Systems Analysis Program Area
- Plenary Presentation -

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Fuel Cell Technologies Office

2014 Annual Merit Review and Peer Evaluation Meeting
June 16-20, 2014

Objectives:

• Assess benefits of hydrogen and fuel cells (on a life-cycle basis) for diverse applications.

• Quantify benefits of integrating hydrogen fuel production with stationary fuel cell power generation:
  o Evaluate potential for biogas, landfill gas, and stranded hydrogen streams.

• Evaluate fueling station costs for early vehicle penetration.

• Evaluate use of hydrogen for energy storage and as an energy carrier.

• Assess the socio-economic benefits (e.g., job creation).
Challenges include market complexities and the limited availability, accuracy, and consistency of data.

Future Market Behavior

- Understanding of drivers of fuel and vehicle markets needed for long-term projections.
- Models need to adequately address interactions—hydrogen/vehicle supply and demand.

Data Availability, Accuracy, and Consistency

- Analysis results depend on data sets and assumptions used.
- Large number of stakeholders and breadth of technologies make it difficult to establish consistency.

Coordination of Analytical Capability

- Analytical capabilities segmented by program element, organizationally by DOE office, and by performers/analysts.
Partnerships with labs, industry, academia

System Analysis Framework
- Provide consistent and transparent data for analytical efforts.
- Determine and prioritize analysis tasks.
- Organize data and results for decision making.
- Conduct analytical workshops to gather key input assumptions for analysis.

Models and Tools
- Validate models with data.
- Assess the life cycle analysis benefits of hydrogen and fuel cells for diverse applications.
- Maintain portfolio of models to perform analyses.

Studies and Analysis
- Perform planned studies and analysis.
- Understand initial phases of technology early market penetration.
- Understand long-term potential and issues.
- Environmental analysis.
- Energy storage analysis.
- Resource supply for hydrogen production.

Deliverables /Results
- Support decision-making processes and milestones.
- Provide direction, planning and resources.
- Provide independent analysis to validate decisions.
- Provide risk analysis of program area targets.

Internal and External Peer Review
Systems Analysis Portfolio

Variety of methodologies are used in combination to provide sound understanding of hydrogen and fuel cell systems and developing markets—and to quantify the benefits, impacts, and risks of different hydrogen and fuel cell systems.

**MARKETS/BENEFITS & POLICY ANALYSIS**
- Energy Market Analysis

**IMPLEMENTATION & IMPACT ANALYSIS**
- Resource Analysis
- Delivery Analysis
- Infrastructure Development & Financial Analysis
- Employment
- Energy Storage

**TECHNOLOGY ANALYSIS**
- Technical Feasibility & Cost Analysis
- Environmental Analysis

Systems Analysis on the Web:  www.hydrogen.energy.gov/systems_analysis.html
DOE’s Fuel Cell Technologies Office model and tool portfolio is versatile, comprehensive and multi-functional.

Model Fact Sheets: http://www.energy.gov/eere/fuelcells/systems-analysis
**Focus:** Determine technology gaps, economic/jobs potential, and benefits of key technology advances; and quantify 2014 technology advancement.

**EMPHASIS**

- Update and refine models for analysis using cost, performance and environmental (emissions, etc.) information.
- Continue life-cycle analyses of cost, greenhouse gas emissions, petroleum use and criteria emissions, and impacts on water use.
- Assess gaps and drivers for early market infrastructure cost for transportation and power generation applications.
  - Assess finance and investment strategies to close the investment gap for infrastructure development.
- Assess programmatic impacts on market penetration, job creation, return on investment, and opportunities for fuel cell applications in the near term.
- Evaluate the use of hydrogen for energy storage and as an energy carrier.

* 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).
Accomplishments: (Financial Analysis)
Single Station Cash Flow Analysis

Hydrogen fueling station positive cash flow is sensitive to station utilization and time to startup.

500 kg per day Station Financial Analysis

Station can reach breakeven cash flow in ~3.5 years.

Preliminary Analysis

Single 500 kg/d Hydrogen Station with Compressed Hydrogen delivery from Central production facility

Source: EIN

Assumptions:

- Delivered H₂ @ $6/gge.
- H₂ selling price $10/gge.
- H₂ station cost $1.5M.
- Full station utilization in 4 yrs.
- Loan 5.5% for 10 yrs.
- 700 bar dispensing.
- O&M: $100,000.
- No charge for credit cards.
- Startup: 1 yr after project start.

Station Cash Flow Sensitivity Analysis

Station Capacity Growth to full capacity, (3.5, 8 years)  
Station Startup, (0.5, 3 years)  
$12/gge, $9.05/gge
$1M, $2M
Station Breakeven Period, yrs.

Based on EIN model

500 kg per day Station Financial Analysis

O&M Costs
Other Expenses
Loan Payments - Total
Profit

$ per Quarter

20,000 40,000 60,000 80,000 100,000 120,000 140,000

Yr. 1 Yr. 2 Yr. 3 Yr. 4 Yr. 5 Yr. 6 Yr. 7 Yr. 8 Yr. 9 Yr. 10 Yr. 11 Yr. 12 Yr. 13 Yr. 14 Yr. 15
Outcomes of investor workshop and DOE infrastructure RFI identified gaps, finance scenarios, and the need for a more inclusive infrastructure workshop.

**H₂ Infrastructure Financing RFI**
- Gather financing and investment strategies for financing infrastructure development.
- 17 responses and suggested financing scenarios.

**Investor Workshop**
- Included investment community, OEMs, and national labs to get insights to investment strategies and hurdles for hydrogen infrastructure.
- Identified key gap in the period when government funding stops and outside investment begins.
- **RECOMMENDATION**: Have a follow-up workshop with broader group of investors and stakeholders.

**NEXT STEPS**
- ✓ Develop analytical scenarios to investigate investment gap with investment community.
  - ✅ Model the scenarios with existing FCTO models.
- ✓ Conduct more comprehensive and inclusive infrastructure financing workshop to vet the scenario results.
Accomplishments: (Component and Infrastructure Assessment)
Station Cost Analysis for Capacity and Fueling Pressure

Focus on 700 bar fueling pressure for FCEV rollout. Assessment of low pressure trade-offs for long term.

Station Cost Analysis

- Hydrogen Delivery Systems Analysis Model (HDSAM) used to model station costs.
- Lower fueling pressure at higher temperature can achieve a fill time target of <3 min and will reduce the capital equipment required for compression, storage and cooling.
- Assumes a Type IV tank and constant volume.
- Assumptions provided in backup slides.

Source: ANL
Accomplishments: (Life-Cycle Analysis)
Water Life-Cycle Analysis for Fuel Pathways

**Water consumption of the hydrogen production from natural gas steam methane reforming is comparable to conventional fuel pathways**

- ANL GREET model being expanded to include water consumption for hydrogen and other fuels.
- Model is able to assess water consumed on a per gge and per mile basis.
- Bio-resourced fuel from corn has high water consumption due to irrigation.
- Preliminary analysis shows fuel production with conventional electricity has high water consumption due to large quantities of water used for cooling.
- Gasoline contains 10% ethanol from corn.
- Additional fuel pathways will be analyzed for water use.

**Preliminary**

<table>
<thead>
<tr>
<th>Fuel Econ.* [mi/gge]</th>
<th>Gaso ICEV</th>
<th>Diesel ICEV</th>
<th>Gaso HEV</th>
<th>Gaso PHEV 10</th>
<th>H₂ FCEV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>25</strong></td>
<td>29</td>
<td>35</td>
<td>47 CD</td>
<td>37 CS</td>
<td>52</td>
</tr>
</tbody>
</table>

* Midsize Vehicle

Source: ANL GREET = the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model
Accomplishments: (Employment Impacts) Employment Impacts of Infrastructure Development for H₂ and Fuel Cell Technologies

JOBS H2 created to analyze employment from equipment manufacturing/installation, station construction, and fuel supply chains (direct + indirect jobs), as well as from ripple employment effects (induced jobs).

JOBS H2 Model

Hydrogen supply chain

Station O&M supply chain

Technical accomplishments and Progress:

- JOBS H2 1.0 developed by ANL and RCF, Inc. Beta tested and launched on 6/16/2014.
- Industry stakeholders peer reviewed model.
- Launch webinar scheduled for June 24th.
- Website: http://JOBSmodels.es.anl.gov
Accomplishments: (Component and Vehicle Assessment) Impact of Fuel Cell System Peak Efficiency, Fuel Consumption, and Cost

Fuel cell R&D to increase the fuel cell efficiency could increase the FCEV fuel economy by 10-13% and reduce the resultant vehicle cost by 8-13%.

Fuel Economy Comparison – Current Efficiency vs. Increased Efficiency

- Fuel cell efficiency of 60% has been achieved and demonstrated. [Link]
- ANL Autonomie model used to evaluate fuel cell and FCEV vehicle costs and performance.
- Fuel economy improvement results from improved fuel cell peak efficiency from 60% to 68%.
- Achieving increased fuel cell efficiency and resultant fuel economy yields reduced fuel requirements for constant driving range, reduced on-board storage tank size and weight.
- Improved fuel economy will help reduce the vehicle cost.
- The fuel economy values in the figure are unadjusted.
Energy Storage

Providing a product hydrogen offtake for chemicals, FCEVs or material handling equipment improves value proposition of a hydrogen energy storage system for the grid.

Hydrogen may be produced from a variety of renewable resources, and hydrogen-based energy storage could provide value to many applications and markets.

Energy Storage Systems

- Energy storage systems investigated: pumped hydro, batteries, electrolyzers, steam methane reforming and fuel cells.
- Hydrogen energy storage systems that do not sell hydrogen as a product are not cost competitive.
- Value chain for energy storage systems (providing service to grid): ancillary service > energy only > baseload
- Adding fuel cells to hydrogen energy storage system increases cost to system with low value recovery.
- Integrating an electrolyzer provides fast response to grid “demand” and flexibility to participate in ancillary service markets.
Accomplishments: Analysis of the Levelized Costs of Electricity (LCOE) from Combined Heat & Power (CHP) and Solar Photovoltaic (PV) Technologies

**PEM stationary fuel cells could produce power at ~7¢-9¢ on an LCOE basis and be competitive with other CHP and solar PV technologies.**

Assumptions:
- PEM and other CHP technology LCOE are based on projected state of technologies in 2020 and at scale.
- LCOE of PV based on published Sunshot targets for 2020.
- Each system assumed to have a 30 year life.
- Efficiency impact of power inverters to convert from DC to AC power included.
- Natural gas prices based on EIA’s 2013 date estimates for 2020.


Assumptions for the analysis are provided in the back-up slides.
Accomplishments: (Technology Analysis) Analysis of Platinum Group Metals (PGMS) for Light Duty Vehicles (LDVs)

**PGM content of LDVs could require ~2.4 gms of PGM per liter/5-6 gms per LDV to meet Tier 3 emission standards in 2020-2025.**

- Projected PGM content of gasoline LDVs expected to remain same or increase slightly to meet future Tier 3 emission standards.

- These PGM projections can be used for fuel cell targets to compare cost and competitiveness.

- Results based on joint analysis and record between FCTO and Vehicles Technologies Office (VTO).

**Platinum Group Metals for U.S. Gasoline LDV (Medium Optimism)**

*Note: After 2017, the more stringent Tier 3 emissions standards will increase PGM loadings per liter (Environmental Protection Agency 2013).*

Source: Record 14001- Platinum Group Metals (PGM) for Light-Duty Vehicles

FCTO model fact sheets provide overview information for models used for FCTO analysis such as website, model objectives, key strengths, inputs and outputs.

- Located on FCTO website:
  [http://www.energy.gov/eere/fuelcells/systems-analysis](http://www.energy.gov/eere/fuelcells/systems-analysis)

- Provide key information about models used for FCTO analysis:
  - Objectives
  - Key Attributes & Strengths
  - Inputs
  - Assumptions & Data
  - Outputs
  - Modeling Platform
  - URL to acquire model (if publically available)
<table>
<thead>
<tr>
<th>Workshop</th>
<th>Date</th>
<th>Objectives/Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COMPLETED</strong></td>
<td></td>
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</tr>
<tr>
<td>H\textsubscript{2} Infrastructure Finance and Investor Workshop</td>
<td>April 2014</td>
<td><strong>Objectives:</strong> Identify investment and financing gaps in initiating infrastructure development and next steps to resolve financial gaps. <strong>Outcomes/Deliverables:</strong> Internal information for next steps including scenario analysis and broader stakeholder workshop.</td>
</tr>
<tr>
<td>Energy Storage Workshop</td>
<td>May 2014</td>
<td><strong>Objectives:</strong> Identify 1) best applications for hydrogen in energy storage service and power-to-gas utilization, 2) barriers for hydrogen to be used for energy storage, and 3) potential collaboration areas for U.S. and Canada to use hydrogen for energy storage. <strong>Outcomes/Deliverables:</strong> Workshop proceedings and identification of next steps, including analysis, R&amp;D topics for FCTO program areas, and opportunities for international collaboration.</td>
</tr>
<tr>
<td><strong>PLANNED</strong></td>
<td></td>
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<tr>
<td>Hydrogen and CNG Workshop</td>
<td>September 2014</td>
<td><strong>Objectives:</strong> Explore intersection of hydrogen FCEVs and compressed natural gas (CNG) vehicles. Identify synergistic opportunities for FCEVs and CNG vehicles, regional issues, and consumer preferences. <strong>Outcomes/Deliverables:</strong> Workshop proceedings and identification of next steps, including analysis, R&amp;D topics for FCTO program areas, and opportunities for collaboration.</td>
</tr>
<tr>
<td>Advanced H\textsubscript{2} Infrastructure Finance and Investor Workshop</td>
<td>September 2014</td>
<td><strong>Objectives:</strong> Build on learnings from first investment workshop and explore gaps and potential resolutions. <strong>Outcomes/Deliverables:</strong> Workshop proceedings and identification of next steps, including investment scenarios to overcome barriers to market entry.</td>
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Recent and Upcoming Activities

- Diverse portfolio and expanded capability of models developed by Systems Analysis are enabling analysts to address barriers to technology development and commercialization.

- Emphasis on *early market* and *infrastructure analysis*:
  - Comprehensive approach to evaluate portfolio of fuel cell applications for light duty transportation, stationary generation, back-up power, material handling equipment, and the electric sector to realize economic, environmental and societal benefits.

- Focus on utilizing biogas as a resource for an alternative fuel for distributed generation.

- Plans continue to enhance existing models and expand analyses.

<table>
<thead>
<tr>
<th>FY 2014</th>
<th>FY 2015</th>
<th>FY 2016-2020</th>
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<tbody>
<tr>
<td>Complete analysis of resources/ feedstock, production/ delivery and existing infrastructure for technology readiness</td>
<td>Provide analysis of FCTO milestones and technology readiness goals—including risk analysis, independent reviews, financial evaluations, and environmental analysis—to identify technology and risk mitigation strategies</td>
<td>Complete analysis of FCTO technology performance and cost status and potential to enable use of fuel cells for a portfolio of commercial applications</td>
</tr>
<tr>
<td>Complete analysis of job growth for hydrogen infrastructure</td>
<td></td>
<td>Complete analysis of H₂ quality impact on H₂ production cost and FC cost for long-range technologies and technology readiness</td>
</tr>
<tr>
<td>Complete infrastructure analysis for H2USA</td>
<td></td>
<td>Complete environmental analysis of impacts for H₂ scenarios</td>
</tr>
<tr>
<td>Complete H₂ infrastructure workshops to identify investment gaps</td>
<td></td>
<td></td>
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<tr>
<td>Complete energy storage workshop to identify gaps.</td>
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</table>
Collaborations

Analysis and peer review input coordinated among national and international organizations.

EXTERNAL INPUT
- H2USA
- CAFCP
- HTAC
- NAS
- AMR

DOE-EERE
Systems Analysis Activities

NATIONAL LABS
- Analysis Support
- Model Development and Support

OTHER EERE OFFICES
- VTO
- BETO
- Renewables

FCTO Program Areas

Industry
- OEMs
  Domestic & International
- Industrial Gas Companies
- USDRIVE Tech Teams
Key Model, Report and Record Releases

**PUBLICATIONS**
Pathways to Commercial Success: Technologies and Products Supported by the Fuel Cell Technologies Program
by PNNL (http://www.pnl.gov/)

**MODELS**
JOBS H₂
by ANL and RCF
http://jobsmodels.es.anl.gov

**RECORDS**
http://hydrogen.energy.gov/program_records.html

14001- Platinum Group Metals (PGM) for Light-Duty Vehicles

14003 - Levelized Costs of Electricity from CHP and PV
## Contacts

**For more information contact:**

<table>
<thead>
<tr>
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<th>Phone Number</th>
<th>Email Address</th>
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</thead>
<tbody>
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</tr>
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</tr>
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Additional Information
Programmatic Analysis: Commercialization

Continued annual growth of >5% in the number of commercial products resulting from DOE Fuel Cell Technologies Office funding

Accelerating Technology Innovation and Application
42 commercial products have resulted from EERE-funded Fuel Cell Technologies R&D

Patents
EERE-funded Fuel Cell Technologies resulted in at least 455 patents.

Cumulative Number of Commercial Technologies Developed with FCT-Office Funding

- Examples -

* Partial data for 2013
Source: PNNL Commercial Pathways report to be published September 2013
### Assumptions for Station Cost Analysis for Capacity and Fueling Pressure

#### Assumptions

<table>
<thead>
<tr>
<th>Vehicle Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fueling Pressure</strong></td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
</tr>
<tr>
<td><strong>Outer Diameter [inch]</strong></td>
</tr>
<tr>
<td><strong>Thickness [inch]</strong></td>
</tr>
<tr>
<td><strong>Tank Length [inch]</strong></td>
</tr>
<tr>
<td><strong>Liner Thickness [inch]</strong></td>
</tr>
<tr>
<td><strong>Volume [L]</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vehicle Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Pressure</strong></td>
</tr>
<tr>
<td>Other initial pressures are modeled (5 and 10 MPa)</td>
</tr>
<tr>
<td><strong>Initial (= Ambient) Temp.</strong></td>
</tr>
<tr>
<td>Hot soak condition (+15°C) is also modeled</td>
</tr>
<tr>
<td><strong>Maximum Press.</strong></td>
</tr>
<tr>
<td><strong>Max. Temp.</strong></td>
</tr>
<tr>
<td><strong>Convective H.T. Coeff. [W/m²K]</strong></td>
</tr>
<tr>
<td><strong>Inlet Temp.</strong></td>
</tr>
<tr>
<td><strong>Fill Strategy</strong></td>
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Assumptions for Analysis of the Levelized Costs of Electricity from CHP and PV Technologies

## Key Assumptions

<table>
<thead>
<tr>
<th></th>
<th>ICE</th>
<th>MT</th>
<th>Medium-FC</th>
<th>PV Comm</th>
<th>Micro-FC</th>
<th>PV Res</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size, kWe</strong></td>
<td>500</td>
<td>200</td>
<td>500</td>
<td>495</td>
<td>7.0</td>
<td>6.8</td>
</tr>
<tr>
<td><strong>Capital Cost/kWe</strong></td>
<td>1,400</td>
<td>1,700</td>
<td>1,000</td>
<td>982</td>
<td>1,300</td>
<td>1,109</td>
</tr>
<tr>
<td><strong>Engineering &amp; Installation, $/kWe</strong></td>
<td>450</td>
<td>1,000</td>
<td>500</td>
<td>382</td>
<td>450</td>
<td>554</td>
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<tr>
<td><strong>Capacity Factor (CF)</strong></td>
<td>0.81 (0.78 - 0.84)</td>
<td>0.81 (0.78 - 0.84)</td>
<td>0.81 (0.78 - 0.84)</td>
<td>0.17 (0.15 - 0.19)</td>
<td>0.81 (0.78 - 0.84)</td>
<td>0.19 (0.17 - 0.21)</td>
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<tr>
<td><strong>Elec. Efficiency (HHV)</strong></td>
<td>35.5%</td>
<td>32.5%</td>
<td>45.1%</td>
<td>N/A</td>
<td>40.6%</td>
<td>N/A</td>
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<tr>
<td><strong>Elec. Efficiency (LHV)</strong></td>
<td>39.3%</td>
<td>36.0%</td>
<td>50.0%</td>
<td>N/A</td>
<td>45.0%</td>
<td>N/A</td>
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<tr>
<td><strong>Combined Effic. (HHV)</strong></td>
<td>78.5%</td>
<td>70.4%</td>
<td>81.2%</td>
<td>N/A</td>
<td>81.2%</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Other O&amp;M, $/kWh</strong></td>
<td>0.81 (0.80 - 0.82)</td>
<td>1.03 (1.02 - 1.06)</td>
<td>0.83 (0.82 - 0.84)</td>
<td>1.47 (1.37 - 1.73)</td>
<td>0.90 (0.89 - 0.92)</td>
<td>1.65 (1.49 - 1.84)</td>
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<tr>
<td><strong>Fuel Price, $/Mbtu</strong></td>
<td>8.3 (7.3 - 10.5)</td>
<td>8.3 (7.3 - 10.5)</td>
<td>8.3 (7.3 - 10.5)</td>
<td>N/A</td>
<td>10.6 (8.9 - 13.7)</td>
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