Understanding Earth's Energy Sources

Grades: 9-12


Owner: ACTS
Energy Sources

Renewable Energy

Hydrogen
Why Hydrogen?

- Fossil fuels release CO$_2$, SO$_x$, NO$_x$
- Declining reserves, national security
Hydrogen Energy

Hydrogen - the use of Hydrogen gas in fuel cells to make electricity. Production of hydrogen can be accomplished with other renewable energy sources.
Energy is as important to modern society as food and water.

What energy-producing technologies can be envisioned that will last for millennia, and just how many people can they sustain?
Sustainable Energy Systems

Energy systems that can last for millennia

Questions:
- Sustainability
- Resource availability
- Energy Payback
- Environmental impacts
- Geopolitical factors
- Security
- The Developing World
- Energy Carrier

Answers:
- Biomass
- Solar-Derived
- Wind
- Geothermal
- Nuclear
- Hydro
- Wave
- Hydrogen
Energy Payback for Wind and PV

- Crystalline PV is about 3-4 years.
- Thin film is about 2-3 years.
  - Both include cells, frames, and supports.
- Wind is 3-4 months!
  - Includes scrapping the turbine at the end of its life.
- Nuclear is about 1 year, but does not include 10,000 years of waste storage.

Nuclear Engineering International magazine
http://www.neimagazine.com/

http://www.rmi.org/sitepages//pid171.php#E05-15
Sustainable Energy Systems

Energy systems that can last for millennia

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- Hydrogen
People take food + oxygen and “burn” the food to release energy (stored Sunlight) and carbon dioxide.
The Sustainable Hydrogen Economy

The production of hydrogen, primarily from water but also from other feedstocks, its distribution and utilization as an energy carrier.

**Energy Generation**
- Biomass
- Nuclear
- Geothermal
- Renewable e-
  - Solar
  - Wind
  - Hydro

**Production**
- Electrolysis
- Thermolysis
- Conversion

**Distribution**
- Used onsite
- Pipelines
- Compressed gas
- Liquid

**Utilization**
- Fuel cells
- Turbines
- IC Engines

**Feedstock**
- Water
- Biomass

Transportation fuel and energy storage.
"Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable....Water will be the coal of the future" (J. Verne, The Mysterious Island, 1874)
Sustainable Paths to Hydrogen

Solar Energy

- Heat
- Mechanical Energy
- Electricity
- Thermolysis
- Electrolysis

Biomass

Conversion

Photolysis

Hydrogen
Direct Conversion Systems

Visible light has sufficient energy to split water (H₂O) into Hydrogen and Oxygen

Combination of a Light Harvesting System and a Water Splitting System

✓ Semiconductor photoelectrolysis
✓ Photobiological Systems
✓ Homogeneous water splitting
✓ Heterogeneous water splitting
✓ Thermal cycles

(Sunlight and Water to Hydrogen with No External Electron Flow)
Sustainable Paths to Hydrogen

Solar Energy

- Heat
- Mechanical Energy
- Electricity
- Conversion
- Biomass
- Photolysis

Thermolysis
Electrolysis

Hydrogen
Biomass Feedstocks

\[ 6 \text{ CO}_2 + 6 \text{ H}_2\text{O} \xrightarrow{\text{sunlight}} \text{C}_6\text{H}_12\text{O}_6 + 6 \text{ O}_2 \]

Potential: 15% of the world’s energy by 2050.

Crop residues
Forest residues
Energy crops
Animal waste
Municipal waste

*Issues: Biomass Availability, Cost and Physical and Chemical Properties*
Biomass and $H_2$ Energy Pathways

**Thermal**
- Combustion
  - Excess air: Heat ($CO_2 + H_2O$)
  - Partial air: Fuel Gases ($CO + H_2$)
  - No Air: Liquids/Vapors

**Biological**
- Pretreatment
- Fermentation
  - Ethanol

**Chemical**
- Hydrolysis
  - (Heat & Pressure)
  - $CH_4$
  - $H_2$

Integrate $H_2$ with Traditional uses:
- Food, Feed, Fiber, and Wood Products
Biomass to Hydrogen Potential for Georgia ~450 million kg

Feedstocks included in this analysis:
- crop residues
- forest residues
- primary mill residues (lumber industry)
- \( \text{CH}_4 \) emissions from landfills and animal manure
- urban wood residues.

Enough \( \text{H}_2 \) for about 2 million fuel cell vehicles (50 miles/kg).
Renewable Hydrogen Production via Electrolysis
Norsk Hydro Large-Scale Electrolyzers

http://www.electrolysers.com/

5150 A at 400 V
Chlor-Alkali Industry

U.S. Chlorine Production = 13 million tons/year

400,000 tons/year byproduct hydrogen

7-10 MW typical
Largest plants ~ 20MW
Total Area Required for a Photovoltaic Power Plant to Produce the Total U.S. Annual Electrical Demand

Hydrogen From Solar Energy and Water: PV/Electrolysis vs. PEC Direct Conversion

PV panel area to produce hydrogen for current US fleet (10% system, 70% electrolysis efficiency)

PEC direct conversion system for same amount of hydrogen
Water Issues

Water Required to Produce Hydrogen for a U.S. Fuel Cell Vehicle Fleet ~100 billion gallons water/year.

- We use about 300 billion gallons of water/year in the gasoline refinery industry alone.
- Domestic water use in the U.S. is about 4,800 billion gallons per year.
- U.S. uses about 70 trillion gallons of water per year for thermoelectric power generation.
- Fossil production of electricity consumes about 0.5 gal water per kWh produced.
- Wind and PV consume no water during their electricity production. This means that every kWh of wind that replaces a kWh of coal saves 0.5 gallons of water. If we aggressively install wind, then our overall water usage would drop.
The ECTOS-hydrogen station,
An example of pre-commercial filling station

Hydrogen Station
Opened April 24, 2003
Only station in the world operating at a conventional gasoline station
(has full commercial license)

Iceland’s Hydrogen-Based Fuel Project
Water-splitting Reaction

\[ \text{H}_2\text{O} + \text{Doors} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2 \]
Fuel Cell Powered Zero Emission Busses

(www.sunline.org)

www.fuel-cell-bus-club.com
California Fuel Cell Partnership Vehicles
Hydrogen-fueled zero-emission vehicles

Clockwise from top left: Hyundai, Daimler-Chrysler, Ford, Nissan, Volkswagen, Honda, GM(center)

www.fuelcellpartnership.org/
PEM Fuel Cells

An electrochemical device that converts the chemical energy in a fuel directly to electricity without the intervening combustion used in a conventional power system.

Fuel cells are like batteries except that the chemicals are continuously fed from an external source.

Composed of 3 basic elements:
- Anode (negative electrode)
  \[ 2H_2 \rightarrow 4H^+ + 4e^- \]
- Electrolyte
- Cathode (positive electrode)
  \[ O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \]

In a typical fuel cell, hydrogen and oxygen react electrochemically at separate electrodes, producing electricity, heat, and water.
Ford Focus Fuel Cell Vehicle Undergoing High Altitude Testing on Pike’s Peak (11/03)
The Sustainable Hydrogen Economy

The production of hydrogen, primarily from water but also from other feedstocks, its distribution and utilization as an energy carrier.

<table>
<thead>
<tr>
<th>Energy Generation</th>
<th>Production</th>
<th>Distribution</th>
<th>Utilization</th>
</tr>
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<tr>
<td>Biomass</td>
<td>Electrolysis</td>
<td>Used onsite</td>
<td>Fuel cells</td>
</tr>
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<td>Renewable e⁻</td>
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</tr>
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<td>Geothermal</td>
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<td></td>
<td></td>
</tr>
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<td>Nuclear</td>
<td></td>
<td></td>
<td></td>
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Feedstock
- Water
- Biomass

Transportation fuel and energy storage.
Efficiency and the Hydrogen Economy

The efficiency of electrolysis is about 70%, and the efficiency of fuel cells is around 50%. The efficiency then of electricity-to-hydrogen and back to electricity is about 35% (.7 x .5).

“Hydrogen energy will be at least twice as expensive as electrical energy.” -Dr. Ulf Bossel

Electricity is always going to be at least twice as expensive as the natural gas used to generate it. Electricity is always going to be at least 4 times as expensive as the coal used to generate it.
While important, energy losses do not necessarily dictate the viability of any technology. Photosynthesis has an efficiency of less than 1%, and yet it powers almost all life on this planet - over 6 billion people.
Current Energy Efficiency of Electrolysis

- Electricity costs are a major contributor to the cost of electrolysis.
- Capital costs, especially for smaller systems, are also significant.
- Larger electrolyzers arrays are needed to take advantage of potential low cost, high volume electricity production methods like wind.

Hydrogen costs via electrolysis (electricity costs only)

- Commercial Systems (54 - 67kWh/kg)
- Ideal System (39 kWh/kg)
- Cost-competitive with gasoline at $1.50-$3.00/kg H2
- Electricity cost $/kWh
- $0.053/kWh
Hydrogen Selling Price (Year 2000 dollars)

Industrial Electricity - 4.8¢/kWh

Decommissioning Costs
Other Raw Material Costs
Other Variable Costs (including utilities)
Fixed O&M
Capital Costs
Feedstock Costs

- Decommissioning Costs
- Other Raw Material Costs
- Other Variable Costs (including utilities)
- Fixed O&M
- Capital Costs
- Feedstock Costs

<table>
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<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecourt - $4.15/kg</td>
<td>$2.41</td>
</tr>
<tr>
<td>(≈1000 kg/day)</td>
<td></td>
</tr>
<tr>
<td>Small Forecourt - $8.09/kg</td>
<td>$4.43</td>
</tr>
<tr>
<td>(≈100 kg/day)</td>
<td></td>
</tr>
<tr>
<td>Neighborhood - $19.01/kg</td>
<td>$3.15</td>
</tr>
<tr>
<td>(~20 kg/day)</td>
<td></td>
</tr>
</tbody>
</table>

Hydrogen Market

($/kg Hydrogen
Central Wind Results – Hydrogen Costs ($/kg)

<table>
<thead>
<tr>
<th>Timeframe</th>
<th>Standalone Wind/hydrogen</th>
<th>With Electricity Co-product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near term</td>
<td>$6.61</td>
<td>$2.75</td>
</tr>
<tr>
<td>Mid term</td>
<td>$3.19</td>
<td>$3.07</td>
</tr>
<tr>
<td>Long term</td>
<td>$2.37</td>
<td>$2.12</td>
</tr>
</tbody>
</table>

DOE Cost Target by 2015 = $2.75/kg

Hydrogen at $6.00/kg and a 50m/kg fuel cell vehicle = 12¢/mile
Economics of Thermochemical Biomass to Hydrogen Processes

- **Biomass Gasification**
  - Central production
  - 74,000 kg H₂/day
  - H2A analysis methodology (10% IRR, equity financing, 40-year plant life, 1.9% inflation)

- **Potential Cost Reduction Strategies**
  - Pyrolysis for lower cost feedstock and chemical co-products
  - Co-reforming with natural gas at existing facilities
  - Combined gasification and reforming operations
  - Feedstock yield improvements

![Biomass Gasification to Hydrogen Cost Targets](chart)

- Cost at the plant gate
- Plant Efficiency
- 63% Efficiency
- $2.6/kg H₂
- $1.3/kg H₂
Transportation costs: Hydrogen vs. Gasoline

• Gasoline at $3.00/gal and a 25mpg vehicle = **12¢/mile**
• Hydrogen at $4.00/kg and a 50m/kg fuel cell vehicle = **8¢/mile**
  - Honda FCV is 70 miles/kg hydrogen
  - GM HydroGen3 is 54 miles/kg
  - GM Sequel (Cadillac SRX) is 39 miles/kg and 300 mile range.
Cost of wind-source GH2 fuel delivered at end-of-pipe at distant city gate

<table>
<thead>
<tr>
<th>PIPELINE LENGTH</th>
<th>320 km / 200 miles</th>
<th>480 km / 300 miles</th>
<th>800 km / 500 miles</th>
<th>1600 km / 1000 miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>@CRF = 12%</td>
<td>$2.19</td>
<td>$2.34</td>
<td>$2.64</td>
<td>$3.38</td>
</tr>
<tr>
<td>@CRF = 15%</td>
<td>$2.72</td>
<td>$2.91</td>
<td>$3.28</td>
<td>$4.21</td>
</tr>
<tr>
<td>@CRF = 18%</td>
<td>$3.26</td>
<td>$3.48</td>
<td>$3.93</td>
<td>$5.04</td>
</tr>
<tr>
<td>@CRF = 21%</td>
<td>$3.75</td>
<td>$4.01</td>
<td>$4.53</td>
<td>$5.82</td>
</tr>
</tbody>
</table>

Assumes: Unsubsidized (no federal PTC, or other); No oxygen sales
Windplant @ $US 830 / kW Total Installed Capital Cost (TICC)
Electrolyzers @ $330 / kW Total Installed Capital Cost (TICC)
Pipeline 20” OD @ $US 29 / inch diam / m length

William C. Leighty, Director, The Leighty foundation; Jeff Holloway, Pipeline Technologies, Inc.; Rupert Merer, Stuart Energy; Dr. Brian Somerday, Dr. Chris San Marchi, Sandia National Laboratory; Geoff Keith, Synapse Energy Economics. Presented at Windpower05, Denver, 15-18 May; 2005 World Solar Congress, Orlando, 6-12 Aug.
Hydrogen as Energy Storage for Firm Power Generation and Seasonal Storage in Geological Reservoirs

Gaseous Hydrogen (GH2) Transmission Pipeline

GH2 Fuel Market: City Gate

Energy Storage in Pipeline

GW-hrs of energy storage are necessary.
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- Turbines
- IC Engines

**Feedstock**
- Water
- Biomass

Transportation fuel and energy storage.
Hydrogen Distribution Systems

70 million gallons of liquid hydrogen per year

245 miles of pipeline serving 50 major customers
Pathway to Hydrogen-based Transportation System

- Hydrogen from current natural gas based technologies
  - 25% less CO$_2$ than gasoline hybrids
  - 50% less than standard ICEs
- Biomass-based production
- Electrolysis when coupled to sustainable energy systems (PV & wind)
Hydrogen Fueling Scenarios

Gasoline Marketers Association

$2 billion to convert 10% of current retail stations to hydrogen.

Shell Hydrogen: $19B for 25% conversion

### Cost of initial nation-wide H₂ Infrastructure

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>TOTAL COST</th>
</tr>
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<tbody>
<tr>
<td>2% of cars run on H₂</td>
<td>$19bn</td>
</tr>
<tr>
<td>H₂ sold at 25% of retail sites</td>
<td></td>
</tr>
<tr>
<td>¼ Onsite electrolysis</td>
<td></td>
</tr>
<tr>
<td>¼ Onsite POx reformer</td>
<td></td>
</tr>
<tr>
<td>¼ Trucked in gas</td>
<td></td>
</tr>
<tr>
<td>¼ Trucked in liquid</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Retail sites selling H₂</th>
<th>Cost of extra central production/liquefaction</th>
<th>TOTAL COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA 43,980</td>
<td>$450m</td>
<td>$19bn</td>
</tr>
<tr>
<td>UK 3,425</td>
<td>$90m</td>
<td>$1.5bn</td>
</tr>
<tr>
<td>Japan 13,831</td>
<td>$140m</td>
<td>$6bn</td>
</tr>
</tbody>
</table>
Hydrogen Safety

- Fuel leak simulation
  - hydrogen on left
  - gasoline on right
  - equivalent energy release

- Hydrogen has safety advantages as well as energy security and environmental advantages.
The Sustainable Hydrogen Economy

The production of hydrogen, primarily from water but also from other feedstocks, its distribution and utilization as an energy carrier.
Utsera Project
Opened July 1, 2004

The wind energy – hydrogen – fuel cell system planned at Utsira

The wind mill connected to the grid will supply consumers with power, but also the hydrogen system consisting of electrolyser, hydrogen storage and fuel cells.
Hydrogen and the Digital Electrical Grid

Reinventing The Grid

In the not-so-distant future, the systems that we use to generate energy will change dramatically. Much of the transmission hardware that makes up the electric grid will look the same as it does today, but advances in technology and regulation will allow it to work far differently. Here's how we'll make power in the future, and how we'll pass it around.

Transmission Grid: The voltage coming from the plant must be very high—up to 760,000 volts—to cover the long distances between where the power is made and where it is used.

Power Plant: Today, most electricity flows outward from remote generating plants fueled by oil, coal, or natural gas. A typical plant utilizes less than 40% of the energy in the fuel.

Users: The voltage decreases as it travels outward from the plant and the power reaches homes and businesses over a lower-voltage distribution grid. The users are clients of the plant and make no power of their own.

2-Way Grid: The future grid will still pass power around over wires, but the main sources of the power will be the same homes and businesses that today are energy power consumers.

Distributed Generation: Tomorrow's grid won't rely solely on distant power plants to produce electricity. Instead, it will be built by surplus power made by individuals using micro generation technologies to harness solar, wind, hydrogen and fossil fuels.

Windfarms: Fossil-fuel power plants will be mostly gone, but clusters of wind generators will supplement the grid, especially at times when solar power is reduced by weather.

Dying Out: Micro-generation systems may disable those who choose to go off the grid entirely.

PV Power: During the sunniest part of the day, rooftop-mounted photovoltaic panels will produce more power than a user needs. The surplus will flow back to the grid.

Hydrogen: Some of the electricity generated by wind and solar will be used by devices called electrolyzers to create hydrogen from water. The hydrogen can be used by fuel cells to power cars or provide more home power.

Figure from Newsweek - Description Electronic Design Magazine

http://www.elecdesign.com/Articles/Index.cfm?ArticleID=7022
Mass Production and Sustainable Energy

Current energy generating systems are characterized by large centralized plants, not amenable to mass manufacturing.

• Sustainable energy systems such as wind, PV, fuel cells, and electrolyzers can all be manufactured as smaller units and added together to produce larger systems.
  – High volumes translate into major cost savings.
  – Small (home/village/city) systems can start producing immediately and then can be increased linearly.

• The DaimlerChrysler Saltillo (Mexico) plant makes 1200 engines/day (460,000 per year) a similar plant in Germany makes 3000 engines/day.
The Path Forward
(J. Turner)

• Push Renewable (Wind) electrons against coal – no sequestration.
  - Solar Cells required on every new home.
  - Improve conservation and energy efficiency everywhere.

• Develop fuel cells for transportation (hydrogen from natural gas).

• Implement electrolysis as electricity from coal diminishes and sustainable energy increases.

Talk about it!!
Hydrogen from Non-fossil Domestic Resources

If 50% of the US light-duty fleet were converted to hydrogen fuel cell vehicles with an efficiency twice the current average, it would require approximately 40 million tons of hydrogen per year. To produce that, you would need:

- **Wind**: 555 GW (current 6.7 GW) (16 years @ 28%)
- **PV**: 740 GW (current ~0.2 GW) (22 years @ 30%)
- **Nuclear**: 216 GW (current 98 GW)

*Assuming all the hydrogen was produced solely by 70% efficient electrolysis powered by that resource.*
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*Assuming all the hydrogen was produced solely by 70% efficient electrolysis powered by that resource.*
Visible light has enough energy to split water (H₂O) into hydrogen (H₂) and oxygen (O₂). However water is transparent and does not absorb this energy (fortunately).

• Photosynthetic algae and photoelectrochemical processes can use this light to produce hydrogen from water.

\[ 2H_2O \rightleftharpoons 2H_2 + O_2 \]
Hydrogen Economy
Closed Energy Cycle

Inputs:
Solar Energy and Water

Stored Hydrogen

Outputs:
Electricity, Heat and Water

Water
# Hydrogen Energy

## BENEFITS
- No harm to the environment.
- Small or large systems available.
- Energy supply is endless.
- Costs will come down when mass production begins.

## CONCERNS
- Currently more expensive than fossil fuels.
- Most of the costs involved are for start-up infrastructure.
Thank You

Science Bowl 2005 National Middle School
Final Tune Ups