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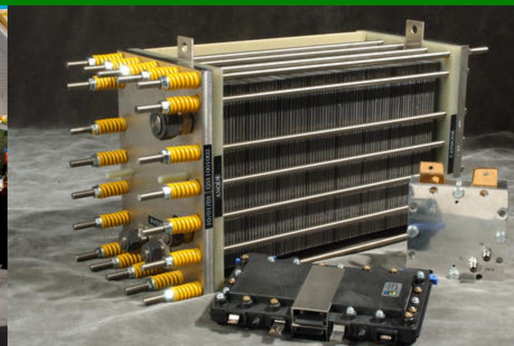
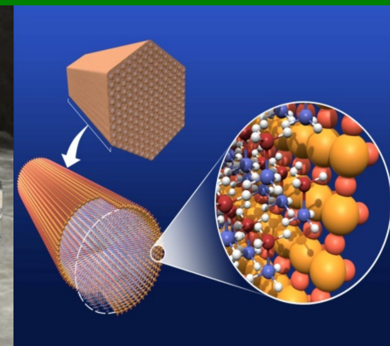


Hydrogen Production
-Session Introduction -

Katie Randolph

2013 Annual Merit Review and Peer Evaluation Meeting
May 16, 2013

Production Goal and Pathway Strategies

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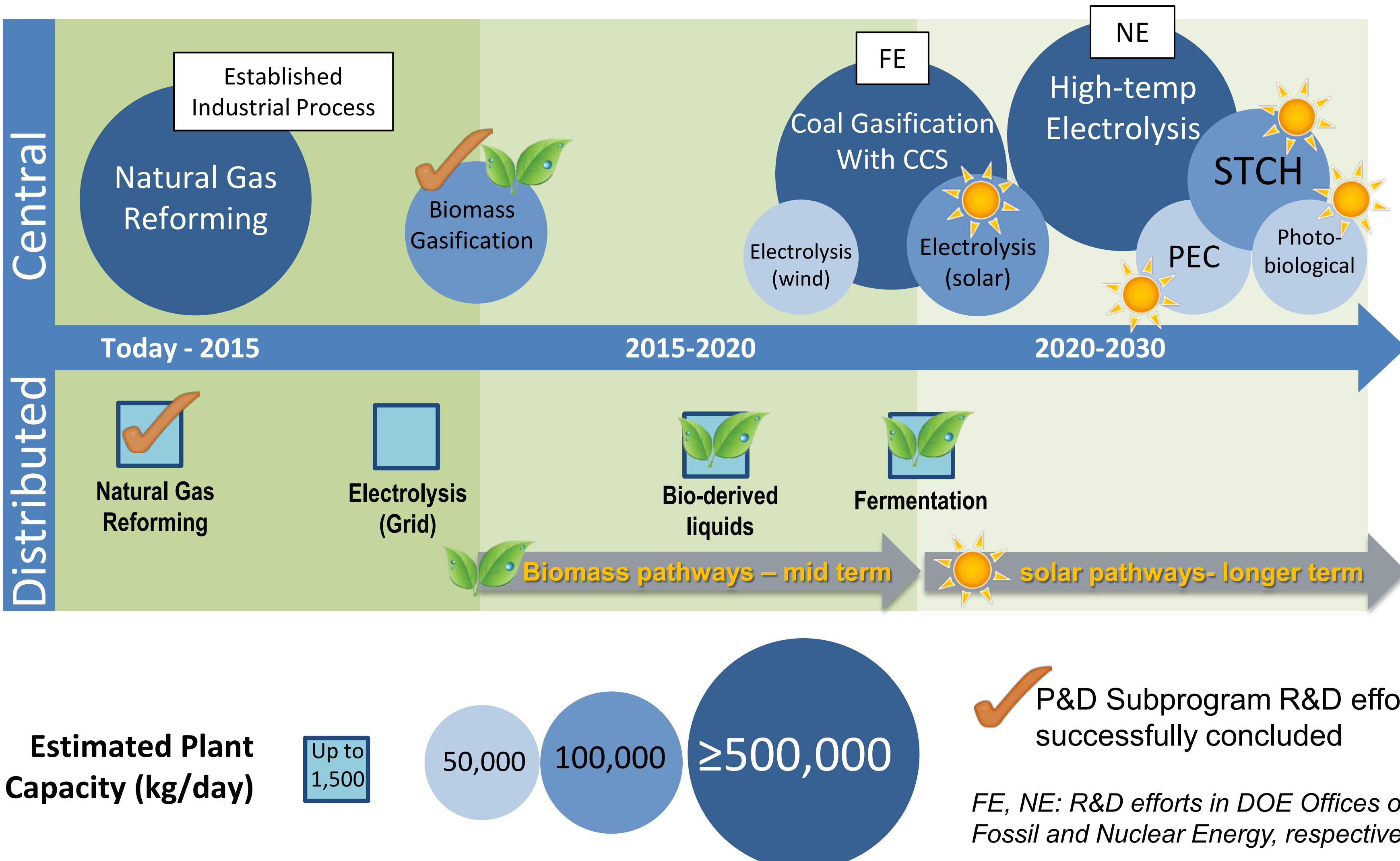
Objective: Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of \$2-\$4/kg H_2 by 2020



FE, NE: R&D efforts in DOE Offices of Fossil and Nuclear Energy, respectively

Cost Status

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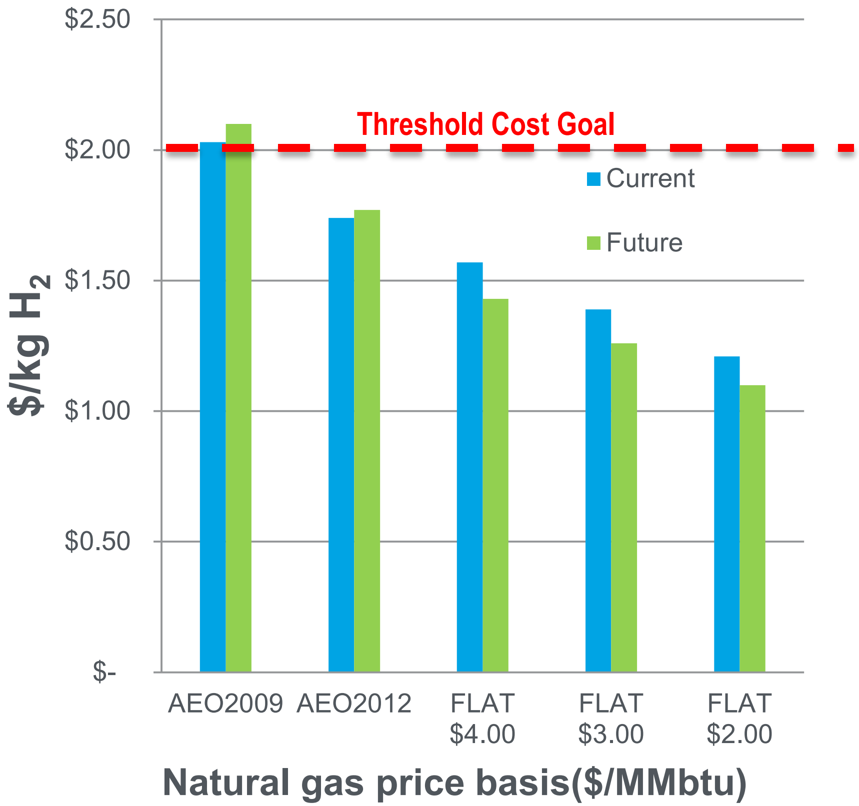
Hydrogen Production from Natural Gas: Bridge to Longer-Term, Low-Carbon Technologies

Distributed H_2 Production from NG SMR (high volume/economies of scale)

- Cost of H_2 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

$/kg H_2 (produced & untaxed, today's technology) for Varying Natural Gas Spot Prices



*Production Cost Using Low-Cost Natural Gas, September, 2012, http://hydrogen.energy.gov/pdfs/12024_h2_production_cost_natural_gas.pdf

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)

H_2 Production Cost: Status vs. Goals

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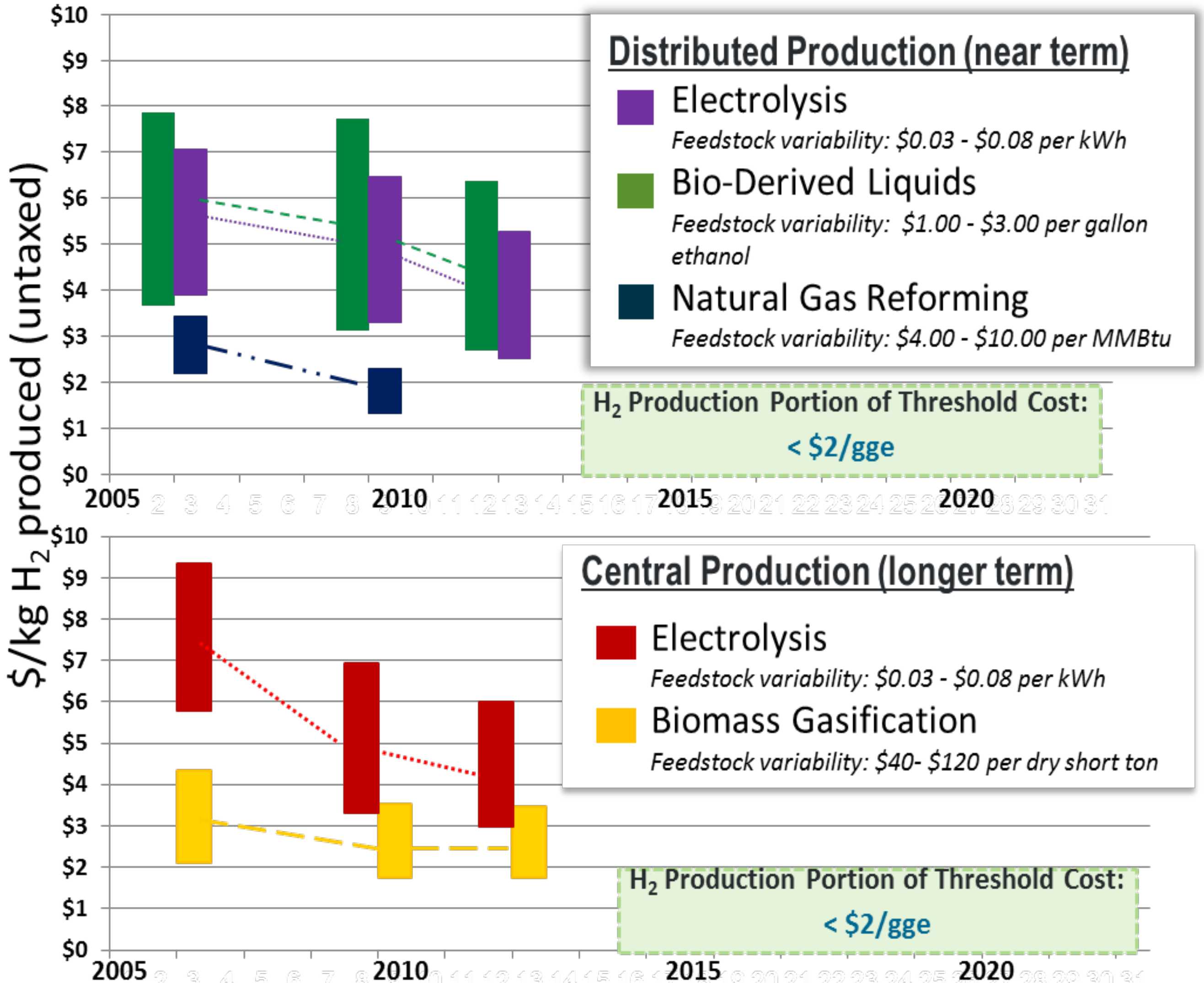
Projected High-Volume Cost of Hydrogen for Near-Term Production Pathways



- **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).**
- **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.**

Current Targets and Status

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	$/kg (production costs only)	2011 Status	2015 Target	2020 Target	Ultimate Production Target
Distributed	Electrolysis from grid electricity	$4.20	$3.90	$2.30	$1-$2
	Bio-derived Liquids (based on ethanol reforming case)	$6.60	$5.90	$2.30	
Central	Electrolysis From renewable electricity	$4.10	$3.00	$2.00	
	Biomass Gasification	$2.20	$2.10	$2.00	
	Solar Thermochemical	NA	$14.80	$3.70	
	Photoelectrochemical	NA	$17.30	$5.70	
	Biological	NA	NA	$9.20	

Apportionment of Threshold Cost: $1-$2/kg for production, $1-$2/kg for delivery.

***Based on the 2012 DOE-FCTP MYRD&D cost status and targets for Hydrogen Production** http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf

Challenges

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Materials performance and capital costs identified as key challenges for ALL production pathways

Bio-Derived Liquids Reforming

- High capital costs
- High operation and maintenance costs
- Design for manufacturing
- Feedstock availability, quality, and cost

Coal and Biomass Gasification

- High capital costs
- System efficiency
- Feedstock cost and purity
- Carbon capture and storage

Water Electrolysis

- Low system efficiency and high capital costs
- Integration with renewable energy sources
- Design for manufacturing
- Electricity costs

> **Meeting H_2 production cost threshold for all near- and longer-term pathways requires improvements in materials efficiency and durability, and reductions in overall capital costs**

Solar Thermochemical

- Cost-effective reactor and system
- Effective and durable reaction and construction materials

Photo-electrochemical

- Efficient and durable photocatalyst materials
- Innovative integrated devices

Biological

- Sustainable H2 production from microorganisms (O_2 tolerance)
- Optimal microorganism functionality (maximize yields and rates)

Hydrogen Production Budget

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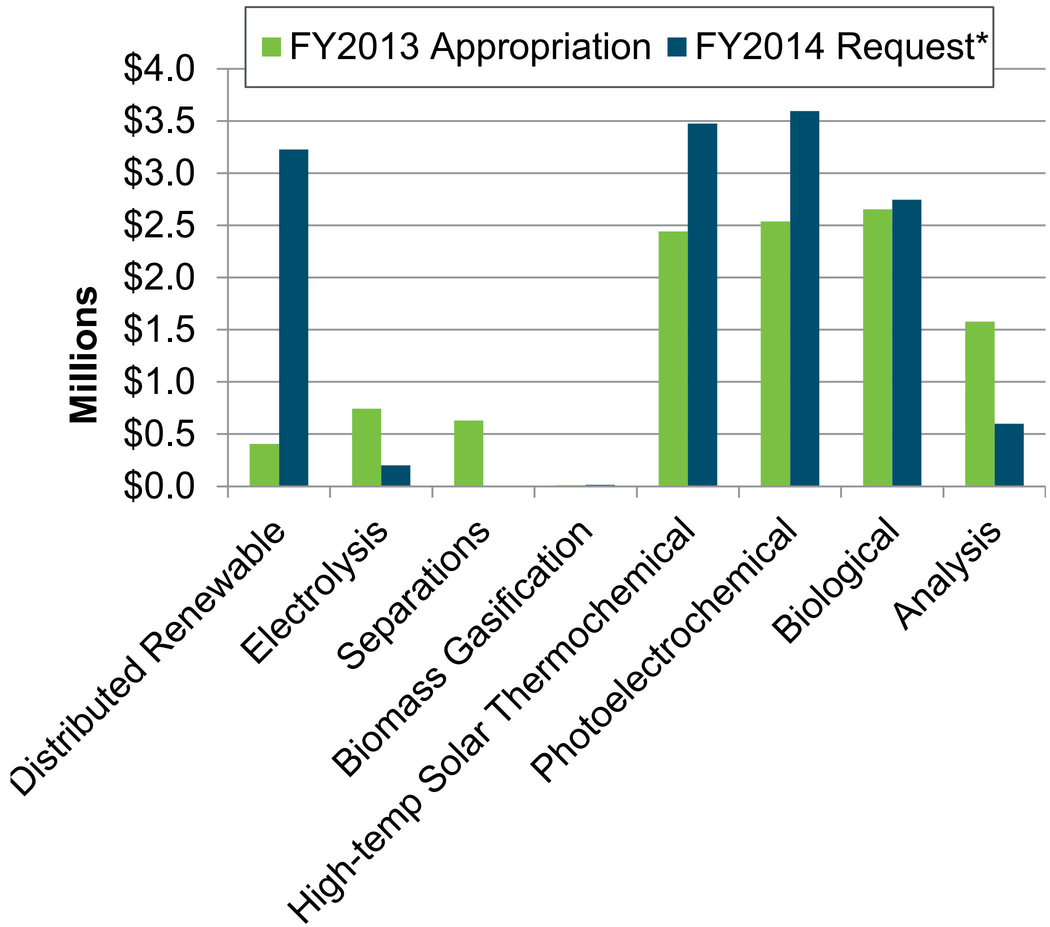
FY 2013 Appropriation = $11.0M

FY 2014 Request = $13.9M



* 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).

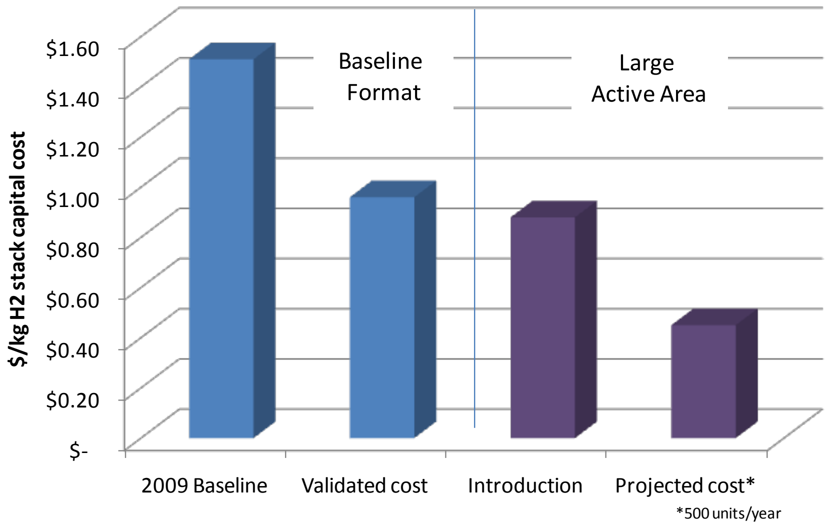
EMPHASIS

- New Hydrogen Analysis Award Made 2013
- Planning multiple FOAs over the next few FYs to replenish portfolio and address critical barriers.
  - Enhance leveraging of production R&D with DOE offices and other agencies.
  - Continue R&D on longer-term solar and bio-based renewable technologies
  - Continue to address key materials, device and reactor needs for production pathways
- Nearer term technologies being transitioned to Tech-Val portfolio and continue to be supported by SBIR Program

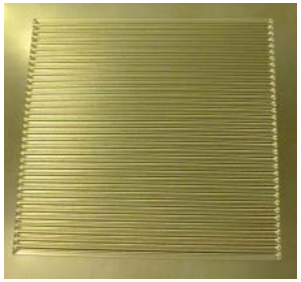
2013 Progress: Electrolysis

Cost Reduction Progress and Successful System Validation

Proton OnSite



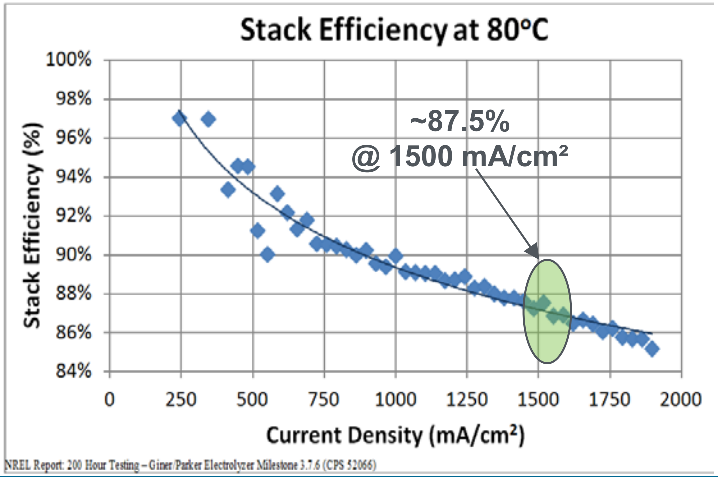
- Electrolyzer stack capital cost reduction of >70% over the last 4 years
- Contributions to cost reduction include:
  - A >50% reduction in catalyst pgm loading from >1 mg/cm^2 with no negative performance impact
  - Advancements in bipolar plate coating, design, and manufacturing enabling an increase in the cell active area



NREL/Giner, Inc.

12 kg H_2/day Giner system validated at NREL in June 2012

- Nominal operating conditions: 390 psig, 1.5-1.9 A/cm^2
- High stack voltage efficiency: 73.6% LHV (>87% HHV) @ 1.5 A/cm^2; Energy efficiency=46.6 kWhe/kg-H_2

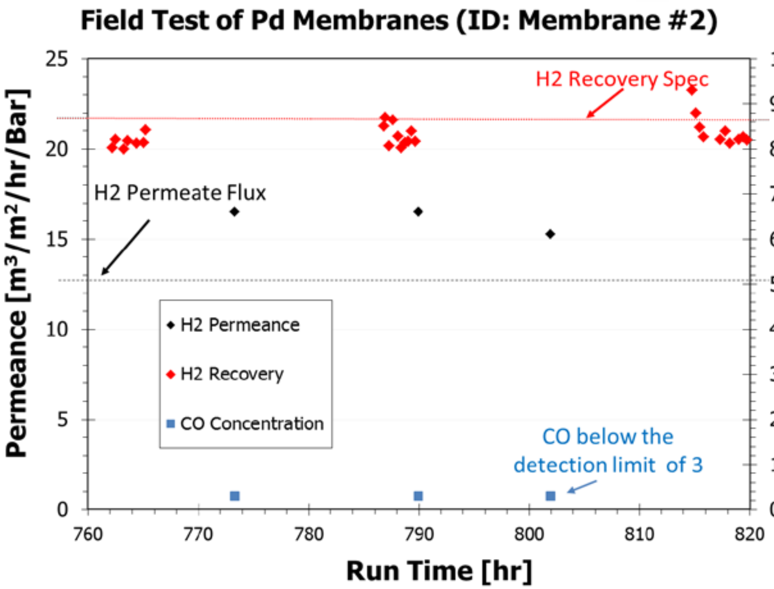


2013 Progress: Separations

Successful demonstrations of separations and purification

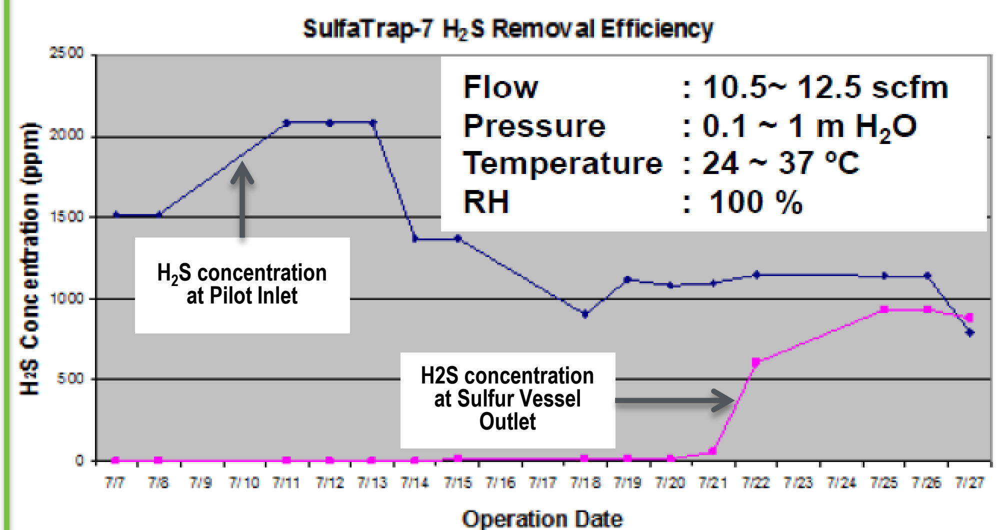
Media and Process Technology, Inc.

- Completed 200 hour full-scale tubular Palladium (Pd) membrane field test
  - ✓ Demonstrated <10ppm CO, >85% H_2 recovery
- Working with industry to replace common Pd foil-based purifiers with their ceramic membranes for back-up power applications



TDA Research, Inc.

- Completed 21 day field test on the 12 CFM gas clean-up skid
  - ✓ Sorbent achieved 17.5 wt. % sulfur capacity
  - ✓ Potential for 2X higher capacity than commercially available sorbents
  - ✓ Sub ppm level of sulfur (undetectable)



2013 Progress: Solar-Thermochemical

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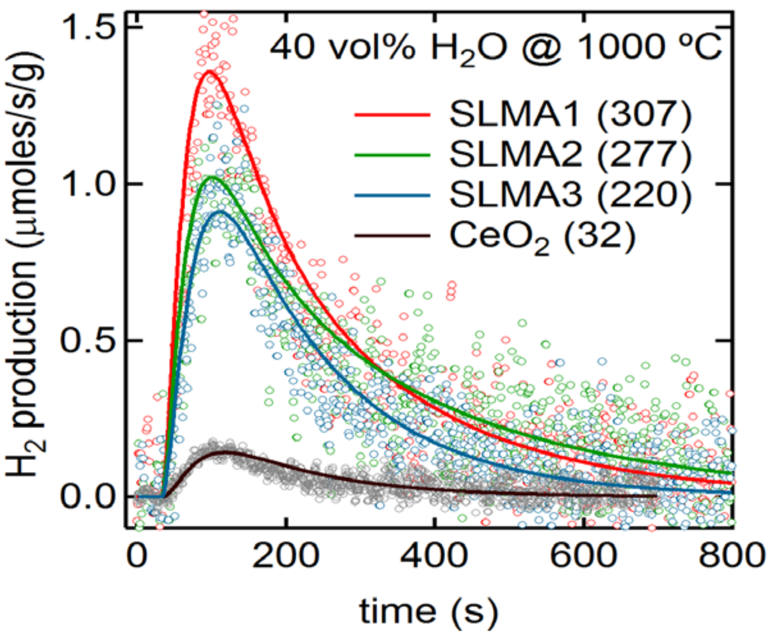
Perovskite compounds, nanostructured hercynite, show production yields ~9-10x that of CeO_2 at low reduction temperatures

Sandia National Laboratory



- Perovskite kinetics benchmarked against CeO_2
- At lower T_R (1350 °C vs. 1500 °C) ~9x more H_2 w/ Perovskite as compared to CeO_2
- Patent filed on a family of perovskite materials

University of Colorado

Temp Swing (TS) & Isothermal (IT) (Red/Ox); Temperature (°C)	CeO_2 (μmole/g)	Nanostructured Hercynite (μmole/ total g)*
1500/1200	159.1 ± 15.7	93.7 ± 19.2
1450/1450		167.4 (avg)
1350/1000	16.4 ± 3.6	31.4 ± 2.3
1350/1350		102 ± 18

*The numbers shown for hercynite are per total g material. If per active g of material, they would be multiplied by 2.13.

- IT hercynite cycle produces ~ the same and 2X more H_2 on a total and active material basis respectively than TS CeO_2 at high reduction T.
- IT hercynite cycle produces about ~ 5X and 15X more H_2 on a total and active material basis respectively than TS CeO_2 at lower reduction T.
- IT hercynite cycle produces substantially more H_2 than TS "hercynite cycle"

2013 Progress: Photoelectrochemical

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Important progress in establishing standardized PEC protocols and in demonstrating manufacturability of large-scale devices

Developed critical standards & protocols for evaluating and reporting PEC materials

EERE PEC Working Group

- ***Original JMR Review paper cited over 100 times to date;***
- ***Expanded form being published as a "Springer Brief"***

REVIEW

This section of Journal of Materials Research is reserved for papers that are reviews of literature in a given area.

Accelerating materials development for photoelectrochemical hydrogen production: Standards for methods, definitions, and reporting protocols

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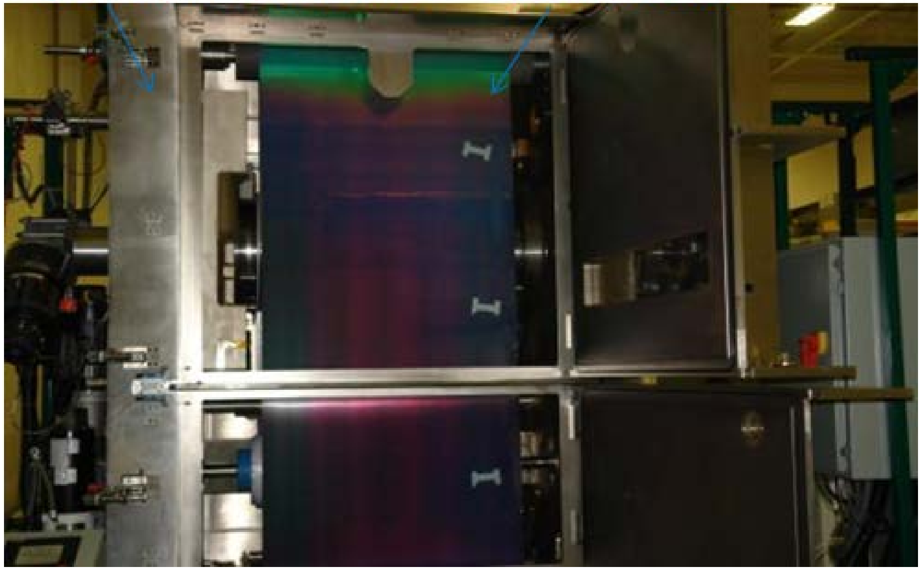
Demonstrated pathway to economical manufacturing of thin-film PEC devices

MWOE

Pay-out chamber of 2MW line *3 ft. wide SS web*



- The 2MW roll-to-roll machine allows the fabrication of integrated thin-film PEC photoelectrodes based on amorphous silicon cells
- The prototype production machine produces large area PEC electrodes (3ft wide and hundreds of feet long) with good uniformity and minimal edge effects

2013 Progress: Photobiological

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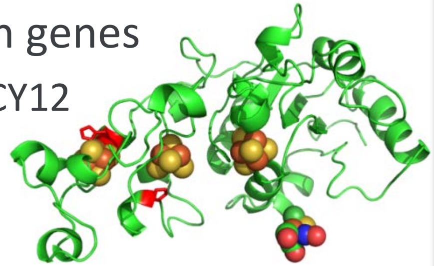
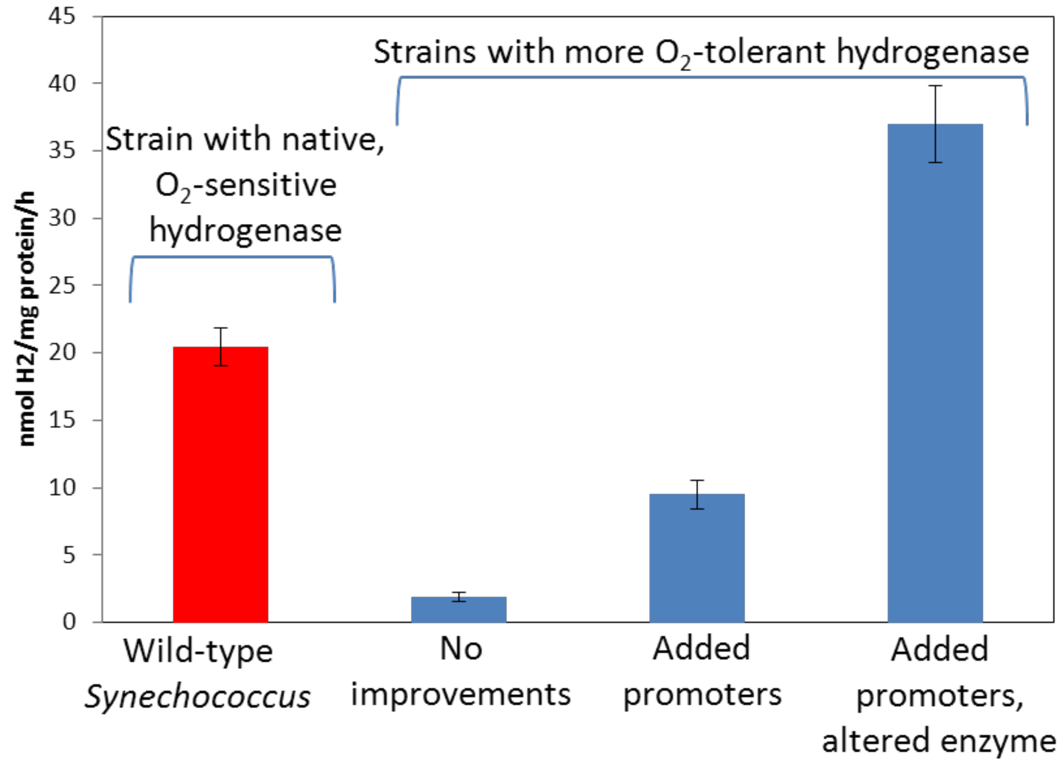
Improved expression of recombinant hydrogenase proteins in cyanobacteria *(JCVI)*

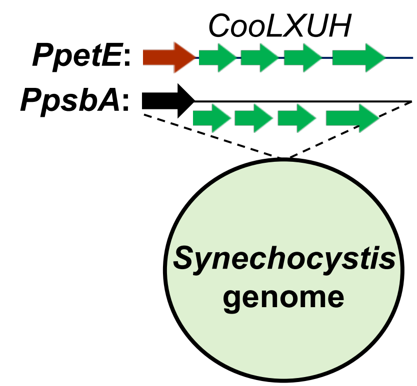
- Added promoters to maturation genes
  - Increased activity by 4 fold in CY12
- Altered protein to improve electron transfer
  - Increased activity by 5 fold in CY12



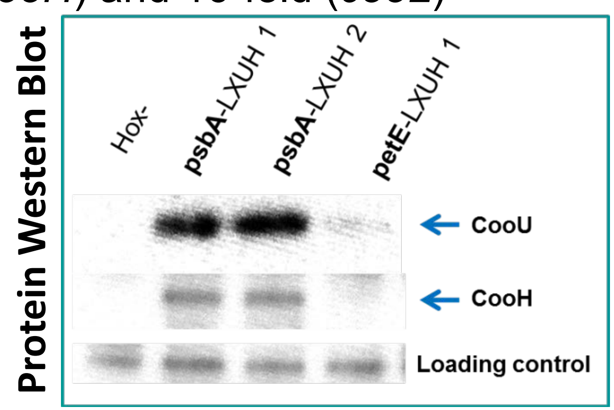


Improved hydrogen evolution in recombinant cyanobacteria *(NREL)*

- Placed native *Synechocystis* promoter *psbA* in front of CBS hydrogenase genes inserted into *Synechocystis* genome



- Increased protein subunits 44-fold (*cooH*) and 16-fold (*cooL*)



Summary

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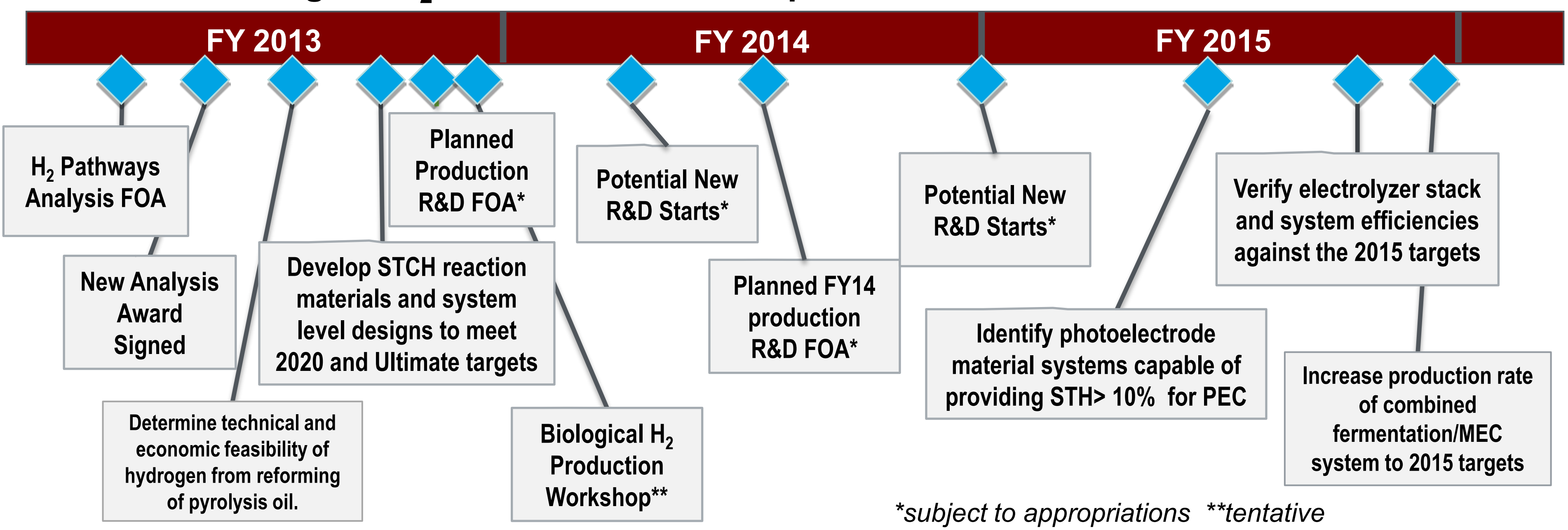
Key milestones and future plans

- **Update of production cost targets and Multi-Year RD&D completed and published online**
- **Released H_2 Pathways Analysis FOA, Award made February FY13**
- **Potential FOA in Production R&D: Tentative*- new starts FY14**
- **Updated Hydrogen Production US Drive Roadmap, to be published this summer**
- **Tentative Biological H_2 Production Workshop this summer**



Key Participants – Hydrogen Production

U.S. DEPARTMENT OF ENERGY

- **Analysis & Testing**
  - ORNL
  - PNNL
  - ANL
  - NREL
  - SA Inc.
- **Bio-Derived Liquids**
  - PNNL
  - NREL
- **Electrolysis**
  - Giner Electrochemical
  - Avalence
  - Proton OnSite
  - ORNL
  - NREL
- **Membranes/Separations**
  - TDA (SBIR Phase III)
- **Biological**
  - NREL
  - J Craig Venter Institute
  - University of California, Berkeley
- **Solar High Temperature Thermochemical H_2 Production**
  - SNL
  - ANL
  - SAIC
  - Univ. of Colorado, Boulder
  - NREL
  - SRNL
- **Photoelectrochemical H_2 Production**
  - LANL
  - LLNL
  - Midwest Optoelectronics
  - MV Systems
  - NREL
  - LBNL

For More Information

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Session Instructions

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- This is a review, not a conference.
- Presentations will begin precisely at scheduled times.
- Talks will be 20 minutes and Q&A 10 minutes.
- Reviewers have priority for questions over the general audience.
- Reviewers should be seated in front of the room for convenient access by the microphone attendants during the Q&A.
- Please mute all cell phones and other portable devices.
- Photography and audio and video recording are not permitted.

Reviewer Reminders

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- Deadline to submit your reviews is Friday, **May 24th at 5:00 pm EDT.**

- ORISE personnel are available on-site for assistance.
  - **Reviewer Lab Hours:**
    - Monday, 5:00 pm – 8:00 pm (Gateway ONLY)
    - Tuesday – Wednesday, 7:00 am – 8:00 pm (Gateway)
    - Thursday, 7:00 am – 6:00 pm (Gateway)
    - Tuesday – Thursday, 7:00 am – 6:00 pm (City)
  - **Reviewer Lab Locations:**
    - Crystal Gateway Hotel—*Rosslyn Room* (downstairs, on Lobby level)
    - Crystal City Hotel—*Roosevelt Boardroom* (next to Salon A)