Hydrogen Production & Delivery

Sara Dillich

2012 Annual Merit Review and Peer Evaluation Meeting
May 14, 2012
Goals and Objectives

**Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of $2–$4/gge H₂ by 2020**

**Central**
- Natural Gas Reforming
- Biomass Gasification
- Coal Gasification With CCS
- Electrolysis (wind)
- Electrolysis (solar)
- High-temp Electrolysis
- Solar Thermo-chemical
- Biological

**Distributed**
- Natural Gas Reforming
- Electrolysis (Grid)
- Bio-Derived Liquids

**Estimated Plant Capacity (kg/day)**
- Up to 1,500
- 50,000
- 100,000
- ≥500,000

P&D Subprogram R&D efforts successfully concluded

FE, NE R&D efforts in DOE Offices of Fossil and Nuclear Energy, resp.
### Challenges & Barriers

#### Distributed Production

**Bioderived Liquid Reforming**
- Capital costs
- Operation and maintenance costs
- Design for manufacturing
- Feedstock quantity and quality

**Electrolysis**
- System efficiency and capital costs
- Integration with renewable energy sources
- Design for manufacturing

#### Central Production

**Solar Thermochemical**
- Cost-effective reactor
- Effective and durable construction materials

**Photoelectrochemical**
- Effective photocatalyst material

**Biological**
- Sustainable H₂ production from microorganisms
- Optimal microorganism functionality
- Cost effective reactor materials

**Biomass Gasification**
- Capital costs
- Feedstock costs & purity
- System efficiency

### Delivery

**Forecourt**
- Compressor reliability
- Station infrastructure (compression, storage, and dispensing) costs

**Tube Trailer Delivery**
- Vessel capacity

**Liquid Delivery**
- Liquefaction efficiency & associated GHG emissions

**Pipelines**
- Embrittlement/cyclic fatigue effects on pipeline steel
- Infrastructure installation and lifetime costs

**Analysis & Standards**
- Impact of code requirements
- Trade study: production pressure vs. station compression.

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*Materials durability, efficiency improvements, and capital cost reductions are key challenges for all pathways.*
Challenges: Production

The hydrogen threshold cost ($2-$4/gge dispensed) is a key driver of Hydrogen Production R&D.

Projected High-Volume Cost of Hydrogen Production\(^1\)—Status

(production costs only, not including delivery or dispensing)

Distributed Production (near term)

- Electrolysis
  
  **Feedstock variability:** $0.03 - $0.08 per kWh

- Bio-Derived Liquids
  
  **Feedstock variability:** $1.00 - $3.00 per gallon ethanol

- Natural Gas Reforming\(^3\)
  
  **Feedstock variability:** $4.00 - $10.00 per MMBtu

Central Production (longer term)

- Electrolysis
  
  **Feedstock variability:** $0.03 - $0.08 per kWh

- Biomass Gasification
  
  **Feedstock variability:** $40- $120 per dry short ton

Notes:

[1] Cost ranges for each pathway are shown in 2007$, based on H2A analyses, reflecting variability in major feedstock pricing and a bounded range for capital cost estimates. Costs shown do not include delivery and dispensing costs.

Production & Delivery Strategy

Technical and economic analyses inform programmatic decisions.

Cost Analysis
- Update of H2A v.3 and HDSAM analysis models
- Apportionment of cost threshold

Identification of R&D pathways.
- Develop near-zero emission H₂ production and delivery technologies
- Hydrogen Production Roadmap
- Hydrogen Delivery Roadmap

Identification of R&D pathways.
- Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan (MYRD&D)

Table 3.1.1 Distributed Forecourt Natural Gas Reforming a, b, c

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2010 Status d</th>
<th>2015 est. e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Levelized Cost (Production Only)</td>
<td>$/kg H₂</td>
<td>$2.03</td>
<td>$2.10</td>
</tr>
<tr>
<td>Production Equipment Total Capital Investment</td>
<td>M</td>
<td>$1.5</td>
<td>$1.2</td>
</tr>
<tr>
<td>Production Energy Efficiency</td>
<td>%</td>
<td>71.4</td>
<td>74.0</td>
</tr>
<tr>
<td>Production Equipment Availability</td>
<td>%</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>Industrial Natural Gas Price</td>
<td>average $/mmBtu</td>
<td>$7.78</td>
<td>$8.81</td>
</tr>
</tbody>
</table>

2009
Identification of R&D pathways.
- Develop near-zero emission H₂ production and delivery technologies
- Hydrogen Production Roadmap
- Hydrogen Delivery Roadmap

2010
Identification of R&D pathways.

2011
Identification of R&D pathways.

2012
Performance Target Analysis
- Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan (MYRD&D)

2013
Informed Prioritization of Funding
# Hydrogen Production Strategies

## Cost status and targets for hydrogen production*

<table>
<thead>
<tr>
<th>Method</th>
<th>2011 Status</th>
<th>2015 Target</th>
<th>2020 Target</th>
<th>Ultimate Production Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distributed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolysis from grid electricity</td>
<td>$4.10</td>
<td>$3.90</td>
<td>$2.30</td>
<td></td>
</tr>
<tr>
<td>Bio-derived Liquids</td>
<td>$6.65</td>
<td>$5.10</td>
<td>$2.25</td>
<td></td>
</tr>
<tr>
<td><strong>Central</strong></td>
<td></td>
<td></td>
<td></td>
<td>$1-$2</td>
</tr>
<tr>
<td>Electrolysis From renewable electricity</td>
<td>$4.10</td>
<td>$3.00</td>
<td>$2.00</td>
<td></td>
</tr>
<tr>
<td>Biomass Gasification</td>
<td>$2.20</td>
<td>$2.10</td>
<td>$2.00</td>
<td></td>
</tr>
<tr>
<td>Solar Thermochemical</td>
<td>NA</td>
<td>$8.00</td>
<td>$3.00</td>
<td></td>
</tr>
<tr>
<td>Photoelectrochemical</td>
<td>NA</td>
<td>$17.00</td>
<td>$6.00</td>
<td></td>
</tr>
<tr>
<td>Biological</td>
<td>NA</td>
<td>NA</td>
<td>$10.00</td>
<td></td>
</tr>
</tbody>
</table>


New H2A v3 Case Studies are Published @ [http://www.hydrogen.energy.gov/h2a_production.html](http://www.hydrogen.energy.gov/h2a_production.html)

*Based on the new DOE-FCTP MYRD&D cost status and targets for Hydrogen Production – in final review.
2012/13 Emphasis

- Update cost projections and 2015 and 2020 targets using H2A v3.

Distributed Production
- Develop production and forecourt technologies for early markets
- Analyze production-to-dispensing pathways to identify optimal capital investments.

Central
- Address key materials needs for renewable hydrogen production: Membranes, Catalysts, PEC Devices, Reactors, and Tanks
- Use recommendations from the HTAC Hydrogen Production Expert Panel in portfolio planning for future new starts.

The Nuclear Hydrogen Initiative was discontinued at end of FY2009 as a separate program. Funding of high temperature electrolysis continued under the NGNP project through FY2011. After INL demonstration of pressurized stack operation in FY 2012, technology readiness will be sufficiently advanced (TRL5) to allow for further development by industry. Congressional direction to DOE for FY2012 was to focus on conversion of coal and biomass to liquid fuel. No funding for H₂ production from coal was provided.
The “New & Improved” H2A Model: Updated Capital Cost (2007 dollars)

General Features

User Input
- Process modeling
- Vendor quotes
- Literature sources

H2A Values
- AEO fuel prices
- Fuel properties
- GREET emissions factors
- Industry cost indexes

H2A Calculations
- Cost escalation
- Plant Scaling
- Financial Calculations
- Cash flow calculations and leveled cost of hydrogen

Hydrogen Analysis Model

Financial Assumptions

Plant Design Specifications

Capital & Operating Costs

Required Selling Price of H2 ($/kg)

Improvements

- Streamlined and clarified user input
- Updated H2A “Built-In” database
- New plant scaling and CSD calculations
Pyrolysis oil: feedstock costs dominate cost of H2 production

Catalytic Autothermal Reforming (NREL)

- An integrated bench-scale system for the production of 100 L/h hydrogen from pyrolysis bio-oil has been constructed. This system includes all the basic unit operations as the design for a 1500 kg/day hydrogen plant. Demonstration of 100 hrs of commercial catalyst performance is ongoing.

Aqueous Phase Reforming (PNNL)

- Pt-Co/ZrO2 catalysts identified as having potential to improve H2 yields from water soluble components of bio-oil up to 2-3X the yields with other Pt-based catalysts.

Segregation of bio-oil carbon, by phase (wt% C in raw bio-oil)

- 45.6% Aqueous
- 54.4% non-Aqueous

Economic and technical analyses indicate bio-oil best suited for semi-central production or co-production of H2 at bio-fuel plants.
2012 Progress: Electrolysis

**Higher pressure H$_2$ production through stack & system design innovations**

**Higher Pressure Stacks 2k to 5k psig**
- 2,000 psig performance testing completed
- 6,500 psig proof pressure testing completed
- 5,000 psig testing to begin shortly.

**System Scale-up at 200-300 psig**
- Fabrication of system level prototype to be delivered to NREL in May for system verification testing against DOE performance and cost targets at their new diagnostics laboratory.

**Proton OnSite**
- Performance testing at 2,400 psig completed.
- 5,000 psig, 2.2 kg/day home refueling system has been fabricated.
- Proof pressure testing to 7,500 psig complete
- Performance tests at 5,000 psig to begin soon.

**Giner Inc.**

The scale up of system designs and prototypes improves the accuracy of H2A projections against DOE targets.

Higher pressure production through stack and system design innovations has the potential to reduce compression at the point of use.
By combining the reactor and membrane into a 1-step process, a ~35% increase in H$_2$ recovery is possible as compared to conventional PSA method because H$_2$ removal via membrane drives the equilibrium limited WGS reaction to products (GTI)

<table>
<thead>
<tr>
<th></th>
<th>PSA</th>
<th>Membrane Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$, $/kg$</td>
<td>2.00</td>
<td>1.82</td>
</tr>
</tbody>
</table>

**Process Diagrams**
Durability in high-efficiency III-V crystalline systems extended to >100 hours

A low-energy $N_2^+$ ion treatment of GaInP$_2$ surfaces forms a capping surface nitride and passivates the interface against corrosion. (NREL)

Next step: Determine the durability benchmarked against the 100-hour operational lifetime at 10% efficiency target.

Stability in acidic electrolyte demonstrated through 10,000 cycles

Highly Stable H$_2$ Evolution by Core-shell MoO$_3$-MoS$_2$ Nanowires (Stanford)

The core-shell nanowires are 100% stable even after 10,000 cycles in sulfuric acid, and the conformal MoS$_2$ completely protects the otherwise unstable MoO$_3$ core.
2012 Progress: Solar-Thermochemical (STCH)

**System improvements through material and design innovations**

- Developed nanostructured materials design for optimal performance of hercynite cycle (U of CO-Boulder)
- Optimized performance of the electrolysis stage of the CuCl cycle (ANL)

- Fast radiative heat transport
- Fast mass flow (large pores & porosity)
- Ultrathin walls to limit sensible heat loss
- Ultrathin active films to eliminate diffusional resistances (i.e. fast kinetics)

- 2012 electrolyzer performance target (0.3 A/cm² @0.7 V) achieved with two best membranes
- 60% reduction in Pt loading
- Copper deposition eliminated and crossover mitigated
- Full size (300 cm²) electrolyzer fabricated & tested
Innovative reactor designs allow successful solar interface for reaction cycles.

- **Designed Particle Bed Reactor** for particle cycling, high solar utilization, and solar efficiency > 30% (theoretical). (SNL)

- **Developed Conceptual High-Temperature Receiver** based on Sandia bayonet reactor for ~100kW peak thermal input for up to ~0.8 kg/hr H2 (SAIC)

**Key Design Attributes:**
- Design focused on High Temp SO₃ decomposition
- Heat recuperation through heat transfer between inlet and outlet flows
- Back reaction minimized; products cooled without contact from catalyst
- DIRECT solar absorption by working material (>90%).
- EFFICIENT heat recovery between Tₜ and T_s (>75%).
- CONTINUOUS on-sun operation.
- INTRINSIC gas and pressure separation (H₂ from O₂).
Significant advancements in system design improve hydrogen yield.

Achieved the highest reported yield for a wild-type algae culture in less than 180 hours: 565 mL per liter of suspended culture, by increasing the space above the culture in a closed reactor. (NREL)

Increased hydrogen production rate over 2 fold through increased cellulose feedstock feeding using new automated bioreactor design for fermentative H₂ production, demonstrating scalability of the system. (NREL)

<table>
<thead>
<tr>
<th>Cellulose feed rate (g/L/day)</th>
<th>Amount of H₂ produced (mmoles)</th>
<th>Max H₂ production rate (mmol L⁻¹ h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>18.5</td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>35.3</td>
<td>2.6</td>
</tr>
<tr>
<td>10</td>
<td>51.9</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Challenges: Delivery

Station costs dominate delivery costs—key focus area.

Fueling Station (CSD) Costs

<table>
<thead>
<tr>
<th></th>
<th>2011 Projected Cost*</th>
<th>2020 Projected Cost*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized Production</td>
<td>$1.90/kg</td>
<td>$1.30/kg</td>
</tr>
<tr>
<td>Distributed Production</td>
<td>$2.50/kg</td>
<td>$1.70/kg</td>
</tr>
</tbody>
</table>

*The portion of $\text{H}_2$ cost attributed to compression, storage, and dispensing. Projections assume a station capacity of 1500kg/day and mature station design and manufacturing technology (n\textsuperscript{th} plant).

Refueling Station (2011 Technology)

Pathway Cost
Ex: CGH\textsubscript{2} Transport by Tube Trailer

FY2012 Analysis Focus

- Identify cost drivers for $\text{H}_2$ delivery in early market applications
- Evaluate options to improve station compressor reliability
- Investigate the role of high-pressure tube trailers in reducing station costs
Strategies: Delivery

Near-term emphasis on station technologies

Reductions in projected costs*
- ~40% reduction in tube trailer transport
- >20% reduction in pipeline transport
- 15% reduction in liquid delivery costs

* Based on the latest data employed in HDSAM (v. 2.3), 350 bar onboard storage, (record in review)

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Tube trailer transport</td>
<td>• Advanced tube trailer GH₂ transport</td>
<td>• Improved liquefaction</td>
<td>• Pipeline GH₂ transport</td>
</tr>
<tr>
<td></td>
<td>• Conventional LH₂ transport</td>
<td>• Cold GH₂ transport</td>
<td>• Advanced energy efficient liquefaction</td>
</tr>
<tr>
<td></td>
<td>• Mobile re-fuelers</td>
<td>• Improved, low-cost forecourt technology (compression &amp; storage)</td>
<td>• Dedicated forecourts with advanced compression/storage/dispensing technology</td>
</tr>
<tr>
<td></td>
<td>• Co-sited forecourts</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Forecourt GH₂ production</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Reference</th>
<th>2011 Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH₂ delivery via tube trailer</td>
<td>Based on HDSAM v 2.3: assumes Indianapolis with 15% market penetration, total of 122,000kg/day delivery over the entire city, plant is 62 mi from city gate. H₂ produced at 20bar. Costs include all processes from the plant gate to dispensing (700bar onboard storage) and are expressed in 2007 dollars. Costs assume mass production. Steel pipeline are based on a recent study by Brown et al., Oil &amp; Gas Journal, v. 109, Jan. 2011. Tube trailer costs assume 560kg H₂ capacity.</td>
<td>$3.7gge</td>
</tr>
<tr>
<td>LH₂ delivery via tanker truck</td>
<td></td>
<td>$3.2/gge</td>
</tr>
<tr>
<td>GH₂ delivery via pipeline</td>
<td></td>
<td>$4.1/gge</td>
</tr>
</tbody>
</table>
New trailer system meets DOE’s 2015 capacity target.

Lincoln Composite’s Titan™ ISO System:
- Capable of transporting 616kg H₂ at 250bar (3625psi)
- 2x increase in capacity over steel vessels
- Received DOT special permit approval

Lincoln Composite’s Titan 5™ integrated CHG trailer system:
- Capable of transporting 726kg H₂
- 18% increase in capacity over Titan™
- Meets DOE’s 2015 capacity target
**2012 Progress: Pipelines for H$_2$(g) Delivery**

*Fiber reinforced polymer (FRP) pipeline can reduce costs 20%, and new compressor technology can reduce capital costs 20%.*

**Collaboration on FRP pipeline testing/characterization (SRNL & ORNL)**
- Can reduce installation costs by 20–40%
- Presented technical background for codification to ASME pipeline committee
- Collecting fatigue and burst data on baseline piping and those with intentional introduced flaws
- Carrying out a study for field testing at Aiken County H$_2$ Facility

**Detailed designs for high speed centrifugal H$_2$ compressors (Mohawk Industries; Concepts NREC)**
- Each designed to meet DOE’s 2015 targets for pipeline compression
- Potential to reduce capital cost by 20% and O/M costs by 30%
- Currently building single stage demonstration systems for testing

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**Mohawk Innovative Technology Inc.**

*Single Stage Compressor*
New magnetic liquefier system can potentially reduce energy consumption by 32%.

Developed a magnetic $\text{H}_2$ liquefaction system (Prometheus)

- Achieved a stable temperature of 120K (met Phase I goal)
- Is projected to increase $\text{H}_2$ liquefaction efficiency 32% (reducing the energy cost of liquefaction from ~40% to ~20% of the lower heating value of $\text{H}_2$)

Planned installation of a Linde 880bar $\text{H}_2$ cryopump (LLNL)

- 100kg/hr peak refueling rate
- Enables cryocompressed storage and refueling testing
- Contract with Linde signed
- High pressure dispenser designed
- Facility construction planning underway (construction begin in Summer 2012)
- Pump delivery planned in December 2012
Advanced concepts are key to reduction of forecourt compression and storage costs

Power monitoring by NREL of the Linde IC-50 Ionic Compressor (350bar) at the AC Transit Emeryville refueling station to verify:

- Potential to reduce energy consumption by 20%
- Fast fueling of 5 kg/min
  - Similar to piston compression, but the piston is replaced by an ionic liquid

Development of composite vessel of 50% steel + 50% concrete that can achieve an estimated 30% cost reduction when compared to current station storage vessel (ORNL)

- Conducting detailed design studies to further reduce projected cost prior to carrying out technology development and demonstration
DOE/EERE

*H₂ Production and Delivery Applied R&D*
- Total of ~40 projects
- 6 SBIR projects:
  - Home Refueling (2)
  - Electrochemical Process Intensification
  - Large Scale PEM Electrolysis
  - Sorbents for Biofueled SOFCs
  - Hydrogen Fueling Station Cost Reduction

**INDUSTRY**
- FreedomCAR & Fuel Partnership
  - Tech teams:
    - H₂ Production
    - H₂ Delivery
- Codes & Standards Organizations

**INTERNATIONAL ACTIVITIES**
- Examples
  - IEA HIA Tasks 21, 23, 24, 25, 26, 27
  - Over 15 countries
  - IPHE

**TECHNOLOGY VALIDATION** (DOE EERE)
- ~183 vehicles & 25 stations

**I²CNER - Japan**

*Director: Dr. Petros Sofronis*

Focus on H₂ production, delivery, and FC technologies

**National Collaboration (inter- and intra-agency efforts)**

- DOE Basic Energy Sciences
  - Over 20 Projects
- DOT/NIST
- DOE Office of Biomass Technology
- NASA
- DOE Fossil Energy
- DOE Nuclear Energy
The Panel focused on R&D priorities for H$_2$ production and opportunities for coordination with other agencies/offices to optimize effectiveness of the H$_2$ production portfolio.

- May 10-12, 2012
- Over two dozen participants from academia, industry, and national laboratories in the field of hydrogen production
- Evaluated current status and future prospects for viable hydrogen production technologies for near and long term applications.
- Recommendations will be provided in a report to DOE through HTAC

- Expert Panel being held as subcommittee of HTAC with strict adherence to all FACA requirements
For More Information

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