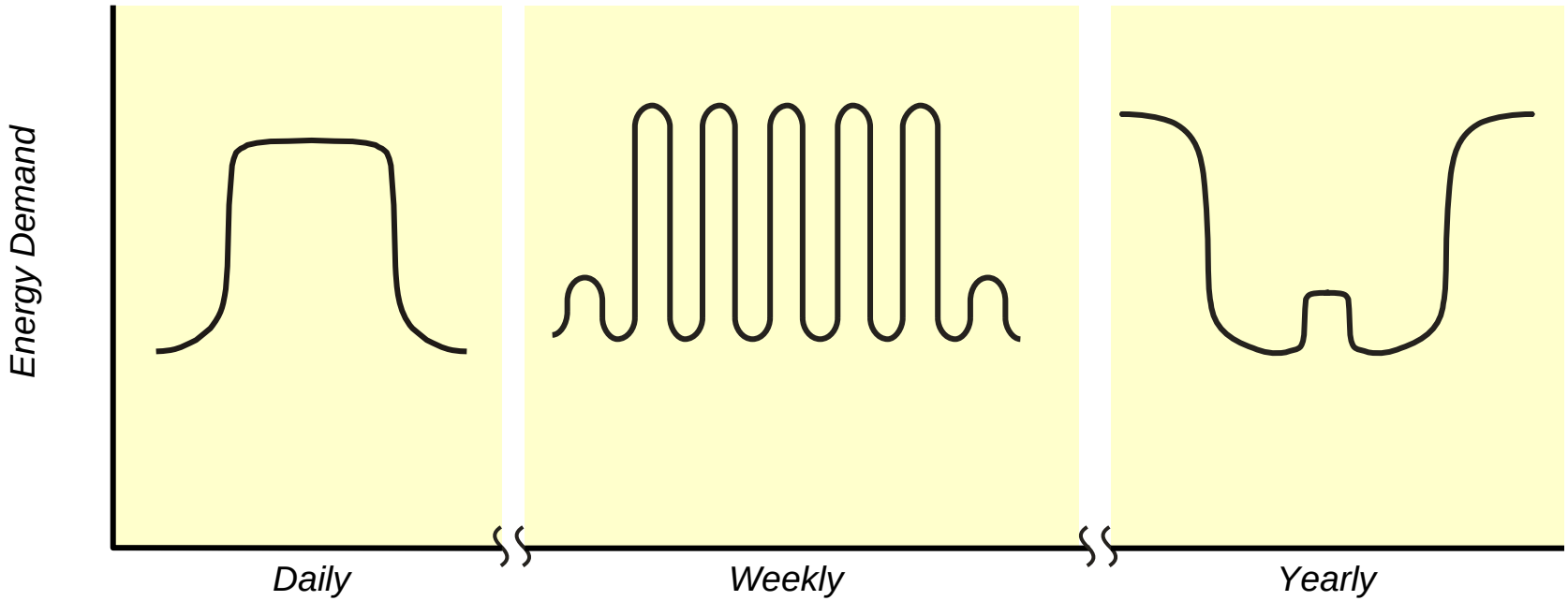
The critical technology for both of these markets is low-cost bulk hydrogen storage for periods of days, weeks, and months because hydrogen demand does not occur at the same time that hydrogen is produced. Low-cost bulk hydrogen storage in underground salt deposits is a commercial technology; however, this technology has not been commercialized for other geologies. HIPES requires the development of several other technologies. These existing markets are not dependent upon future uses of hydrogen such as a transport fuel.

Characteristics of the Electricity and H_2 Markets

Characteristics of Energy Sources

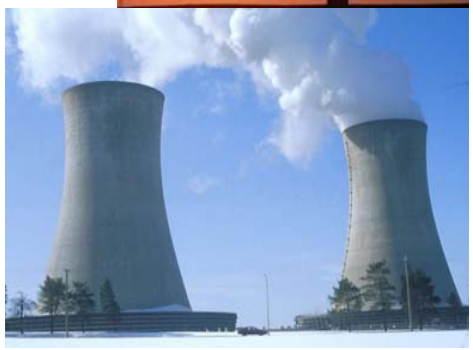
Electricity Demand Varies with Time-of-Day, Weekly, and Seasonally

(A Large-Scale H_2 Economy will have Similar Characteristics)



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

Different Hydrogen Sources have Different Economic Characteristics

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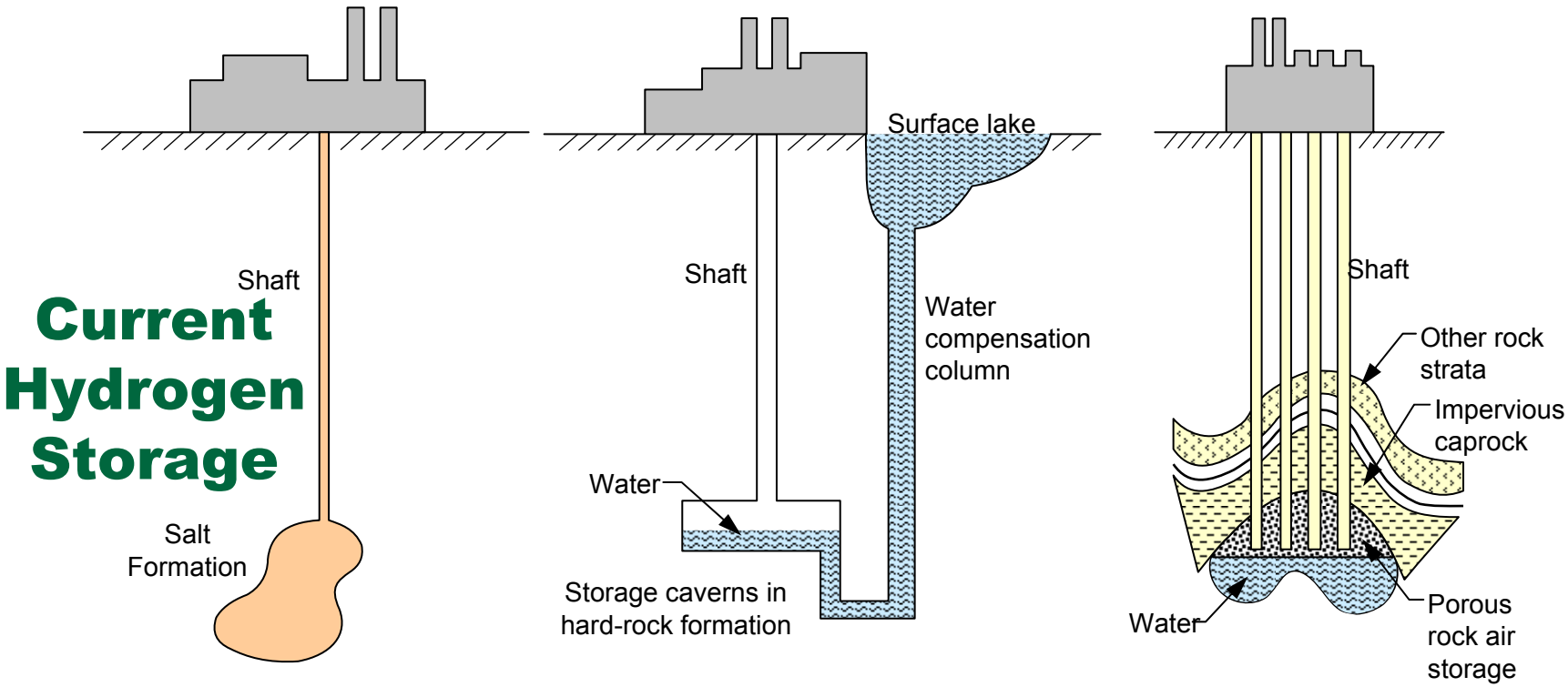
"Base-Load" Operations are Required for Low-Cost Nuclear and Renewable Hydrogen

Base-Load Nuclear Plant Operations are Required for Economic Nuclear Energy

Electricity and/or Hydrogen

Implications of Hydrogen Storage

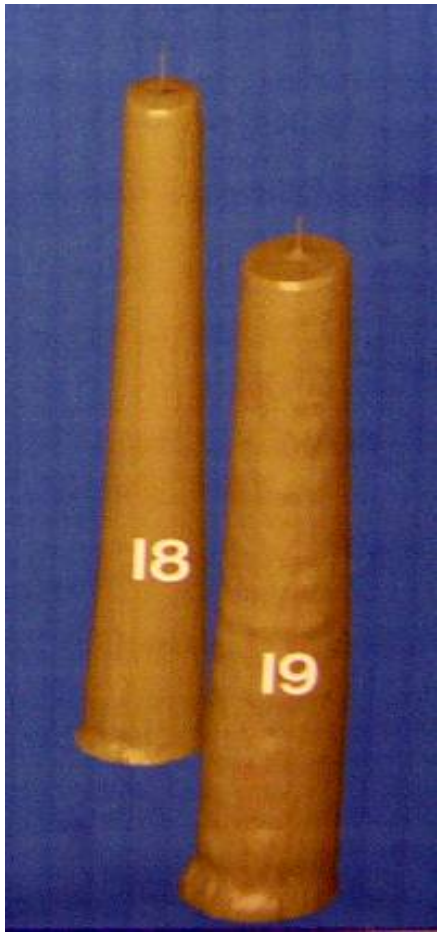
Hydrogen (Like Natural Gas) is Stored Underground



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

Large-Scale Hydrogen Storage is Inexpensive

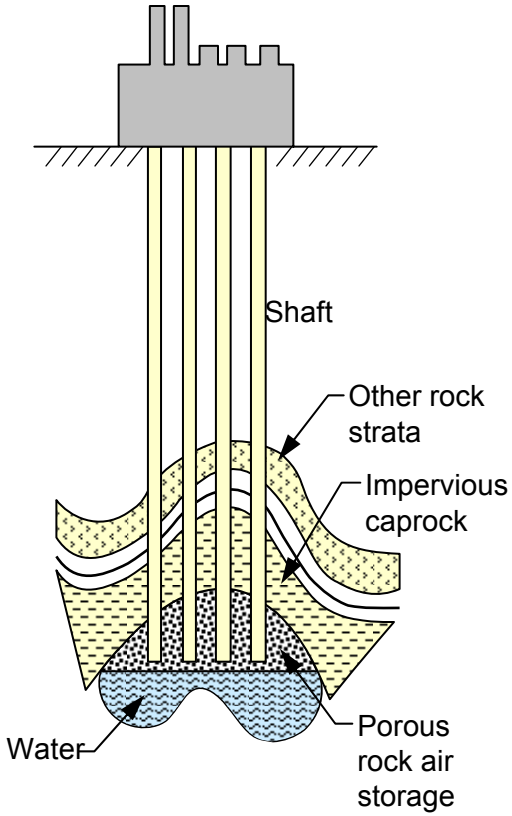
- Commercial technology in salt
- Not currently commercial in other geologies
- Based on natural-gas storage technology
- <u>Small-scale H_2 storage is expensive</u>



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

Geology determines siting

*Based on Natural Gas Experience

Implications of Low-Cost H_2 Bulk Storage – I

Economics Favors Nuclear H_2 Production with Storage

- Storage less expensive than variable nuclear H_2 production to match demand (Capital-intensive production technology)
  - Storage is cheap
- Storage less expensive than "standby" H_2 production for refueling and other nuclear outages

Implications of Low-Cost H_2 Bulk Storage – II

Electrolysis with Storage may Boost Nuclear Electricity Production

- Hydrogen production with storage can match H_2 demand over time
- Electrolysis with low-value night-time and weekend electricity can fill in the valleys of electrical demand – increase base-load demand
- Nuclear electricity is most competitive for the production of base-load electricity
- Programs are underway to develop lower-capital-cost electrolysis
  - Room temperature or high-temperature electrolysis
  - Electricity is the primary cost of electrolytic H_2

Implications of Low-Cost H_2 Bulk Storage – III

H_2 Storage Economics Matches Large-Scale H_2 Production

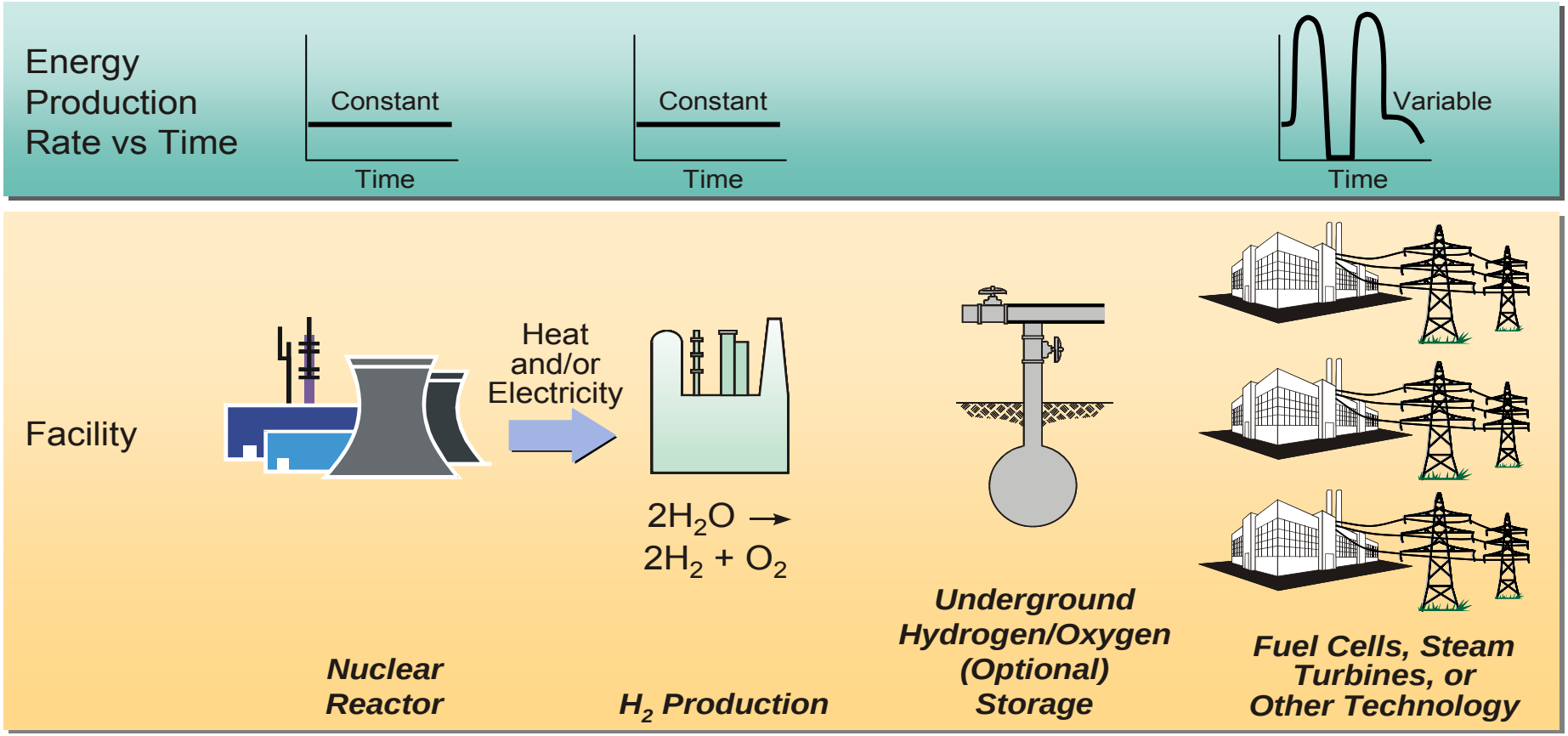
- Hydrogen storage favors large H_2 production facilities
- Small scale H_2 production not match large-scale storage
- Decentralized H_2 production has the cost penalty of H_2 transport to low-cost bulk storage facilities

Nuclear Hydrogen for Peak Electricity Production

A Potential New Nuclear Energy Market

Hydrogen Intermediate and Peak Electrical System to Meet Variable Electrical Loads

(A Daily, Weekly, and Seasonal Solution to the Variable Electrical Demand)



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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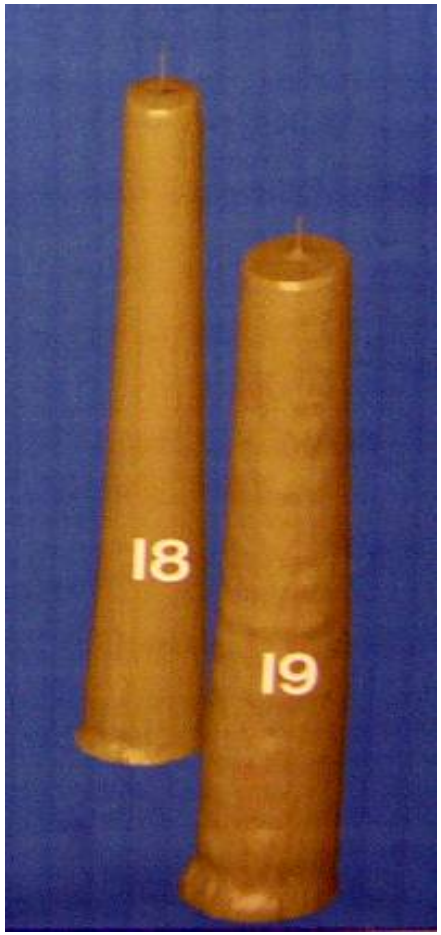
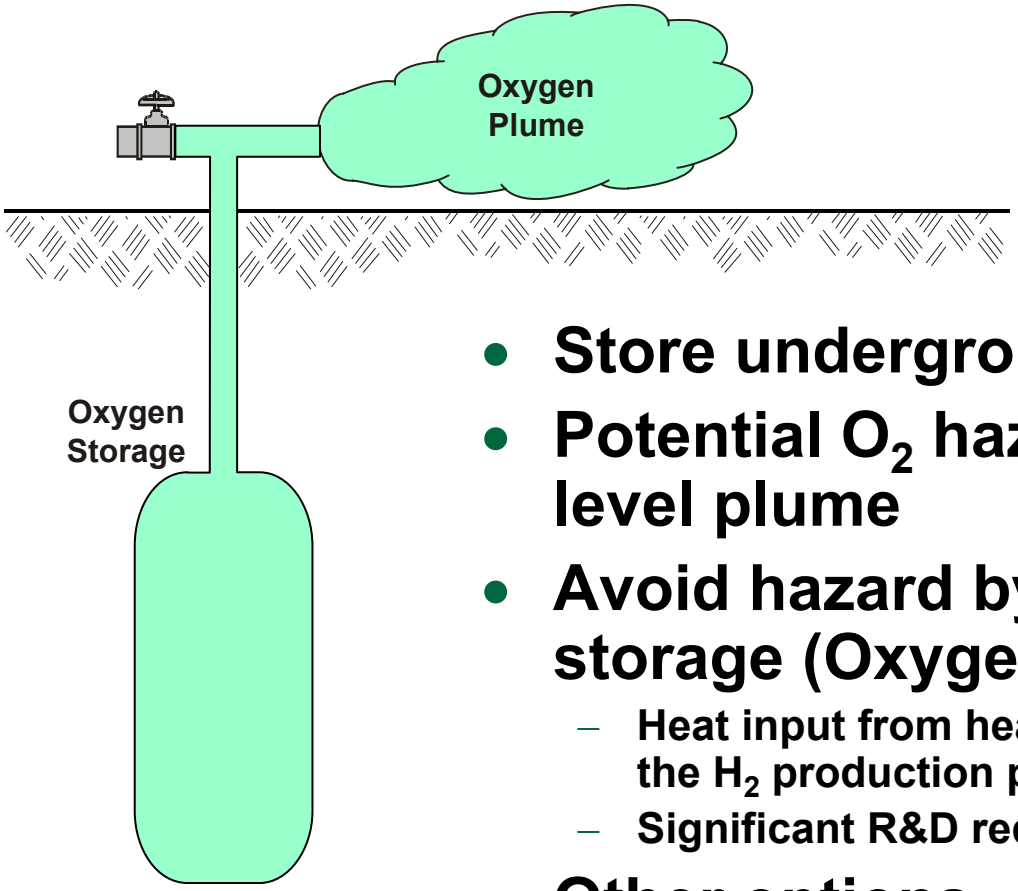


Chevron-Phillips Clemens Terminal

(160' X 1,000' Cylinder Salt Cavern)

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
- 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

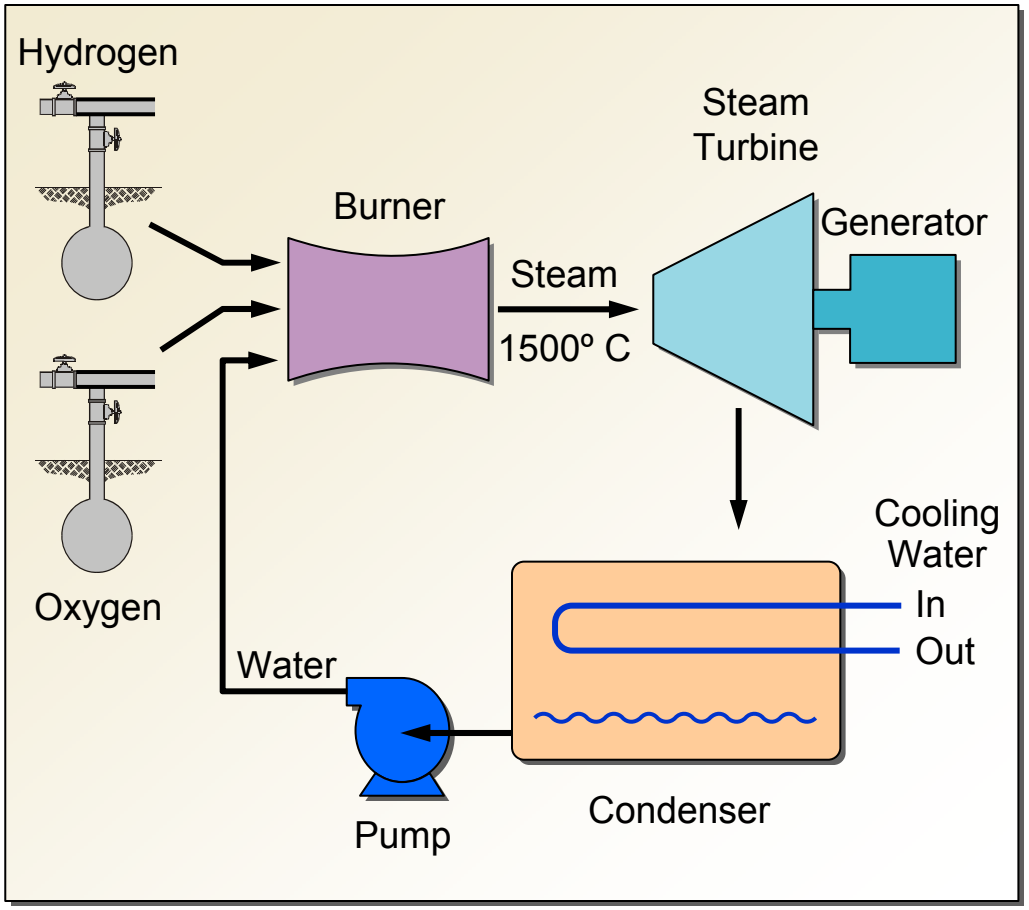
HIPES Requires Low-Cost Efficient Conversion of H_2 and O_2 to Electricity

- Hydrogen production systems operate at high load factors
- 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

HIPES Steam Turbine for Electricity*

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

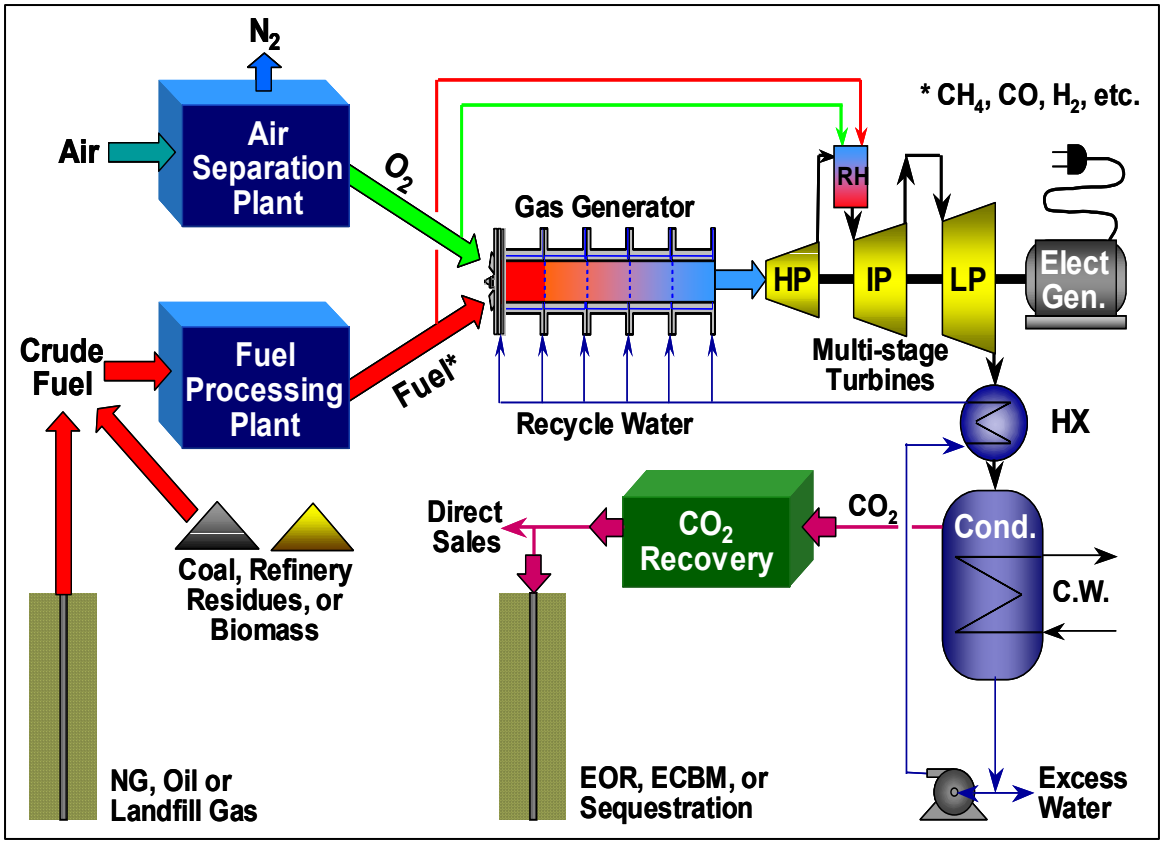
- **Nuclear H_2 "extra value" synergies**
  - **H_2 and O_2 available**
  - **Size**
- **High-temperature steam cycle**
  - **$H_2 + O_2 \rightarrow$ Water**
- **Low cost**
  - **No boiler**
  - **High-efficiency (70%)**



*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%

Conclusions

- The viability of nuclear H_2 is strongly coupled to bulk storage
- Hydrogen bulk storage costs are small
- Hydrogen is an enabling nuclear electric technology
  - Potential use for excess night-time and weekend low-value electricity
  - Potential to meet peak electric demands

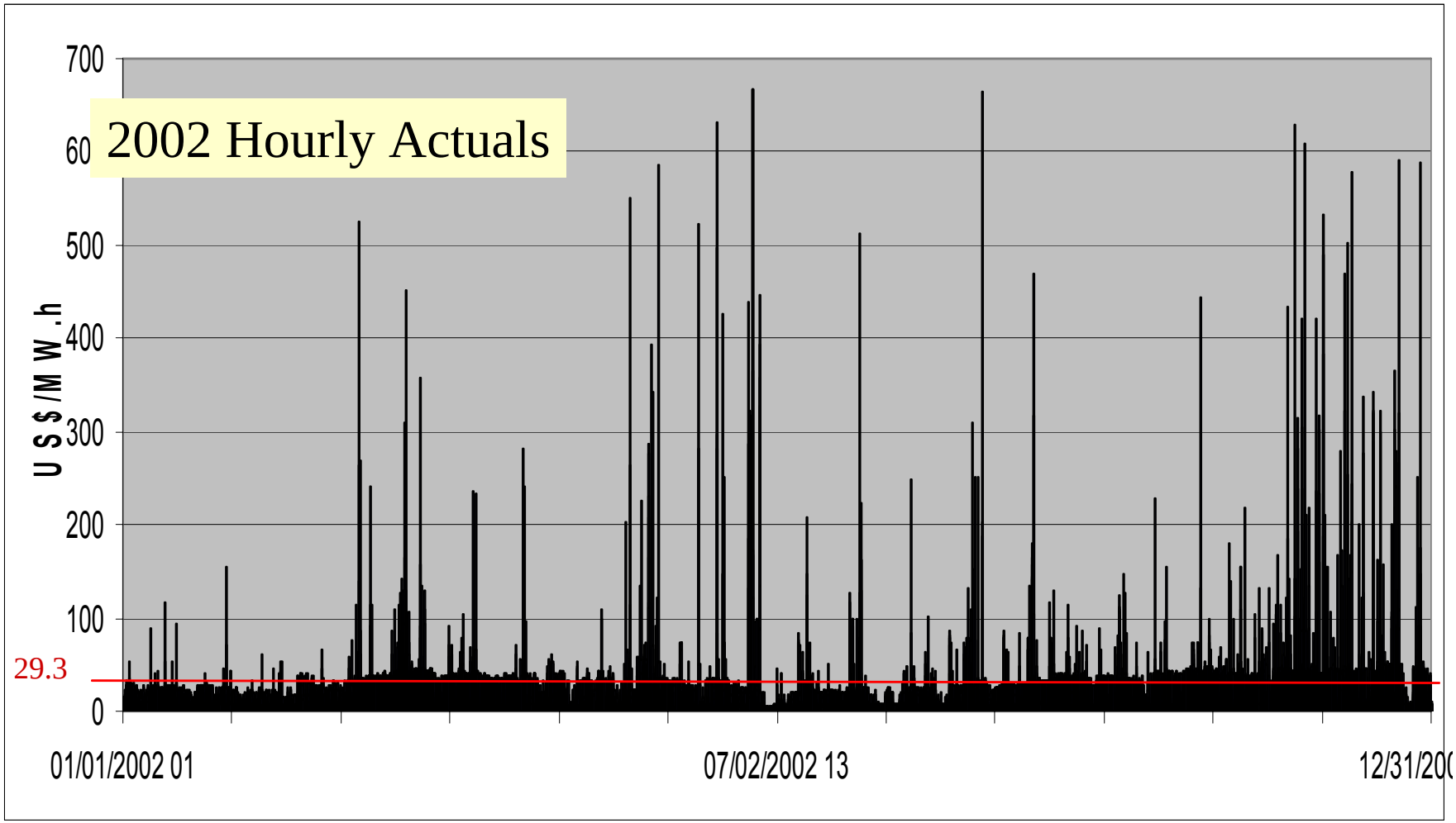
Added Information

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.

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



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

HIPES may Open the Peak Electricity Market for Nuclear Energy

- HIPES requirements match nuclear H_2
  - H_2 and O_2
  - Bulk storage of H_2 and O_2
  - Heat
- Low cost bulk H_2 and O_2 storage are the critical technologies
  - Favors centralized production to avoid collection pipelines
  - Favors centralized production to avoid O_2 shipment

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