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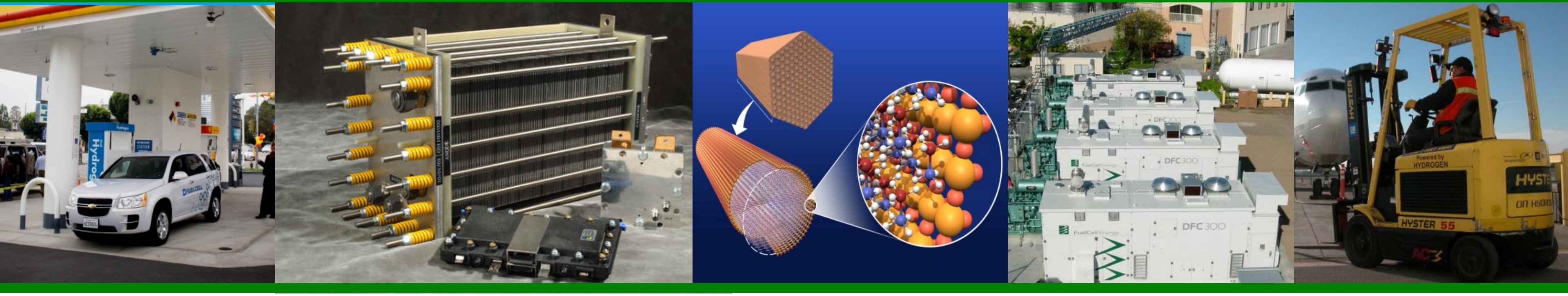

Systems Analysis Program Area
- Plenary Presentation -

Fred Joseck

Fuel Cell Technologies Office

2014 Annual Merit Review and Peer Evaluation Meeting

June 16-20, 2014

Goals and Objectives

GOAL: Support infrastructure development and technology readiness through system-level analysis—evaluating technologies and pathways, guiding selection of RD&D technology approaches/options, and estimating potential value of RD&D efforts.

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:
  - 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

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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.

Strategy

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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

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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

TECHNOLOGY ANALYSIS

- Technical Feasibility & Cost Analysis
- Environmental Analysis

SYSTEMS ANALYSIS

IMPLEMENTATION & IMPACT ANALYSIS

- Resource Analysis
- Delivery Analysis
- Infrastructure Development & Financial Analysis
- Employment
- Energy Storage

Systems Analysis on the Web: www.hydrogen.energy.gov/systems_analysis.html

Systems Analysis Model Hierarchy

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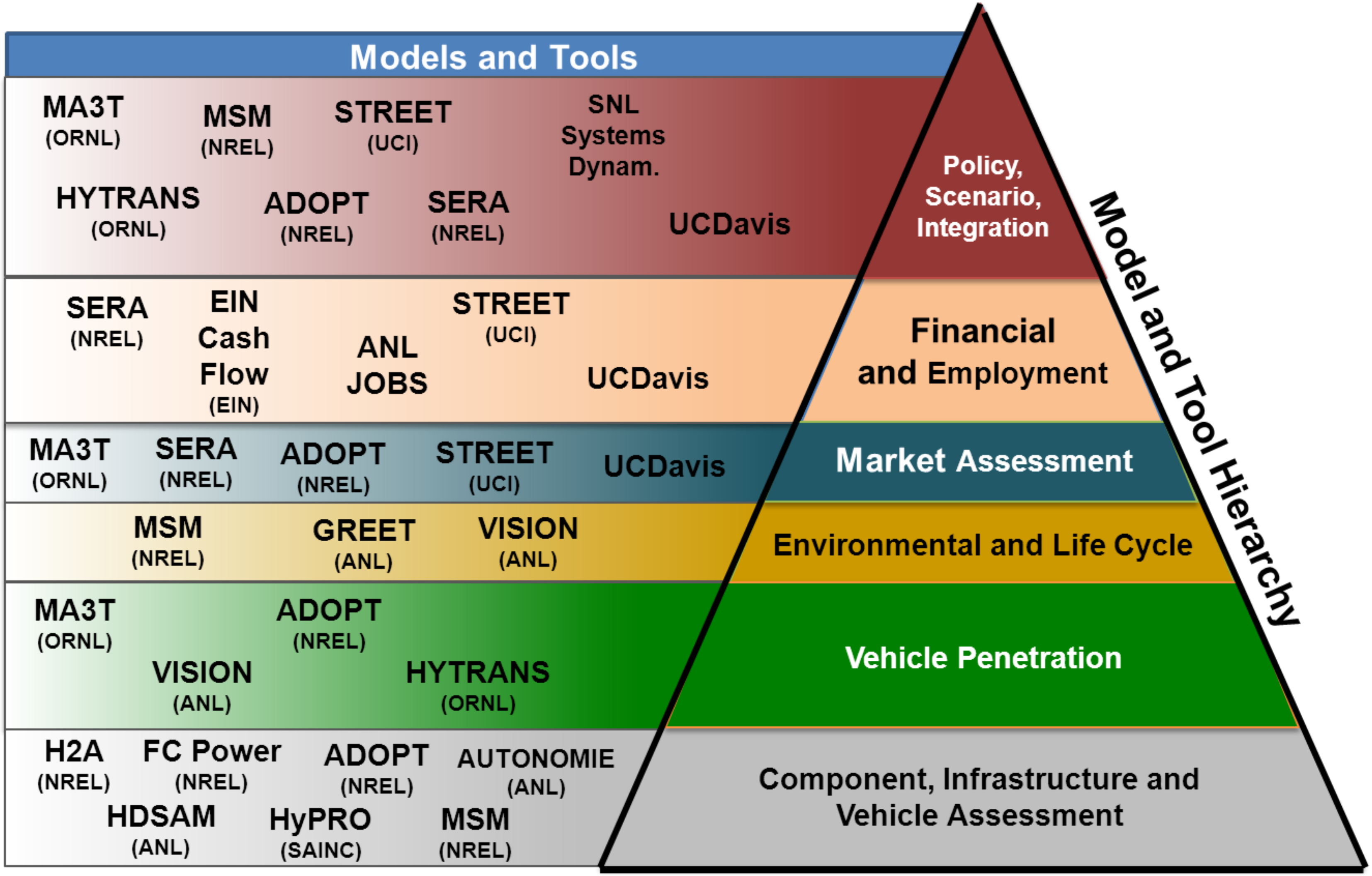
DOE's Fuel Cell Technologies Office model and tool portfolio is versatile, comprehensive and multi-functional.



Model Fact Sheets: http://www.energy.gov/eere/fuelcells/systems-analysis

Budget

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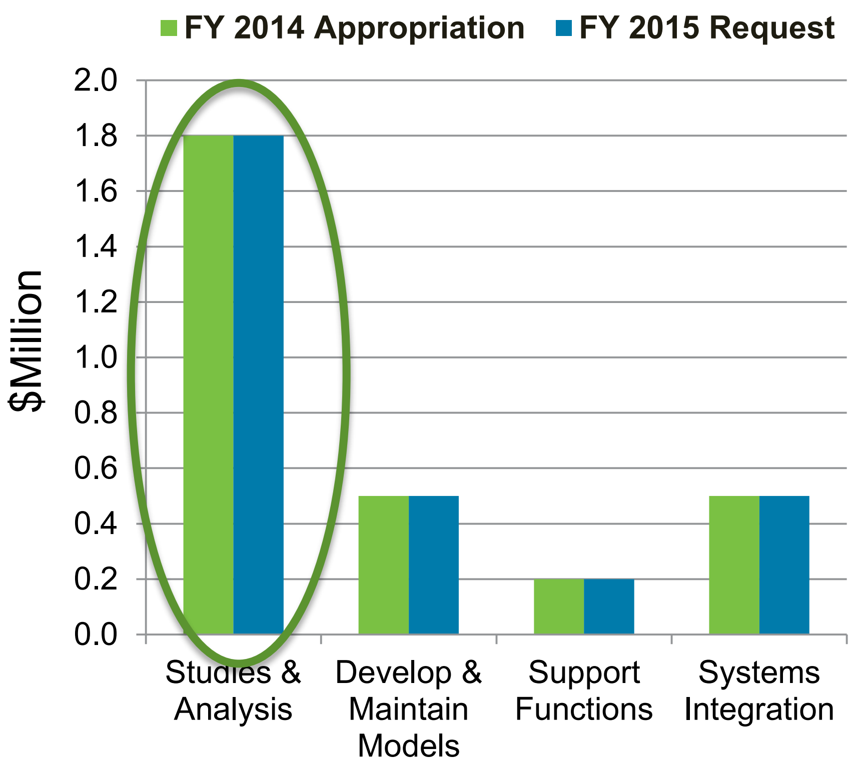
Focus: Determine technology gaps, economic/jobs potential, and benefits of key technology advances; and quantify 2014 technology advancement.

FY 2014 Appropriation = $3.0 M

FY 2015 Request = $3.0 M



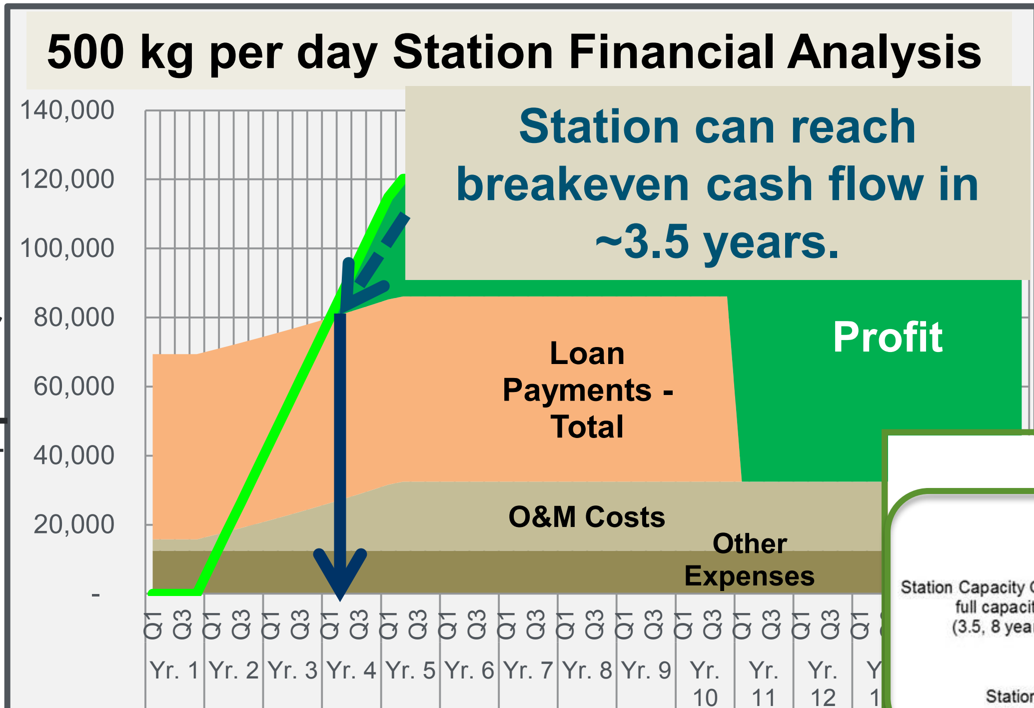
* Subject to appropriations, project go/no go decisions and competitive selections. Exact amounts will be determined based on R&D progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements (FOAs).

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.

Accomplishments: (Financial Analysis) Single Station Cash Flow Analysis

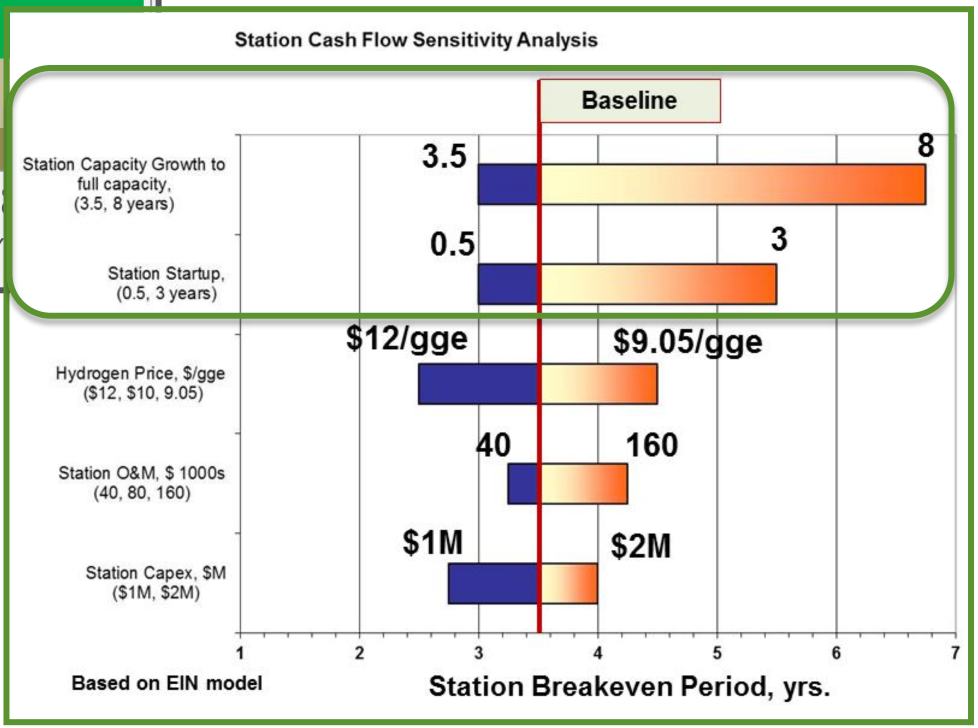
Hydrogen fueling station positive cash flow is sensitive to station utilization and time to startup.



Source: EIN

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

Preliminary Analysis



Assumptions:

- ✓ Delivered H_2 @ $6/gge.
- ✓ H_2 selling price $10/gge.
- ✓ H_2 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.

Infrastructure Financing/Investment: H_2 Infrastructure Request for Information (RFI) and Investor Workshop

Outcomes of investor workshop and DOE infrastructure RFI identified gaps, finance scenarios, and the need for a more inclusive infrastructure workshop.

H_2 Infrastructure Financing RFI

- Gather financing and investment strategies for financing infrastructure development.
- 17 responses and suggested financing scenarios.

NEXT STEPS

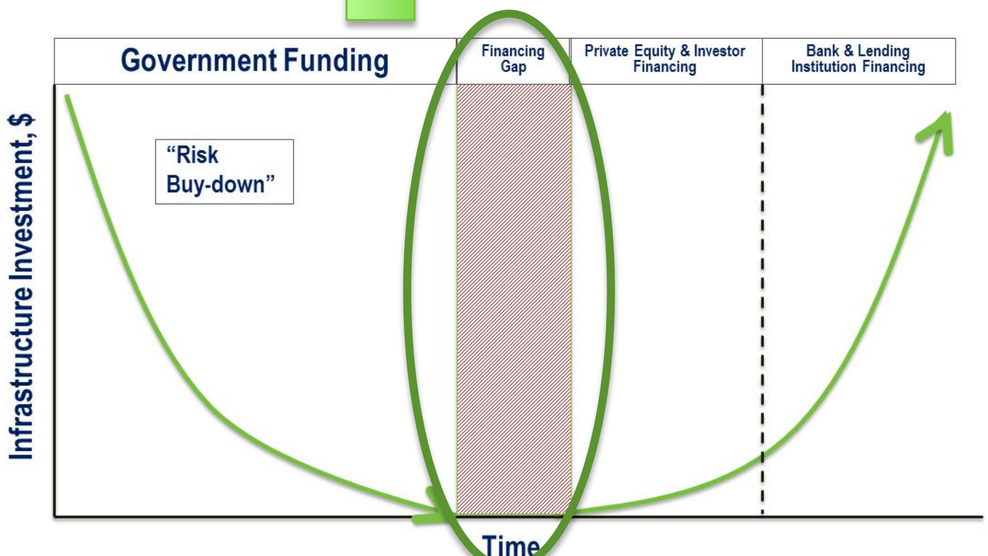
✓ Develop analytical scenarios to investigate investment gap with investment community.

❖ Model the scenarios with existing FCTO models.

✓ Conduct more comprehensive and inclusive infrastructure financing workshop to vet the scenario results.

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.



"Financing Gap"- when government funding of infrastructure stops and investor resistance to invest money in a risky technology/market.

Station Cost Analysis for Capacity and Fueling Pressure

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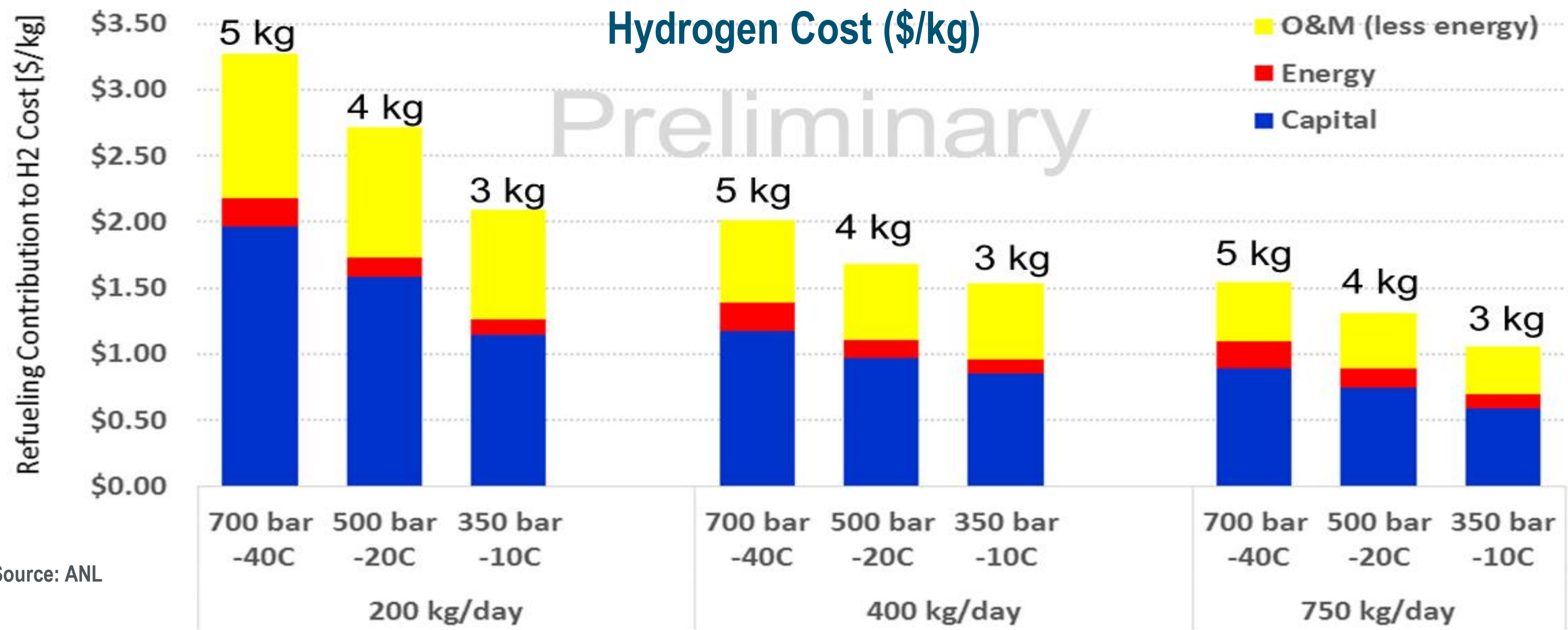
Focus on 700 bar fueling pressure for FCEV rollout. Assessment of low pressure trade-offs for long term.



Source: ANL

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.

Water Life-Cycle Analysis for Fuel Pathways

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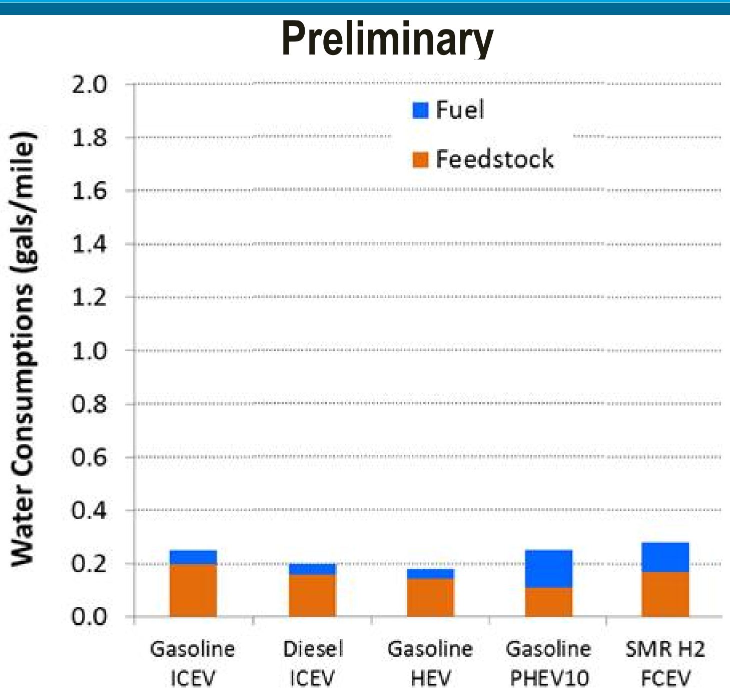
Water consumption of the hydrogen production from natural gas steam methane reforming is comparable to conventional fuel pathways



Source: ANL GREET = the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model

	Gaso ICEV	**Diesel ICEV**	**Gaso HEV**	**Gaso PHEV 10**	**H_2 FCEV**
Fuel Econ.* [mi/gge]	25	29	35	47 CD 37 CS	52

*** Midsize Vehicle**

- 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.

Accomplishments: (Employment Impacts) Employment Impacts of Infrastructure Development for H_2 and Fuel Cell Technologies

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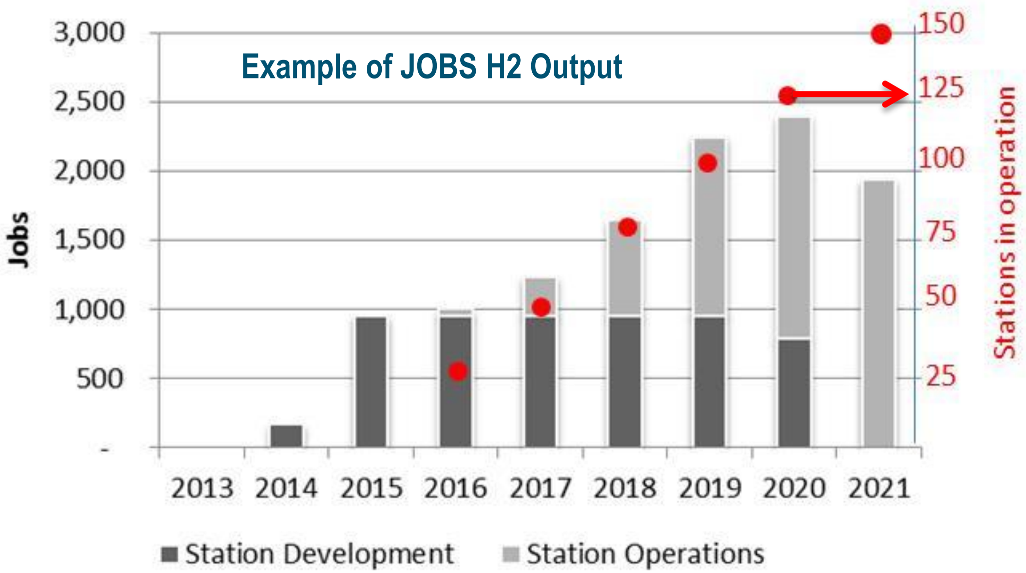
JOBS H2 created to analyze employment from equipment manufacturing/installation, station construction, and fuel supply chains (direct + indirect jobs), as well as from ripple employment effects (induced jobs).

JOBS H2 Model



Source: ANL

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

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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

Source: ANL

- Fuel cell efficiency of 60% has been achieved and demonstrated. http://www.nrel.gov/hydrogen/cdp_topic.html
- 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

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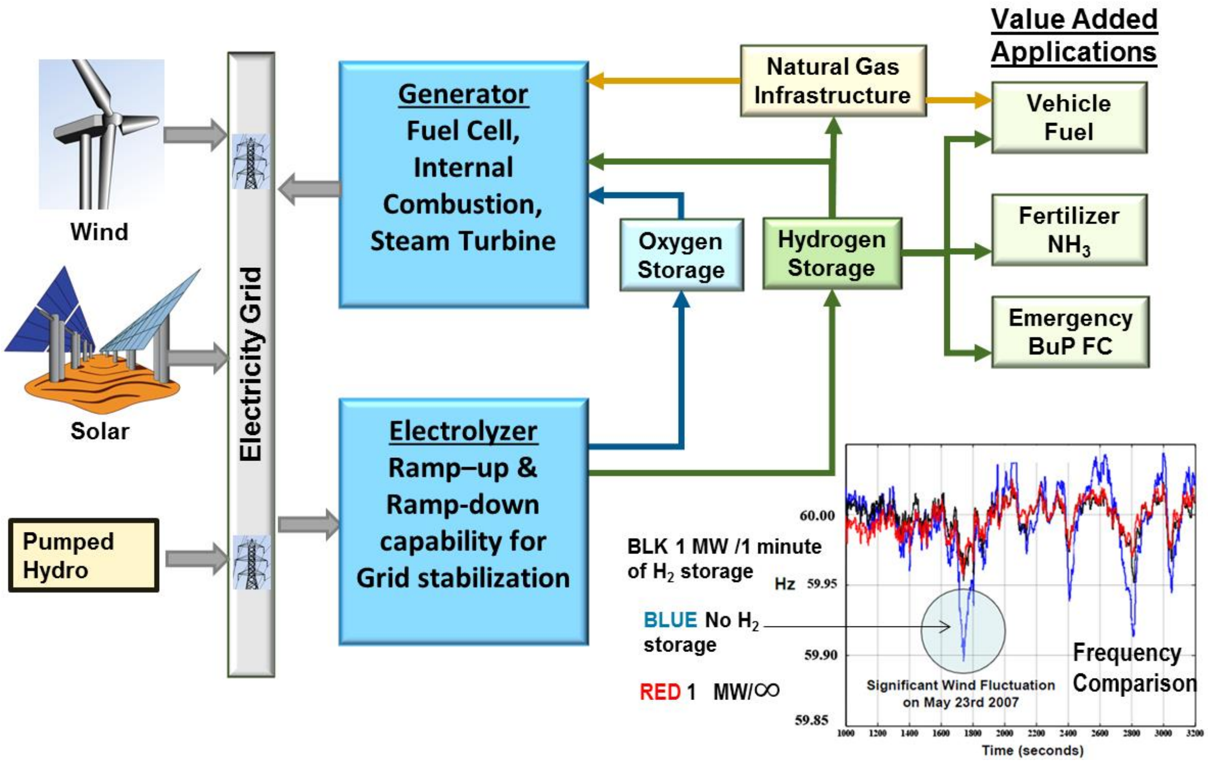
Providing a product hydrogen offtake for chemicals, FCEVs or material handling equipment improves value proposition of a hydrogen energy storage system for the grid.

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

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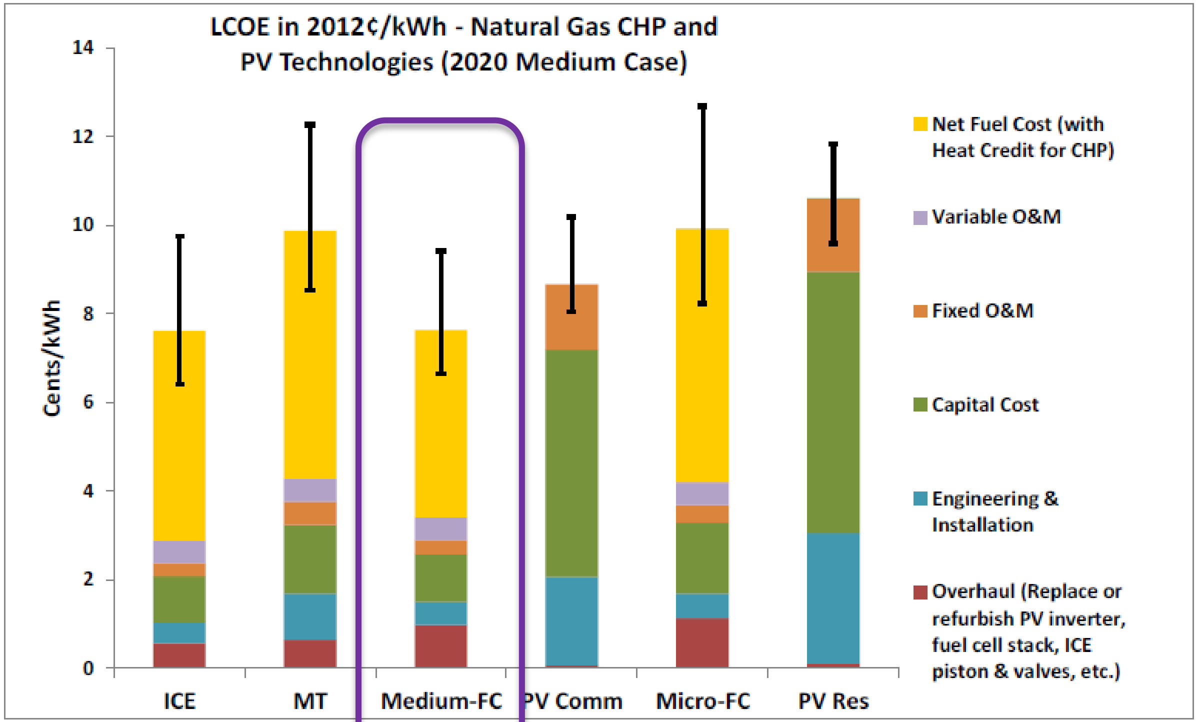
PEM stationary fuel cells could produce power at ~7¢-9¢ on an LCOE basis and be competitive with other CHP and solar PV technologies.

LCOE in 2012 Cents/kWh (Technology in 2020, No Incentive Assumed)



Low/high: sensitivity to uncertainties associated with capacity factor, fuel prices, and heat utilization (heat recovery applies only to CHP systems)

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.

Source: ***http://hydrogen.energy.gov/pdfs/14003_lcoe_from_chp_and_pv.pdf***
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)

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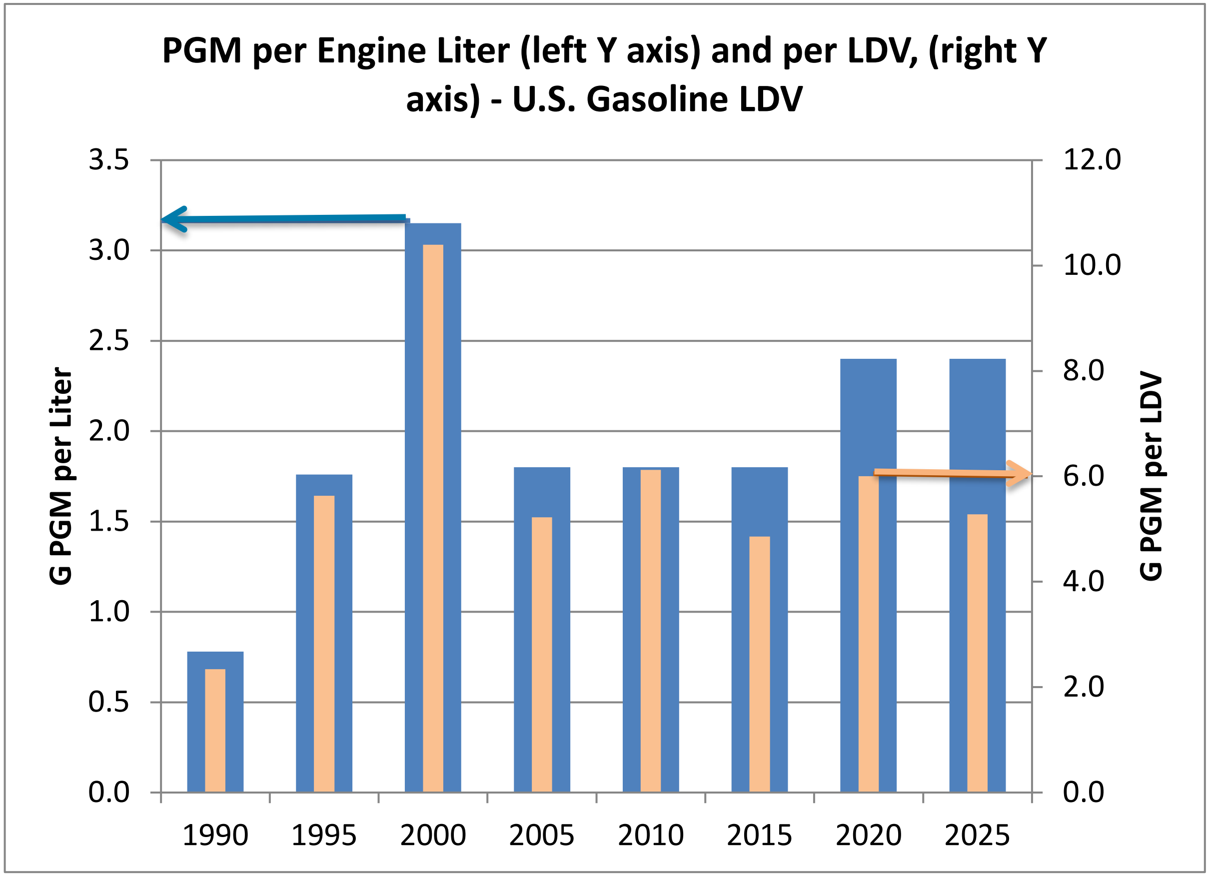
PGM content of LDVs could require ~2.4 gms of PGM per liter/5-6 gms per LDV to meet Tier 3 emission standards in 2020-2025.



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).

- 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).

PGM-Platinum Group Metals

Source: **Record 14001- Platinum Group Metals (PGM) for Light-Duty Vehicles** **http://hydrogen.energy.gov/pdfs/14001_pgm_light_duty_vehicles.pdf**

Model Fact Sheets

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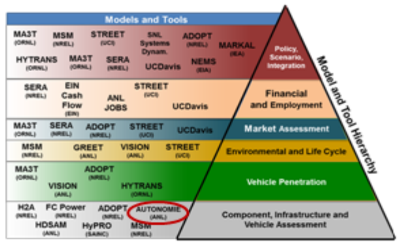
FCTO model fact sheets provide overview information for models used for FCTO analysis such as website, model objectives, key strengths, inputs and outputs.

Fact Sheet Example

Autonomie Model
(Argonne National Laboratory)

Objectives
Perform simulations to assess the energy consumption and performance of advanced component and powertrain technologies in a vehicle system context.

Key Attributes & Strengths
Developed over the past 15 years, Autonomie has been validated using component and vehicle test data, providing confidence in the results. Thus, the tool is widely accepted by the industry and has been licensed to more than 150 organizations worldwide. The model supports the rapid evaluation of new component and powertrain/propulsion technologies through virtual design and analysis in a math-based simulation environment. Autonomie is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from sub-systems to systems and entire architectures), as well as processes (e.g., calibration, validation, etc.).



Platform, Requirements & Availability
MATLAB®-based software environment and framework for automotive control system design, simulation and analysis. Graphical user interfaces support the selection of processes, configuration, and database management for any data type. Links with commercial off-the-shelf software applications for detailed, physically-based models, including GT-Power®, AMESim®, CarSim®, and AVL-DRIVE®.

Available through licensing agreements. LMS International (http://www.lmsintl.com/) acts as Argonne's exclusive and worldwide agent for Autonomie and will distribute and support Autonomie.

For information on commercial, university and not-for-profit licenses, please contact autonomie.licensing@lmsintl.com and for information on licenses to support U.S. government activities, please contact partners@anl.gov.

INPUTS	ASSUMPTIONS & DATA	OUTPUTS
• Component costs, weights, and losses (e.g., efficiency, fuel consumed, etc.). • Powertrain characteristics (e.g., transmission ratios, final drive ratio, wheel radius, etc.). • Vehicle-level energy control.	• Vehicle performance requirements (e.g., gradeability, acceleration, etc.) from U.S. Department of Energy/industry technical teams. • Component performance (e.g., engine fuel rate as a function of torque and speed, hydrogen consumed by the fuel cell system as a function of power, etc.), weight, and cost from U.S. Department of Energy/industry technical teams.	• Advanced vehicle energy consumption (including fuel and electrical), performance, and cost for different vehicle classes, timeframes, fuels, and drive cycles. • Impact of component technical targets at the vehicle system level.

- Located on FCTO website:

  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)

Workshops

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Workshop	Date	Objectives/Deliverables
COMPLETED		
H_2 Infrastructure Finance and Investor Workshop	April 2014	**Objectives:** Identify investment and financing gaps in initiating infrastructure development and next steps to resolve financial gaps. **Outcomes/Deliverables:** Internal information for next steps including scenario analysis and broader stakeholder workshop.
Energy Storage Workshop	May 2014	**Objectives:** 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. **Outcomes/Deliverables:** Workshop proceedings and identification of next steps, including analysis, R&D topics for FCTO program areas, and opportunities for international collaboration.
PLANNED		
Hydrogen and CNG Workshop	September 2014	**Objectives:** Explore intersection of hydrogen FCEVs and compressed natural gas (CNG) vehicles. Identify synergistic opportunities for FCEVs and CNG vehicles, regional issues, and consumer preferences. **Outcomes/Deliverables:** Workshop proceedings and identification of next steps, including analysis, R&D topics for FCTO program areas, and opportunities for collaboration.
Advanced H_2 Infrastructure Finance and Investor Workshop	September 2014	**Objectives:** Build on learnings from first investment workshop and explore gaps and potential resolutions. **Outcomes/Deliverables:** Workshop proceedings and identification of next steps, including investment scenarios to overcome barriers to market entry.

Recent and Upcoming Activities

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- 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.

FY 2014	FY 2015	FY 2016-2020
Complete analysis of resources/ feedstock, production/ delivery and existing infrastructure for technology readiness	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	Complete analysis of FCTO technology performance and cost status and potential to enable use of fuel cells for a portfolio of commercial applications
Complete analysis of job growth for hydrogen infrastructure		Complete analysis of H_2 quality impact on H_2 production cost and FC cost for long-range technologies and technology readiness
Complete infrastructure analysis for H2USA		Complete environmental analysis of impacts for H_2 scenarios
Complete H_2 infrastructure workshops to identify investment gaps		
Complete energy storage workshop to identify gaps.		

Collaborations

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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

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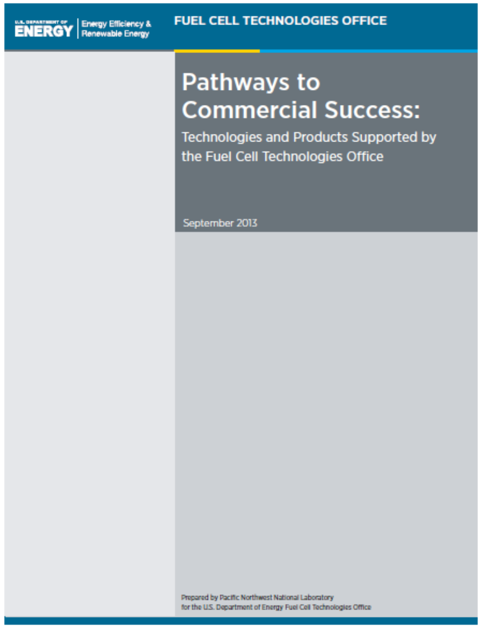
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FUEL CELL TECHNOLOGIES OFFICE

Pathways to Commercial Success:

Technologies and Products Supported by the Fuel Cell Technologies Office

September 2013

Prepared by Pacific Northwest National Laboratory for the U.S. Department of Energy Fuel Cell Technologies Office

PUBLICATIONS

Pathways to Commercial Success: Technologies and Products Supported by the Fuel Cell Technologies Program

by PNNL (http://www.pnl.gov/)

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pathways_2013.pdf

MODELS

JOBS H_2

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
http://hydrogen.energy.gov/pdfs/14001_pgm_light_duty_vehicles.pdf

14003 - Levelized Costs of Electricity from CHP and PV
http://hydrogen.energy.gov/pdfs/14003_lcoe_from_chp_and_pv.pdf

Contacts

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http://energy.gov/eere/fuelcells/fuel-cell-technologies-office

Additional Information

Programmatic Analysis: Commercialization

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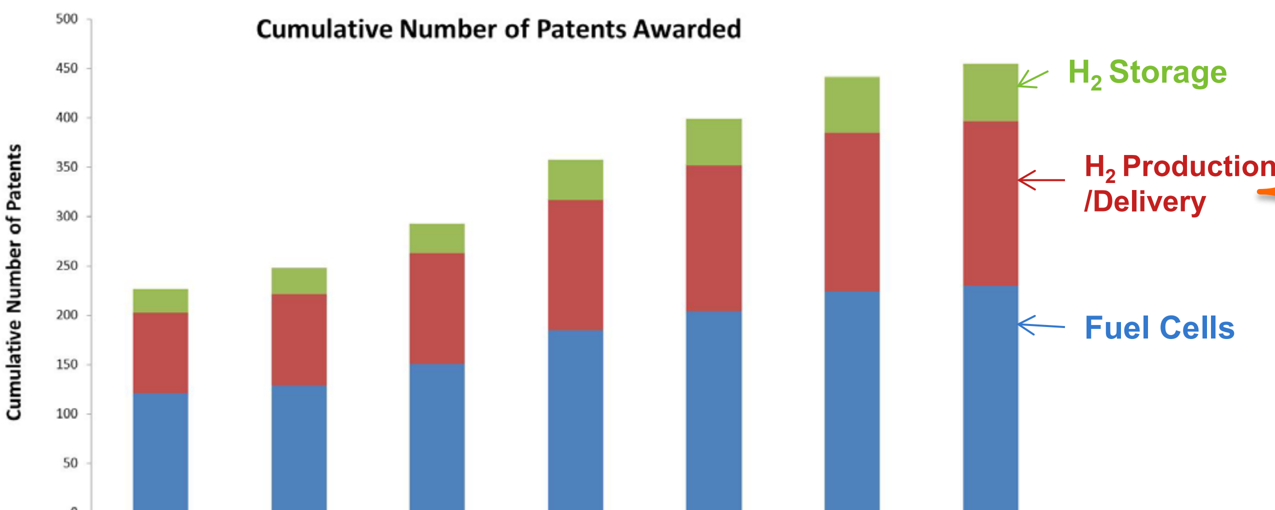
Continued annual growth of >5% in the number of commercial products resulting from DOE Fuel Cell Technologies Office funding

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



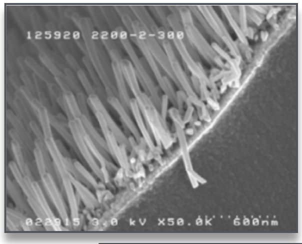
	2007	2008	2009	2010	2011	2012	2013*
Storage	24	26	30	41	47	57	58
Production/Delivery	82	93	112	132	148	161	167
Fuel Cell	121	129	151	185	204	224	230
Total	227	248	293	358	399	442	455

*Partial data for 2013

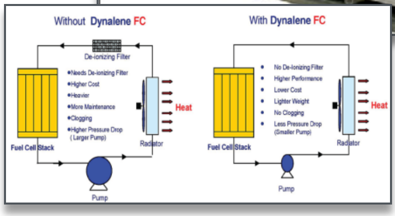
* Partial data for 2014 Source: PNNL *Commercial Pathways* report to be published September 2013

- Examples -

3M



Proton Onsite



Dynalene

Plug Power

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Assumptions

Vehicle Tank			
Fueling Pressure	700 bar	500 bar	350 bar
Capacity	5 kgH_2	4 kgH_2	3 kgH_2
Outer Diameter [inch]	19.5		
Thickness [inch]	1.83		
Tank Length [inch]	49.2		
Liner Thickness [inch]	0.20		
Volume [L]	129		

Vehicle Tank	
Initial Pressure	2 [MPa] Other initial pressures are modeled (5 and 10 MPa)
Initial (= Ambient) Temp.	298 [K] Hot soak condition (+15°C) is also modeled
Maximum Press.	1.25 x Service Pressure (700 bar)
Max. Temp.	358 K [85°C]
Convective H.T. Coeff. [W/m^2K]	325 (inside), 5 (outside)
Inlet Temp.	Precooled to 0, -10, -20, -30, and -40°C
Fill Strategy	Constant Pressure Ramp Rate (Other filling methods are being considered)

Assumptions for Analysis of the Levelized Costs of Electricity from CHP and PV Technologies

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Key Assumptions

	ICE	MT	Medium-FC	PV Comm	Micro-FC	PV Res
Size, kWe	500	200	500	495	7.0	6.8
Capital Cost/kWe	1,400	1,700	1,000	982	1,300	1,109
Engineering & Installation, $/kWe	450	1,000	500	382	450	554
Capacity Factor (CF)[2]	0.81 (0.78 - 0.84)	0.81 (0.78 - 0.84)	0.81 (0.78 - 0.84)	0.17 (0.15 - 0.19)	0.81 (0.78 - 0.84)	0.19 (0.17 - 0.21)
Elec. Efficiency (HHV)	35.5%	32.5%	45.1%	N/A	40.6%	N/A
Elec. Efficiency (LHV)	39.3%	36.0%	50.0%	N/A	45.0%	N/A
Combined Effic. (HHV)	78.5%	70.4%	81.2%	N/A	81.2%	N/A
Other O&M, ¢/kWh	0.81 (0.80 - 0.82)	1.03 (1.02 - 1.06)	0.83 (0.82 - 0.84)	1.47 (1.37 - 1.73)	0.90 (0.89 - 0.92)	1.65 (1.49 – 1.84)
Fuel Price, $/Mbtu	8.3 (7.3 - 10.5)	8.3 (7.3 - 10.5)	8.3 (7.3 - 10.5)	N/A	10.6 (8.9 - 13.7)	N/A