Technology Readiness of DOE Funded Production Pathways

P&D Subprogram R&D efforts successfully concluded

FE, NE: R&D efforts in DOE Offices of Fossil and Nuclear Energy, respectively
• Status of hydrogen cost (production only, does not include delivery or dispensing costs) is shown in vertical bars, reflecting values based on a range of assumptions (feedstock/capital costs).

• Targets for hydrogen cost are shown in circles.

• Targets shown are normalized for consistency in feedstock assumptions and year-cost basis (2007 dollars)

• Targets prior to 2015 are extrapolated based on 2015 and 2020 targets in the FCT Office’s Multi-year RD&D Plan.

• Cost ranges are shown in 2007 dollars, based on projections from H2A analyses, and reflect variability in major feedstock pricing and a bounded range for capital cost estimates.

• Projections of costs assume Nth-plant construction, distributed station capacities of 1,500 kg/day, and centralized station capacities of ≥50,000 kg/day.
Distributed H₂ production from natural gas steam methane reforming (high volume/economies of scale, 1500 kg/day production)

- Cost of H₂ production not limiting factor
- Cost goals can be met by a wide range of NG prices*
- Focus shifting to longer term, early development, renewable pathways


Based on H2A v3 Case Studies @ http://www.hydrogen.energy.gov/h2a_production.html
AEO2009 avg NG prices (HHV, $/MMbtu): $7.10 (Current, 2010-2030); $8.44 (Future, 2020-2040)
AEO2012 avg NG prices (HHV, $/MMBtu): $5.28 (Current, 2010-2030); $6.48 (Future, 2020-2040)
Defining Our Strategy

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

- Updated MYRD&D Chapters posted online
- Updated Production and Delivery Roadmaps submitted to U.S. DRIVE
- Analysis FOA & Project Initiation
- MOU: FCTO & NSF MOU prepared for joint funding of hydrogen and fuel cells R&D
- Hydrogen Production Expert Panel (HPEP) Report prepared
- Independent Panel Review of Compression, Storage, and Dispensing (CSD) Costs
- Workshop on CSD Cost Reduction March, 2013, ANL
- 2013 SBIR topic: H₂ Dispensers

Table 3.1.1 Distributed Forecourt Natural Gas Reforming

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2010 Status</th>
<th>2015 est.</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</td>
</tr>
<tr>
<td>Production Equipment Availability</td>
<td>%</td>
<td>87</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>

- Update of analysis models
- Apportionment of cost threshold goal

2011
- H₂A Case Studies & MYRD&D Updates

2012
- FOA for new starts in FY2014

2013
- 2014
H₂ Production and Delivery Challenges & Strategy

**Barriers**
- Production and delivery cost of renewable & low-carbon hydrogen
  - Feedstock costs
  - Capital costs
  - O&M costs

**Strategy**

*Near-term*
- Minimize cost of 700 bar hydrogen at refueling stations

*Long-term*
- Improve performance and durability of materials and systems for production from renewable sources

**R&D Focus**
- Reliability and cost of compression, storage and dispensing
- Renewable integration
- Balance of plant improvements
- Technoeconomic analysis

**Key Areas**

*Production*
- Electrolysis
- Bio-Derived Liquids
- Hybrid fossil/renewable approaches
- Solar Water Splitting: PEC, STCH, Biological
- Fermentation

*Delivery*
- Polymers & composites for delivery technologies
- Liquefaction technologies
- Compressor reliability
- Low cost onsite storage

Materials durability, efficiency improvements, and capital cost reductions are key challenges for all production and delivery pathways

---

**H₂ Production and Delivery  MYRD&D  chapters available at:** [http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html](http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html)
**Budget – P&D subprogram**

**FY 2013 Appropriation: $16.5M**  
**FY 2014 Request: $21M**

### 2013/14 Emphasis
- **FOAs for FY14 new starts:** based on updated MYRD&D, Roadmaps and HPEP report

### Distributed Production
- Develop production and forecourt CSD technologies for improvements in
  - Cost
  - Balance of plant
  - Reliability

### Central
- Innovations in materials, devices and reactors for renewable H₂ production.
- Advanced polymers and composites for H₂ delivery systems

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*Subject to appropriations, project go/no go decisions and competitive selections. Exact amounts will be determined based on R&D progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements (FOAs).*

---

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.
Team:

Strategic Analysis, Inc.
PI: Brian James
Partners: NREL, ANL

Scope:

• Establish cost and performance baselines and track progress for R&D projects (with R&D project teams)

• Update pathway cases and develop new pathway case studies as needed

• Standardize assumptions & metrics for longer term pathways (with DOE and project teams)
2013 Progress: Autothermal Reforming of Bio-Derived Liquids

**Hydrogen yields depend on composition and properties of bio-oil**

<table>
<thead>
<tr>
<th>Feed-stock</th>
<th>H₂ g/100g bio-oil</th>
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<tbody>
<tr>
<td>Poplar</td>
<td>11.0</td>
</tr>
<tr>
<td>Oak</td>
<td>8.5</td>
</tr>
<tr>
<td>Pine</td>
<td>10.5</td>
</tr>
<tr>
<td>Oak, lignin-free</td>
<td>3.0 (12)*</td>
</tr>
</tbody>
</table>

*hydrogen yield on water-free basis (lignin-free oak bio-oil fraction contained 74.6% water)*

Reforming of poplar and pine bio-oils delivered > 10g H₂ per 100 g bio-oil.

Lower yield from oak bio-oil due to lower carbon and higher oxygen contents, and lower carbon-to-gas conversion.

**Optimum Process Conditions Identified:**

800-850°C, steam-to-carbon ratio of 2.5-3.5, Pt/Al₂O₃ catalyst, Space velocity ~ 2000 h⁻¹

**H₂A v3: $4.26/kg H₂**

(Production only, CSD not included)

Distributed Production: 1500 kg/day

Production Cost Break-down

- **Capital** $1.03, 24.2%
- **Fixed O&M** $0.55, 13%
- **Feedstock** $2.40, 56%
- **Other** $0.28, 6.6%

Production Cost Break-down for Poplar bio-oil: $236/ton

NREL
Greater than 60% reduction in cost of PEM electrolyzers stacks achieved since 2007 (Giner Inc.)

- 75% reduction in part count leading to a 50% reduction in manufacturing labor
- 30% thinner frame reduce cathode and anode support material
- 90% cost reduction of DSM MEA's through fabrication with chemically etched supports
- 66% end plate material cost reduction by using carbon steel in place of stainless steel

Alkaline exchange membrane (AEM) technology offers potential for efficiency & small footprint of PEM stacks, but at lower cost (Proton OnSite)

- Developed OER catalysts for AEM electrolysis
- Demonstrated performance over >100 h of operation
- > 80% HHV AEM efficiency shown at bench scale
- Material cost savings potential of > 80% using AEM technology are projected
- Leveraging ARPA-e project on AEM technology for regenerative fuel cell systems

Electrolyzer Performance, 400 mA/cm²
Innovative chemical reaction materials and reactor designs used to produce hydrogen from sunlight and water through thermochemical processes.

R&D Focus
- Materials efficiency and durability (SNL, U of CO)
- Reactor design (SNL, Univ. of Colorado)
- Membranes and electrocatalysts (ANL, SAIC, SRNL)
- Technoeconomic analysis to establish efficiency and durability requirements for meeting DOE cost goal

High Temp 2-Step cycles
- Metal oxides, Perovskite compounds (SNL)
- Nanostructured hercynite (Univ. of Colorado)

Hybrid Cycles wt Electrolysis Step
- Cu-Cl cycles (ANL/GTI/Penn State)
- Sulfur-ammonia (SAIC)
- Hybrid sulfur (SRNL)

Reactor Designs
- Particle receiver-reactor (SNL)
- Absorbing cavity w/ multi-tubular fixed beds (Univ. of Colorado)
- Bayonet-type reactor (SAIC)

Field Concepts
- Central tower/Heliostat field
- Central tower/Heliostat with molten salt storage (SAIC)
- Dish field -- one reactor/dish (SNL)
Novel perovskite compounds, nanostructured hercynite, split $H_2O$ in 2-step thermochemical cycles

- Synthesized 45 perovskite compounds from 9 elements (Al, Cr, Ce, Fe, La, O, Sr, Ti, Zr) using Sol-gel or Solid State Reactive Sintering (SNL)

![Perovskite structure](image)

- Verified stability of Hercynite redox activity via Raman analysis and $>150$ cycles testing
- Increased $H_2O$ pressure increases total $H_2$ produced and peak rates of $H_2$ production
  
  (Univ. of Colorado)

<table>
<thead>
<tr>
<th>Property</th>
<th>Ceria (CeO$_2$)</th>
<th>Perovskite (ABO$_3$)</th>
<th>Ideal</th>
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</thead>
<tbody>
<tr>
<td>Redox kinetics</td>
<td>FAST</td>
<td>TBD</td>
<td>FAST</td>
</tr>
<tr>
<td>Redox capacity</td>
<td>LOW</td>
<td>HIGH</td>
<td>HIGH</td>
</tr>
<tr>
<td>Reduction $T_H$</td>
<td>HIGH</td>
<td>LOW</td>
<td>LOW</td>
</tr>
<tr>
<td>Durability</td>
<td>HIGH</td>
<td>TBD</td>
<td>HIGH</td>
</tr>
<tr>
<td>Earth abundance</td>
<td>LOW/MED</td>
<td>HIGH</td>
<td>HIGH</td>
</tr>
</tbody>
</table>

Patent filed on a perovskite family of Sr- and Mn- substituted LaAlO$_3$.

U.S. Patent Issued on Coated Redox Materials for Chemical and Thermochemical Reduction
2013 Progress: Solar - Thermochemical

**High performance membranes and electrocatalysts are key for hybrid cycles**

**Sulfur Ammonia Cycle (SAIC)**
- Demonstrated long term voltage stability of complete electrochemical system (500+ hour extended run)
- Identified new membranes with up to 2 orders of magnitude lower sulfite crossover fluxes

**Cu-Cl Cycle (ANL / GTI / Penn State)**
- 5cm² electrolyzer ran successfully for 168 h at milestone value of 300 mA/cm² at 0.7V
- One cell, 300 cm², electrolyzer ran at >500 mA/cm² at 0.7V (exceeding 2015 design target)
# 2013 Progress: Photoelectrochemical

## Innovative wide band gap semiconductor material systems to produce hydrogen from sunlight and water through low-temperature photoelectrochemical processes

### R&D Approach and Focus

- Innovative crystalline, thin-film and nano-structured material systems to meet efficiency, durability and cost requirements
- Technoeconomic analysis to establish efficiency and durability requirements for meeting DOE cost goal

### Efficient Crystalline Systems

- III-V materials and integrated tandem devices *(NREL)*
- Stabilization of III-V PEC interfaces *(NREL, LANL)*

### Durable, low-Cost Thin-Film systems

- Novel metal oxide, copper chalcopyrite and silicon carbide thin-film materials and devices *(MVSystems, UH)*
- Large-scale integrated thin-film PEC electrode device fabrication *(MWOE)*

### Innovative Nano-structured Systems

- Quantum-confined MoS$_2$ photocatalysts on nano-structured support scaffold *(Stanford, LBNL)*
- Mixed oxide photocatalyst particles *(UH)*

### Cross-Cutting PEC Materials R&D Efforts

- Theoretical modeling of PEC interfaces and bulk bandgaps *(LLNL, UTA)*
- Advanced spectroscopic characterization *(UNLV)*
- Standardized PEC protocols *(PEC WG)*

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**III-V material systems R&D utilizing advanced theory, synthesis and characterization capabilities**

**Durable, low-cost thin-film systems**

**Innovative nano-structured systems**

**Cross-cutting PEC materials R&D efforts**

**Thin-film and nano-structured materials R&D leveraging theory, synthesis and characterization tools**
2013 Progress: Photoelectrochemical

Significant new PEC progress this year in stabilizing high-efficiency crystalline materials and in developing new lower-cost thin films

Developed reproducible process to extend III-V durability at high production rates (NREL / UNLV / LLNL)

Reproducible N$_2^+$ ion treatment to protect high-efficiency GaInP$_2$/GaAs tandem PEC devices from corrosion achieved.

Durability demonstrated under operating conditions comparable to 25% STH

No detectable etching in treated tandem photoelectrodes after 24 hours at high current density of ~20mA/cm$^2$

Demonstrated bandgap tuning to optimize a promising thin-film material class (MVSystems / U. Hawaii)

Reproducible control over bandgap achieved in copper chalcopyrite material systems is critical to the design and development of efficient PEC tandem devices based on lower cost thin-films

- Chalcopyrites with bandgap ranging from 1.1eV (selenides) to 2.5eV (sulfides) successfully fabricated,
- In/Ga ratio in sulfides adjusted to match 2.0eV Eg target
- PEC tests show significant charge carriers generation.
Innovative reactor configurations and genetic engineering used to improve microbial hydrogen production

### R&D Approach and Focus

**Develop O$_2$-tolerant photolytic organisms**
- Engineered cyanobacterial strains with non-native, oxygen-tolerant hydrogenases (*NREL, JCVI*)
- Algae with modified or replaced hydrogenases to reduce oxygen sensitivity (*NREL*)

**Improved photo-biological activity**
- Increase light utilization by reducing collection of excess photons (*UC-Berkeley*)
- Improved energy flow from photosynthesis to hydrogen production pathways (*NREL, JCVI*)

**Feedstocks**
- Improved utilization of less refined biomass feedstocks (cellulose, corn stover) through genetic engineering, optimized mixtures of strains (*NREL*)
- Optimized Microbital Electrolysis Cells (MEC) to produce hydrogen from fermentation wastewater (*Penn State*)

**Reactor designs**
- Improved sequence-batch bioreactor systems (*NREL*)
- Innovative MEC designs to reduce or eliminate external power requirements (*Penn State*)

Genetic engineering to improve strain’s hydrogen production capacity

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Diagram showing reaction mechanisms and equipment setup.
Genetic engineering to improve biological hydrogen production

Eliminating competing metabolic pathways (NREL)
- Developed *Clostridium thermocellum* strain (Δhpt) for improved mutant generation method
- Generated strain missing the pyruvate-to-formate pathway (ΔhptΔpfl), which consumes pyruvate that could be used for hydrogen production

Next steps: determine effect on hydrogen production, and knock-out other competing pathways

Improving oxygen tolerance (NREL)
- Demonstrated light-induced hydrogen production in algae with bacterial Ca1 hydrogenase at oxygen concentrations equivalent to 80% of air, more than double the oxygen that wild-type algae can tolerate

Next steps: genetic engineering for high, stable Ca1 hydrogenase expression
Delivery: Compression, Storage and Dispensing (CSD) Cost Reduction

- Advanced tube trailer GH₂ transport
- Conventional LH₂ transport
- Mobile re-fuelers
- Forecourt GH₂ production

- Improved liquefaction
- Cold GH₂ transport
- Improved, low-cost forecourt technology (compression & storage)

- Pipeline GH₂ transport
- Advanced energy efficient liquefaction
- Dedicated forecourts with advanced compression/ storage/dispensing technology

Delivery Costs

- Compression 53%
- Refrigeration 8%
- Dispenser 5%
- Storage 24%
- Remainder of Station 7%

Station CSD costs add >$2.00 to the cost of hydrogen delivery. Compression and Storage accounts for 77% of the cost of CSD.

Delivery method

- Tube trailer transport
- Liquid tanker transport
- Pipeline transport
- Forecourt

Today-2015
2015-2020
2020-2030

Cost of Hydrogen Delivery from Centralized Hydrogen Production Facilities

Funding will continue to focus on compression and storage

1.) Record 12021, Cost Projections for Delivery Operations at a Distributed H₂ Production/Refueling Site, may 2012, http://www.hydrogen.energy.gov/program_records.html
Delivery Challenges and Priorities

Lowering the Cost of Forecourt CSD is a top priority for FY13/14

Near-term

- Improve forecourt compressor cost, reliability & efficiency through improved seals and other R&D advancements
- Address dispenser cost and reliability through SBIR projects and investigation of existing failure modes
- Decrease the footprint and cost of storage at the forecourt through advanced composite designs

 Longer-term

- Focus on materials research to enable high volume hydrogen delivery (FRP pipelines, High-pressure composite tube trailers, Carrier technologies…)
- Research and develop advanced compression technologies for high reliability and through-put

CSD Workshop Proceedings posted on FCTO website!
Direct fills from high pressure tube trailers can reduce capital at the forecourt by ~40%

Compression, Storage, and Dispensing (CSD) Independent Panel review of the assumptions used by the hydrogen delivery scenario analysis model (HDSAM) V2.32. Report finalized Q3 FY13

CSD cost minimized by:
- Optimized compression to storage capacity
- 4-5 cascade storage banks
- Direct fills from high-pressure tube trailers
Demonstrated that high pressure steel-concrete composite vessels (SCCV) for hydrogen storage can exceed the relevant cost targets (ORNL)

Near Term Forecourt Storage (ORNL)

- Validated ability to meet 2020 target of $1000/kg of hydrogen stored at 860 bar using optimized design (target exceeded).
- Successfully demonstrated ability to use Friction Stir Welding (FSW) to lower manufacturing cost.
- Completed a manufacturing study – posted on OSTI: ORNL/TM-2013/113

Long Term Forecourt Compression (FCE)

- Reduced electrochemical compressor cell part count through design innovations by >50%
- Increased operating current density by ~3X over the 2010 baseline
- Combined, this results in a greater than 50% cost reduction over the 2010 baseline

50/50 split between steel and concrete was selected as the optimal design for cost and strength.
Fiber reinforced polymer (FRP) pipelines and new compressor technology can reduce cost

FRP pipeline testing (SRNL)

Can reduce installation costs by 20–40%

- Fatigue testing completed over the range of 750 to 3000 psig
- Calculated FRP fatigue design curve from data
- Report submitted to ASME for inclusion in B31.12

Detailed designs for high speed centrifugal H₂ compressors (Mohawk)

Potential to reduce capital cost by 20% and O/M costs by 30%

- Selected double-entry design over single-entry
- Completed single stage prototype fabrication and verified achievement of performance goals through testing in air and He at 55,000 RPM
2013 Progress: Gaseous and Liquid Delivery

**High pressure composite tube trailers show significant potential to meet the 2020 tube trailer delivery targets**

### Tube Trailer Delivery
*(Hexagon Lincoln)*
- Exceeded DOE 2015 delivery capacity target using Hexagon Lincoln's TITAN™ V Magnum Trailer System (originally designed for the 2010 targets)
- 350 bar design shows promise toward the 2020 targets.

<table>
<thead>
<tr>
<th></th>
<th>250 Bar (Available)</th>
<th>350 bar (Designed)</th>
<th>DOE 2015 Target</th>
<th>DOE 2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delivery Capacity (Kg)</strong></td>
<td>720</td>
<td>907</td>
<td>700</td>
<td>940</td>
</tr>
<tr>
<td><strong>Capital Cost ($/kg)</strong></td>
<td>744</td>
<td>710</td>
<td>730</td>
<td>575</td>
</tr>
</tbody>
</table>

### Liquid Delivery
*(LLNL)*
- Cryogenic liquid pumps have the potential to reduce energy consumption and capital cost at the forecourt
- Pump installation in progress, efficiency validation to follow
- Successful test of high pressure cryogenic 3 ft. hose segment
- Completed electrical and civil work necessary for pump installation

Pump rated at 900 bar
Hydrogen P&D Collaborations

**DOE/EERE**

- **H₂ Production and Delivery Applied R&D**
  - > 30 projects
  - 14 SBIR projects:
    - Home Refueling
    - Electrochemical Process Intensification
    - Large Scale PEM Electrolysis
    - Sorbents for Biofueled SOFCs
    - Hydrogen Fueling Station Cost Reduction

**INTERNATIONAL ACTIVITIES**

- **Examples:**
  - IEA HIA Tasks 21, 23-28
  - Infrastructure Workshop
  - IPHE

**INDUSTRY**

- **U.S. DRIVE Partnership**
  - Tech teams: H₂ Production, H₂ Delivery
- Codes & Standards Organizations

**TECHNOLOGY VALIDATION (DOE EERE)**

- >180 vehicles & 25 hydrogen stations

**INTERNATIONAL ACTIVITIES**

- **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 25 Projects
- DOT/NIST
- DOE Bioenergy Technologies Office
- National Science Foundation
- DOE Fossil Energy
- DOE Nuclear Energy
- ARPA-E
### Hydrogen Production & Delivery Team

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
<th>Contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sara Dillich (DOE Headquarters)</td>
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</tr>
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<td></td>
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</tbody>
</table>

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- Kim Cierpik (CNJV)