New Technologies: Hydrogen

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2009 World Nuclear University Institute
Cambridge, England
Wednesday July 8, 2009
Overview

Hydrogen May be the Future of Liquid Fuels, Metals, and Peak-Electricity Production

Hydrogen Production Technologies Match Nuclear Energy Characteristics

Nuclear-Hydrogen May be the Transformational Energy Technology and the Enabling Technology for Large-Scale Use of Renewables

Many Questions Remain
Outline

- Perspective on Nuclear Hydrogen Futures
- Nuclear Hydrogen Applications
  - Peak Electricity
  - Nuclear-Biomass Liquid Fuels
  - Materials Production
- Nuclear Hydrogen Production
- Hydrogen: An Intrinsically Large-Scale Technology that Matches Nuclear Power
- Conclusions
Perspectives on Nuclear Hydrogen Futures
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
World Oil Discoveries Are Down and World Oil Consumption Is Up

The Era of Conventional Oil Is Ending

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

Share of Total Primary Energy Supply* in 2005

World

U.S. Goal: 80% Reduction in Greenhouse Gas Releases by 2050

11 434 Mtoe

* Share of TPES excludes electricity trade. Note: For presentational purposes, shares of under 0.1% are not included and consequently the total may not add up to 100%.

For more detailed data, please consult our on-line data service at http://data.iea.org.
Hydrogen Can Replace Fossil Fuels For Many Applications

- Hydrogen is an energy carrier
  - Today: Produced using fossil fuels
  - Can be produced from water using electricity and/or heat from nuclear or renewable energy sources

- Hydrogen from nuclear and renewable sources may replace fossil fuels where its unique chemical characteristics give it unique capabilities
  - Peak electricity production
  - Liquid fuels production
  - Metals production

- Hydrogen is unlikely to replace fossil fuels as a one-to-one substitute: Not a substitute heat source
Hydrogen Production Today

- Major hydrogen markets:
  - Ammonia fertilizer production
  - Conversion of heavy oil and coal into liquid fuels

- Primary production method
  - Steam reforming of fossil fuels
  - Two step process
    - $\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3 \text{H}_2$
    - $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$
  - Fossil fuels are burnt to provide the heat to drive the chemical process

- Energy required to make hydrogen is dependent upon the feedstock
  - Natural gas: Chemically reduced hydrogen (Lowest energy input to make hydrogen)
  - Coal: Hydrogen deficient
  - Water: Oxidized hydrogen
Nuclear Energy Hydrogen Production

Today: Alkaline Electrolysis
- Commercial technology
- \( 2\text{H}_2\text{O} + \text{electricity} \rightarrow 2\text{H}_2 + \text{O}_2 \)

Mid-term: High-Temperature Electrolysis (HTE) based on solid-oxide fuel cell operated in reverse
- \( 2\text{H}_2\text{O} + \text{electricity} + \text{heat} \rightarrow 2\text{H}_2 + \text{O}_2 \)
- Electrical efficiency up to 100% LHV plus heat requirement

Long-term: Thermochemical cycles
- \( 2\text{H}_2\text{O} + \text{heat} \rightarrow 2\text{H}_2 + \text{O}_2 \)
Future Markets: Peak Electricity Production
Electricity Demand Varies By the Day, Week, and Season

Example: Hourly load forecasts for 3 weeks in Illinois
Today a Mixture of Technologies Are Used To Minimize Electricity Costs

- High-capital-cost low-operating-cost plants operate at full output
  - Nuclear
  - Wind and Solar

- Low-capital-cost high-operating-cost plants operate with variable outputs to match electricity production with demand
  - Fossil plants
Fossil Fuel Characteristics Enable Its Use For Peak Electricity 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

Only two options for peak electricity production
- Fossil fuel (Usually natural gas)
- Hydroelectricity (Available in only some locations)

What replaces peak electricity from fossil fuels if fossil fuel use is limited or expensive?
Electricity Generation and Demand in a Low-Carbon World

Generation

- Nuclear: Not match seasonal variation
- Wind: Regional resource that peaks in the spring—time of low electric demand
- Solar: Regional resource with production match in southwest U.S. and a mismatch elsewhere
- Fossil fuels: Regional resource dependent on sequestration sites

All low-carbon options have high-capital cost and low-operating costs—expensive for variable electricity production
Requirements To Minimize Electricity Costs in a Low-Carbon World

- Capital intensive nuclear and renewables facilities must operate at maximum output to minimize energy generation costs
- Require methods to match electricity production with electricity demand
  - Daily swing can be met with many storage technologies such as pump hydro storage and batteries
  - New technologies required for seasonal (fall, winter, spring, and summer) electricity storage
Nuclear Peak Electricity Systems

Energy Production Rate vs Time
- Constant
- Variable

Facility
- Base-Load Operation
- Electricity To Grid

Nuclear Reactor
- Heat and/or Electricity

$2H_2O \rightarrow 2H_2 + O_2$

Underground Hydrogen/Oxygen (Optional) Storage

Fuel Cells, Steam Turbines, or Other Technology

Relative Capital Cost/KW
- $$$$$
- $$
- $
Example Nuclear Hydrogen Peak Electricity System

Light-Water Reactor Nuclear Power Plant

High-Temperature Electrolysis / Fuel Cell

Hydrogen and Oxygen Storage

Off-Peak Electricity and Heat

H₂ / O₂ Off-Peak

H₂ / O₂ Peak

Peak Electricity

Oxy-Hydrogen Steam Turbine
Nuclear Energy
Hydrogen Production

- **Today: Alkaline Electrolysis**
  - \( 2\text{H}_2\text{O} + \text{electricity} \rightarrow 2\text{H}_2 + \text{O}_2 \)

- **Mid-term: High-Temperature Electrolysis (HTE)**
  - \( 2\text{H}_2\text{O} + \text{electricity} + \text{heat} \rightarrow 2\text{H}_2 + \text{O}_2 \)

- **Long-term: Thermochemical cycles**
  - \( 2\text{H}_2\text{O} + \text{heat} \rightarrow 2\text{H}_2 + \text{O}_2 \)
Low-Cost Hydrogen / Oxygen Storage for Weeks or Months

- Underground storage is the only cheap hydrogen storage technology today—but only viable on a large scale (match nuclear)

- Commercial hydrogen storage technology based on natural-gas storage technology

- Same technology applicable to oxygen storage but not demonstrated for oxygen

- ←Chevron Phillips↑
  Clemens Terminal for H₂

- 160 x 1000 ft cylinder salt cavern

- Many geology options
Peak Electricity Production From Stored Hydrogen

Requires High Efficiency and Low Capital Cost (System Operates a Limited Number of Hours per Year)

Today: Gas Turbine

Mid-term

- High-temperature fuel cell
  - High-temperature electrolysis system operating in reverse

- Fuel cell / gas turbine (Siemens)
  - ~70% efficiency
  - Siemens

- Oxy-hydrogen steam cycle

Courtesy of Clean Energy Systems
A Single System May Convert Electricity to Hydrogen and Back

Combined High-Temperature Electrolysis (HTE) – Fuel Cell (FC)

- Peak power requires low capital costs
- Capital cost associated with:
  - Conversion of electricity to hydrogen
  - Conversion of hydrogen to electricity
- High-temperature electrolysis units can be operated as high-temperature fuel cells (same technology)
- Minimize capital costs with dual use
- Technology under development
Oxy-Hydrogen Steam Cycle for Peak Electricity Production

- High-temperature (1500° C) steam cycle
  - 2H₂ + O₂ → Steam
- Low cost
  - No boiler
  - High efficiency (+70%)
- Lowest capital-cost peaking system
- Unique feature: Direct production of high-pressure high-temperature steam
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

Courtesy of Clean Energy Systems
Peak-Power Production Economics

The price of peak electricity is several times that of base-load electricity

Requirements for peak electricity production
- Low capital costs because of the limited number of hours equipment is operated each year
- Higher fuel costs are acceptable

Likely future peak-power requirements
- No greenhouse gas emissions
- Large capacity to provide backup for renewables when the wind does not blow and the sun does not shine
- Cover seasonal variations in electricity demand

Potential match with nuclear-hydrogen systems
Variable Demand Results in Variable Marginal Electricity Prices

Price vs. Hours/year

Data for Los Angeles Department of Water and Power

Incentive to Use Low-Price Electricity for Hydrogen Production

FY 2004 FERC Marginal Price ($/MWh)
Future Markets:
Nuclear-Biomass Liquid Fuels
We Will Not Run Out of Liquid Fuels — Chemical Engineers Can Convert Any Biomass or Fossil Fuel into Gasoline

But the Less a Feedstock Looks Like Gasoline, the More Energy it Takes in the Conversion Process
Vehicle Greenhouse-Gas Emissions Versus Fossil-Fuel Feedstock to Make Diesel Fuel

No Problem Replacing Oil; But, Massive Increases in Greenhouse Gas Emissions

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<td>Illinois #6 Coal Baseline</td>
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<td>Pipeline Natural Gas</td>
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<td>End Use Combustion</td>
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Three Inputs into Liquid Fuels

**Carbon:**
- Fossil fuel
- Biomass

**Energy:**
- Fossil fuel
- Biomass
- Nuclear

**Hydrogen:**
- Fossil fuel
- Biomass
- Nuclear

**Products:**
- Ethanol
- Biofuels
- Diesel

The Greater the External Energy Input in Heat and Hydrogen, the More Fuel per Ton of Fossil Fuel or Biomass Input
Biomass Fuels Are the Low-Carbon Liquid Fuel Option

But, Conversion Processes Require Energy

\[ C_xH_y + (X + \frac{y}{4})O_2 \rightarrow CO_2 + (\frac{y}{2})H_2O \]

Biomass

Energy

Biomass

Nuclear

Other

Fuel Factory

Atmospheric Carbon Dioxide

Liquid Fuels

Cars, Trucks, and Planes
Biomass: Worldwide Resources Measured in Billions of Tons per Year
Without Significantly Impacting Food, Fiber, and Timber

Agricultural Residues
Logging Residues
Urban Residues
Algae and Kelp (Ocean)

But, The Capability to Replace Oil Is Dependent Upon the Conversion Process
Liquid Fuels From Biomass Depends Upon the Bio-refinery Energy Source

Energy Value of 1.3 Billion Tons/year of U.S. Renewable Biomass Measured in Equivalent Barrels of Diesel Fuel per Day (World Situation Is Similar)
## Nuclear-Biomass Liquid Fuel Options

Each Option Sequentially Increases the Liquid Fuels Yield per Ton of Biomass with More External Energy Inputs

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Nuclear Energy Input</th>
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<tr>
<td>Starch (Corn, potatoes, etc) to ethanol [Today]</td>
<td>Low-temperature heat</td>
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<tr>
<td>Cellulose to ethanol, gasoline, and diesel</td>
<td>Low-temperature heat and some hydrogen</td>
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<tr>
<td>Biomass to gasoline and diesel</td>
<td>Hydrogen*</td>
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*Biomass to gasoline and diesel may also be possible using high-temperature heat; however, both the reactor and the process must be developed.
Nuclear heat economics are favorable today and no new technology is required. Has been done in Canada. Renewed interest today.
Cellulosic Liquid-Fuel Options

Cellulose Is the Primary Form of Biomass

Biomass (1.3 billion tons/year)

Cellulose (65-85% Biomass)

Lignin (15-35% Biomass)

Ethanol Plant
Steam Plant
Lignin Plant
Nuclear Reactor
Ethanol Plant

Ethanol
Gasoline/Diesel
Nuclear
Biomass

Heat
Steam

Hydrogen (small quantities)

Electricity

50% Increase Liquid Fuel/Unit Biomass
Nuclear-Cellulosic Liquid-Fuel Option Requires a Lignin-to-Fuel Process

- Conventional cellulose-to-ethanol process **burns lignin** biomass for energy
- Nuclear cellulose ethanol fuel option
  - Nuclear steam for cellulose ethanol production
  - Lignin conversion to liquid fuels (not a boiler fuel)
    - Leading candidate is to hydrocrack lignin to a gasoline-type fuel
    - Hydrogen to convert lignin to hydrocarbon fuels
Full Conversion of Biomass to Diesel and Gasoline

Maximize liquid fuels by:
- Conversion of all carbon into liquid fuels
- **Maximize energy carried per carbon atom**
  - Produce only high-energy liquid fuel
  - Diesel and gasoline

Routes to maximize total energy content of liquid fuels per ton of biomass
- Fischer-Tropsch with nuclear hydrogen input (current technology option)
- Fischer-Tropsch with high-temperature heat for steam gasification (Need development of high-temperature reactor and the conversion process)
- Direct hydrogenation of biomass with nuclear hydrogen (Need development of conversion process)
Biomass provides the chemically-reduced **carbon** for the liquid fuel

Nuclear primary input is **hydrogen** (Oxygen is a minor input)
Biofuels are the near-term non-fossil-fuel option
  ● Workable
  ● Some production routes are now economic without tax breaks
  ● Large potential for improvements

Longer-term transport fuel options; but, each has special challenges
  ● Liquid fuels from air
  ● Hydrogen as a fuel
  ● All electric car

In all cases will likely require liquid fuels for application such as air transport
Fuels From Intercepted Carbon Dioxide: “Unlimited” But Larger H₂ Requirements
Includes Option of Extracting Carbon Dioxide from Air
Electric Transport Options

- 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

- Plug-in hybrids and other technologies may cut gasoline use in half—but not eliminate the need for transport fuels

Courtesy of the Electric Power Research Institute
Future Markets: Materials Production

Iron, Cement, and Other Materials
Hydrogen Can Replace Carbon For Materials Production

- We use massive quantities of steel, concrete, and other materials.
- 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

Non-Fossil Hydrogen Can Be the Chemical Reducing Agent For Materials Production
Nuclear Hydrogen Production

Multiple Technology Options
Alkaline Electrolysis

- Commercial technology for almost a century
- \(2\text{H}_2\text{O} + \text{electricity} \rightarrow 2\text{H}_2 + \text{O}_2\)
  - Efficiency: 66% LHV
  - Cell lifetime: 20 years
- Capital costs are decreasing and efficiency is increasing
High-Temperature Electrolysis (HTE)

Steam Electrolysis of Water

- Technology being developed
  - $2 \text{H}_2\text{O} + \text{Electricity} + \text{Heat} \rightarrow 2\text{H}_2 + \text{O}_2$
  - Solid oxide membrane
    - Oxygen transport though membrane
    - Operating temperature ~800° C
    - Same technology as fuel cell
- More efficient than electrolysis
  - Cold Electrolysis: Electricity
    - Converts liquid water to gases
    - Breaks chemical bonds
  - HTE: Electricity and Heat
    - Heat converts water to gas (steam) and weakens chemical bond
    - Electricity breaks chemical bond
- Efficiency dependent upon the temperature of delivered heat
  - Potential to exceed 50% with high-temperature reactors

High-Temperature Electrolysis Cell
(Courtesy of INL and Ceramatec)
High-Temperature Electrolysis (HTE) Using Light-Water Reactors

2 H₂O + Electricity + Heat → 2 H₂ + O₂ (Cell at 800°C)

LWR variant
- Steam at 200 to 300°C
- Heat steam to cell temperatures
  - Counter-flow of product H₂ and O₂ from electrolytic cell
  - Final temperature boost from electrical inefficiencies

Estimated LWR efficiencies
- Electricity: 36%
- Cold electrolysis: 25.7%
- HTE: 33 to 34%

High-Temperature Electrolysis Cell (Courtesy of INL and Ceramatec)
Thermochemical Cycles

- $2\text{H}_2\text{O} + \text{Heat} \rightarrow 2\text{H}_2 + \text{O}_2$

- Potential for better economics
  - Heat is cheaper than electricity
  - Potential to scale up to large equipment sizes

- Many proposed cycles with different peak temperatures from $\sim 500^\circ \text{C}$ to $1000^\circ \text{C}$

- Significant potential for lower costs; but, much R&D is required
Thermochemical Hydrogen Production

(Example [leading candidate]: Iodine–Sulfur Process)

\[
\begin{align*}
I_2 + SO_2 & \rightarrow 2HI + H_2SO_4 \\
H_2O + SO_2 + \frac{1}{2}O_2 & \rightarrow H_2SO_4 \\
I_2 + SO_2 + 2H_2O & \rightarrow 2HI + H_2SO_4 \\
2HI & \rightarrow H_2 + I_2
\end{align*}
\]
Nuclear Hydrogen May Determine World Energy System Architecture

- Today we have two parallel energy systems
  - Liquid and gaseous fuels
  - Electricity
- Hydrogen may couple these energy systems
  - Can convert hydrogen to electricity and back (Successful development of reasonable cost, efficient HTE/fuel cell)
  - Hydrogen is storable on a seasonal basis
- In a low-carbon world, the electrical production system will have low-cost off-season electricity that can be converted to hydrogen—implies coupled fuels/electricity system
Nuclear-Hydrogen-Renewable System

Electricity

Nuclear Energy

Off-Peak Electricity and Heat

Peak Electricity

Renewables

Bio-Liquid Fuels

←High-Temperature Electrolysis / Fuel Cell

H₂ / O₂ Off-Peak

H₂ / O₂ Peak
Hydrogen: An Intrinsically Large-Scale Technology

There Is a Long-Term Natural Coupling of Nuclear Energy and Hydrogen Production

Electricity is Not an Intrinsically Large-Scale Technology
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
- *Centralized hydrogen storage favors centralized hydrogen production to avoid transport costs*

**Technology**
- Underground storage in multiple geologies
- Used for natural gas (~400 existing facilities in U.S.)
- Existing hydrogen storage technology

←Chevron Phillips↑ Clemens Terminal-H₂
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

- **H₂ transport characteristics favor centralized production, storage, and transport**
Hydrogen Production Favors High-Capacity Centralized Systems

- H₂ properties create major problems in small systems
  - H₂ leakage (Surface area dependent)
  - Inefficient H₂ compression

**Economics of Scale**

- Electricity (**Electrons**):
  - 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 (**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-H₂ plant with total output from four trains of 15.6 • 10⁶ m³/day*
Nuclear Energy Characteristics Match Hydrogen Production Needs

Natural Coupling of Nuclear and Hydrogen Production Technologies
Conclusions

- We may soon see the greatest change in energy systems since the beginning of the industrial revolution with the transition to fossil fuels.
- The future is unknowable; but, nuclear hydrogen is on the short list of transformational energy technologies.

**Hydrogen is not a one-to-one substitute for fossil fuels**
- Used where its chemical properties give it unique advantages.
- Deployment dependent upon development of both production and user technologies.

- Nuclear energy characteristics match hydrogen production, storage, and distribution characteristics.

- Nuclear hydrogen may become the enabling technology for the large-scale use of renewables.
  - Peak power backup for large-scale use of wind and solar.
  - Biomass liquid fuels.
Biography: Charles Forsberg

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, a Fellow of the American Association for the Advancement of Science, 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. 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.
References

## Today’s Methods For Peak Electricity Production

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<th>Requirement</th>
<th>Hydro</th>
<th>Fossil</th>
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<tr>
<td><strong>Energy Storage</strong></td>
<td>Lake behind dam</td>
<td>Oil tank or natural gas</td>
</tr>
<tr>
<td><strong>Electricity Production</strong></td>
<td>Hydro-turbine</td>
<td>Gas turbine</td>
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<tr>
<td><strong>Limitation</strong></td>
<td>Hydro sites (water storage)</td>
<td>Climate change</td>
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Carbon dioxide sequestration likely to be prohibitively expensive for fossil peak power units that operate a few hours per day.
CES is Developing a Natural Gas–Oxygen Steam System

Enabling Technology for Oxy-Hydrogen Steam Cycle

Courtesy of Clean Energy Systems (CES)