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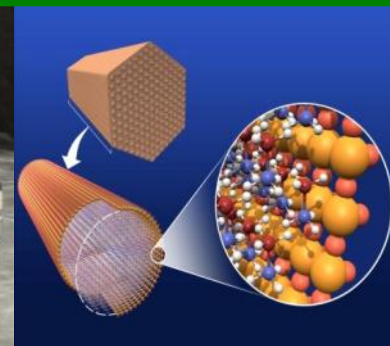

Hydrogen Production
- Session Introduction -

Eric L. Miller

2012 Annual Merit Review and Peer Evaluation Meeting
May 16, 2012

Goal & Objectives

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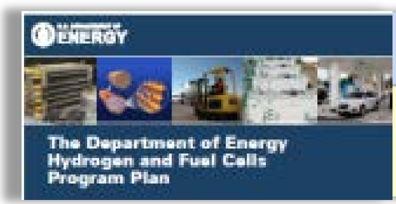
Develop distributed and central technologies to produce H_2 from clean, domestic resources at a dispensed cost threshold of $2-4/gge H_2

Near-term: Distributed Production (up to 1,500 kg/day H_2)
(produced at station to enable low-cost delivery)

- Renewable liquid reforming
- Electrolysis (grid- or renewable- coupled)

Longer-term: Centralized and Semi-Centralized Production (up to 500,000 kg/day H_2)
(large investment in delivery infrastructure needed)

- Biomass gasification
- Wind-and solar-driven electrolysis
- Solar high-temperature thermo-chemical water splitting
- Photoelectrochemical and biological production



http://www.hydrogen.energy.gov/pdfs/program_plan2011.pdf

In the United States, about 9 million tons of hydrogen are produced annually for industrial purposes, and there are >1,200 miles of hydrogen pipelines.

Production Strategies

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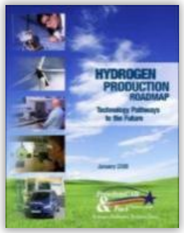
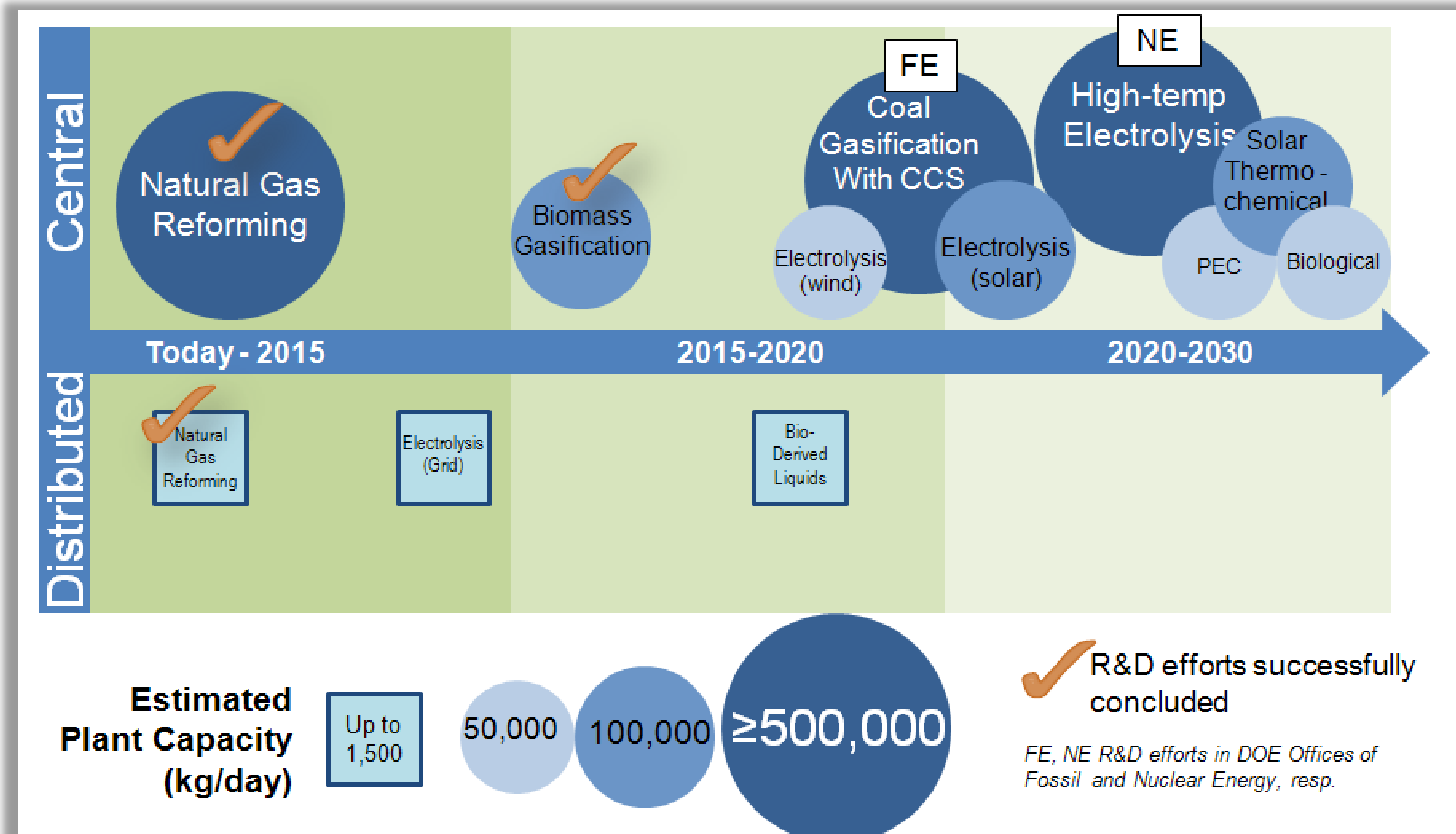
Informed prioritization of R&D needs in H_2 production pathways



- **Independent analyses and H2A case studies of hydrogen production pathways used to establish status, targets and projected costs, providing a basis for prioritizing R&D**



Challenges

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The key driver of production pathway R&D is the hydrogen production threshold cost <$2/gge ($2-$4/gge dispensed).

Projected High-Volume Cost of Hydrogen Production[1]—Status of Near-Term Pathways

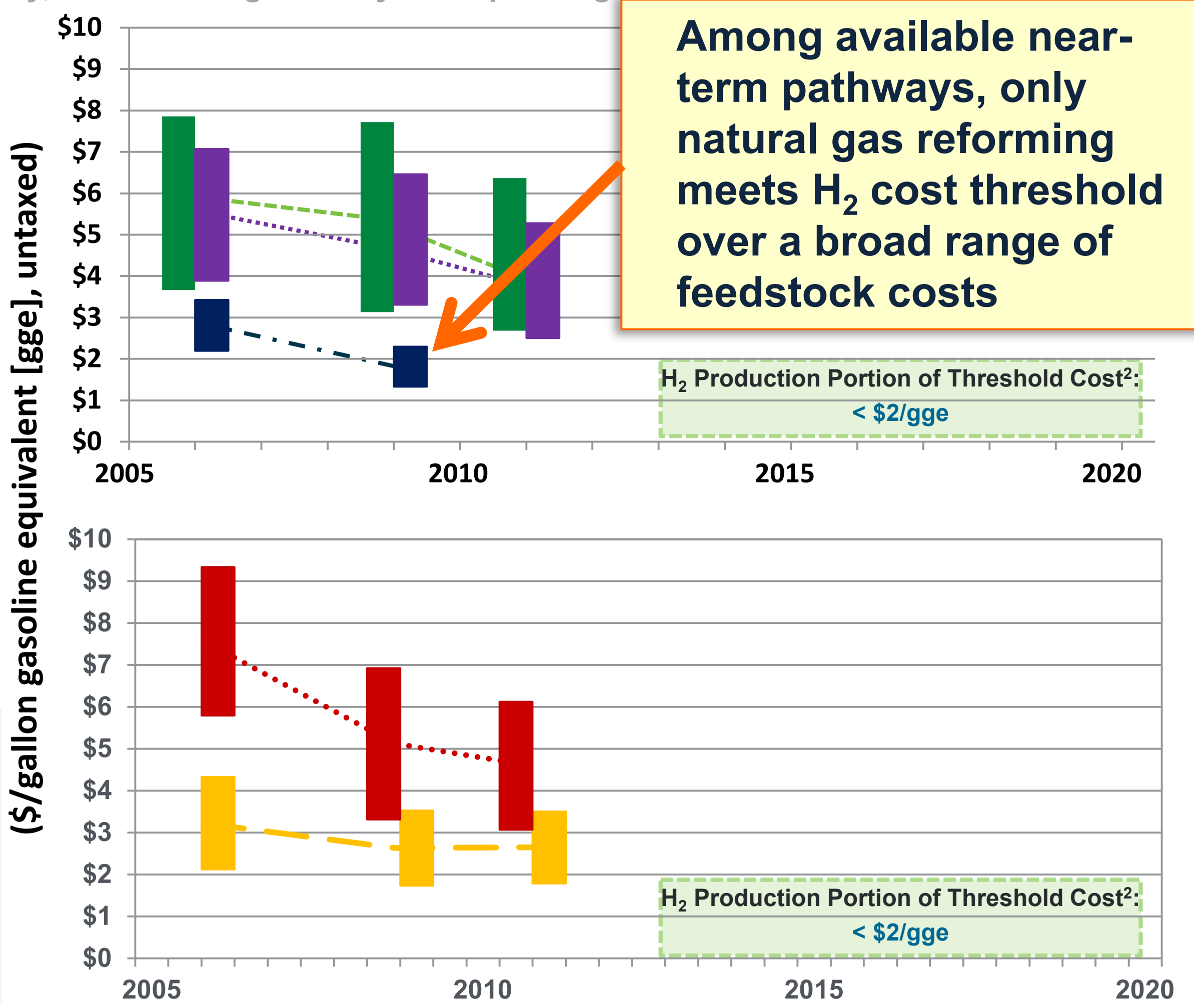
production costs only, not including delivery or dispensing

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 dollars, based on projections from 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. Projections of costs assume Nth-plant construction, distributed station capacities of 1,500 kg/day, and centralized station capacities of ≥50,000 kg/day.

[2] The Hydrogen Production Threshold Cost of <$2/gge reflects the Production apportionment (Record 12001, in preparation) of the 2010-revised Hydrogen Production and Delivery Cost Threshold of $2-4/gge (Record 11002, Hydrogen Threshold Cost Calculation, 2011, http://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf).

[3] DOE funding of natural gas reforming projects was completed in 2009 due to achievement of the threshold cost. Incremental improvements will continue to be made by industry.

Challenges

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Materials performance and capital costs identified as key challenges in ALL distributed and central production pathways

Distributed Natural Gas Reforming	Bio-Derived Liquids Reforming	Coal and Biomass Gasification
Critical Challenges	*Critical Challenges*	*Critical Challenges*
▪ High capital costs ▪ High operation and maintenance costs ▪ Design for manufacturing	▪ High capital costs ▪ High operation and maintenance costs ▪ Design for manufacturing ▪ Feedstock quantity and quality	▪ High reactor costs ▪ System efficiency ▪ Feedstock impurities ▪ Carbon capture and storage

➤ **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**

Thermochemical	Water Electrolysis	Photo-electrochemical	Biological
Critical Challenges	*Critical Challenges*	*Critical Challenges*	*Critical Challenges*
▪ Cost-effective reactor ▪ Effective and durable materials of construction ▪ Longer-term technology	▪ Low system efficiency and high capital costs ▪ Integration with renewable energy sources ▪ Design for manufacturing	▪ Effective photocatalyst material ▪ Low system efficiency ▪ Cost-effective reactor ▪ Longer-term technology	▪ Efficient microorganisms for sustainable production ▪ Optimal microorganism functionality in a single organism ▪ Reactor materials ▪ Longer-term technology

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_production_roadmap.pdf; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_tech_roadmap.pdf

Production Budget

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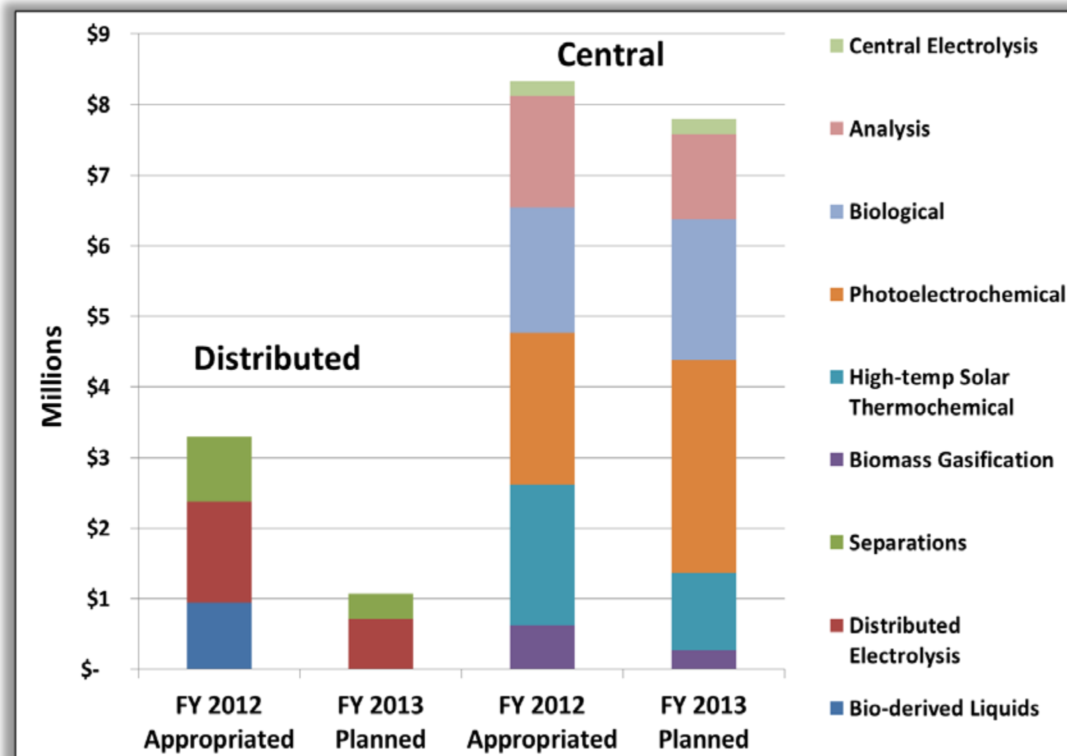
FY 2012 Planned Funds $11.6M; FY 2013 Requested Funds $8.9M



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 H_2 production from coal was provided.

Emphasis

- **Update cost projections and 2015 and 2020 targets for all pathways using new H2A v3 tool with common techno-economic assumptions**
- **Incorporate recommendations from the HTAC Hydrogen Production Expert Panel in portfolio planning**
- **Enhance leveraging of production R&D with DOE offices and other agencies**
- **Verify/validate near-term technologies, such as advanced electrolysis, for early markets**
- **Continue R&D on longer-term solar and bio-based renewable technologies**
- **Continue to address key materials, device and reactor needs for production pathways**

2012 Progress: Technoeconomic Pathway Analysis

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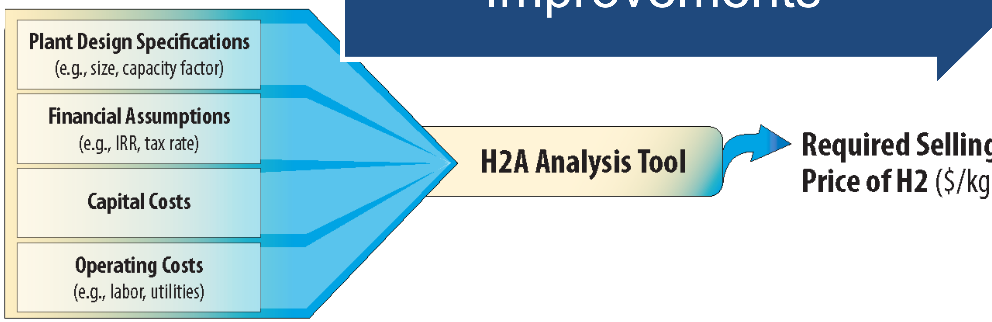
The "new & improved" H2A Model with unified cost assumptions

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



Improvements

- **Streamlined and clarified user input**
- **Updated H2A "Built-In" database**
- **New plant scaling and CSD calculations**
- **Allows for cross-the-board assessment of status and targets for production pathways**

Updated Production Targets*

		2010 Status	2015 Target	2020 Target	Ultimate Production Target
Distributed	Electrolysis from grid electricity	$4.10	$3.90	$2.30	$1-$2
	Bio-derived Liquids (based on ethanol reforming case)	$6.65	$5.10	$2.25	
Central	Electrolysis From renewable electricity	$4.10	$3.00	$2.00	
	Biomass Gasification	$2.20	$2.10	$2.00	
	Solar Thermochemical	NA	$8.00	$3.00	
	Photoelectrochemical	NA	$26.00	$4.00	
	Biological	NA	NA	$10.00	

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

**Production only. Preliminary numbers. All units are per gge*

2012 Separations Progress (near-term pathway)

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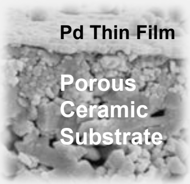
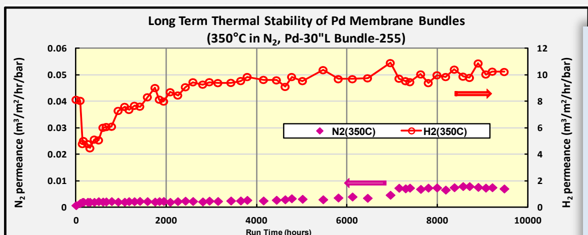
Successful optimization of separations and purification

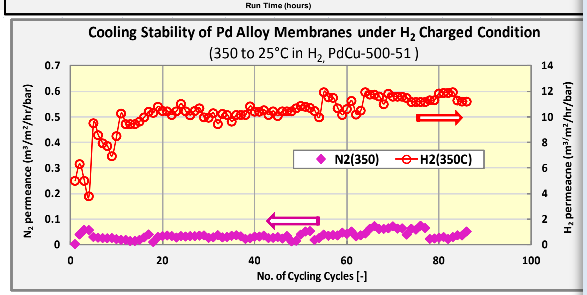
Developed palladium thin-film membranes meeting DOE targets

Media & Process Technology, Inc.



Cross Section of Pd Membran





- Demonstrated excellent long term thermal stability: ~10,000 hrs at 350°C
- Demonstrated cyclic cooling stability from 350 to 25°C in H2 charged environment for > 85 cycles.

Demonstrated Pd membranes meeting DOE 2015 targets of 0.6 scfh @ 20 psi per unit dollar cost.

Demonstrated system to purify biogas for fuel cell applications

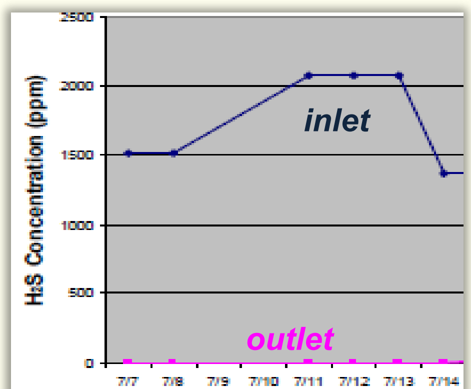
TDA Research, Inc.: SBIR Phase 3

Completed Sorbent Production and Scale-up

- Increased the production batch size from 20 mL to 35 L by optimizing sorbent formulation to remove all the organic and inorganic sulfur species.
- Optimized the binder composition and drying conditions

Demonstrated Gas Cleanup System –

- Completed fabrication of skid-mounted field-deployable prototype biogas clean-up system



Demonstrated efficient H_2S and siloxane removal in 12 CFM biogas cleanup skid.

2012 Electrolysis Progress (near-term pathway)

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Previous R&D reduced electrolyzer stack capital cost (80% since 2011) and increased efficiency (>70%)

Latest progress in high-pressure electrolysis and renewable integration

Developed higher pressure stacks to reduce dispensing costs

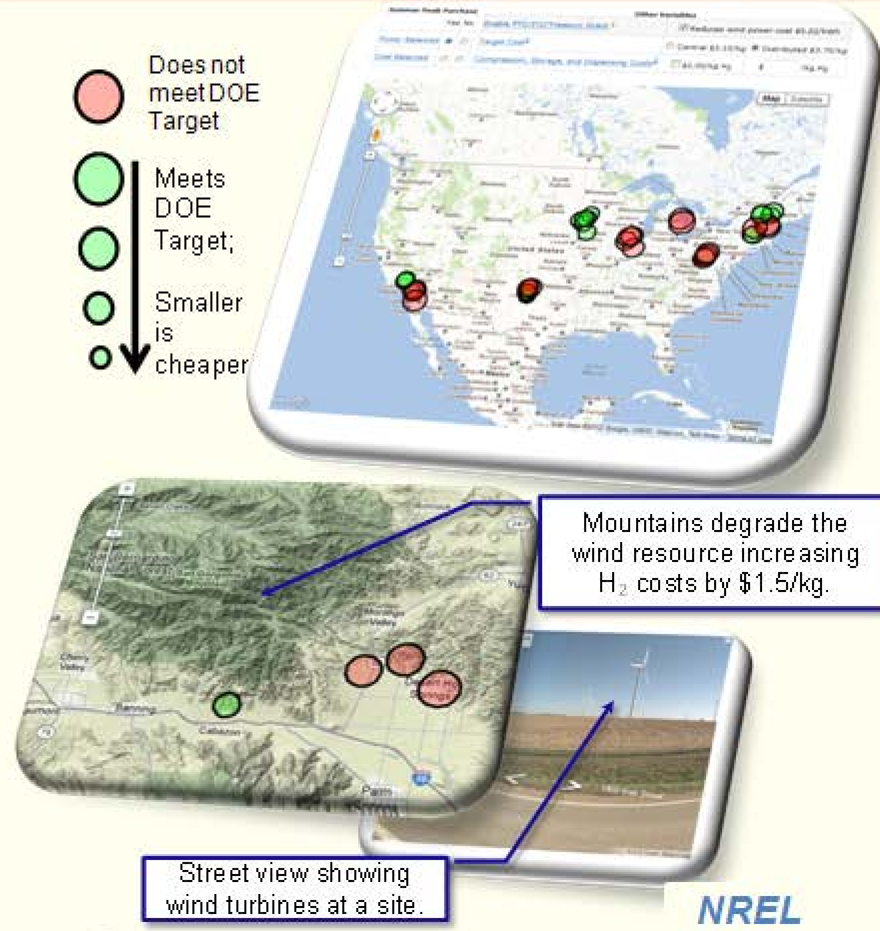
Giner, Inc.

Completed electrolysis testing with inherent electrochemical compression up to 2,000 psig. Verified stack and component compatibility with 6,500 psig, and initiated stack testing at 5,000 psig.

Proton OnSite

Completed electrolysis testing to 2,400 psig. Fabricated a 5,000 psig system at 2.2 kg/day for home refueling. Completed system proof pressure testing to 7,500 psig and initiated production tests at 5,000.

Developed tool to analyze the viability of wind-based hydrogen electrolysis



NREL

http://www.nrel.gov/hydrogen/production_cost_analysis.html

2012 PEC Progress (longer-term pathway)

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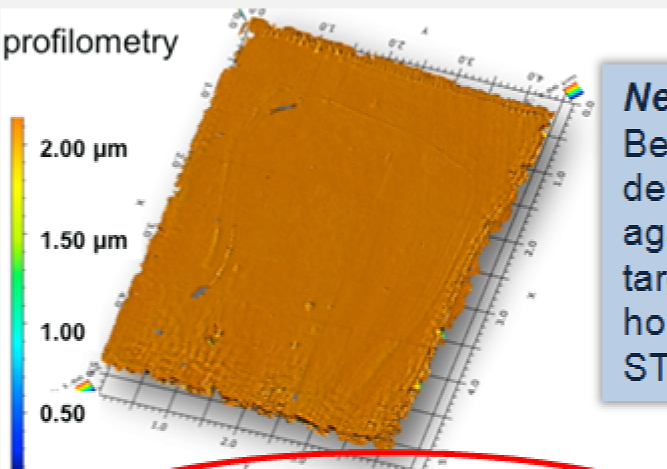
2011 reported new PEC efficiency benchmarks: 16% & 4% STH in crystalline & thin-film materials

Significant new PEC durability benchmarks achieved this year

Extended durability in high-efficiency III-V crystalline systems to >100 hours

NREL

Low-energy N_2^+ ion treatment of $GaInP_2$ surfaces forms a capping surface nitride that passivates the interface against corrosion. Tests indicate that $GaInP_2$/GaAs tandem cells with this treatment can operate at conditions compatible with 10% solar-to-hydrogen (STH) conversion efficiency for > 100 hr.



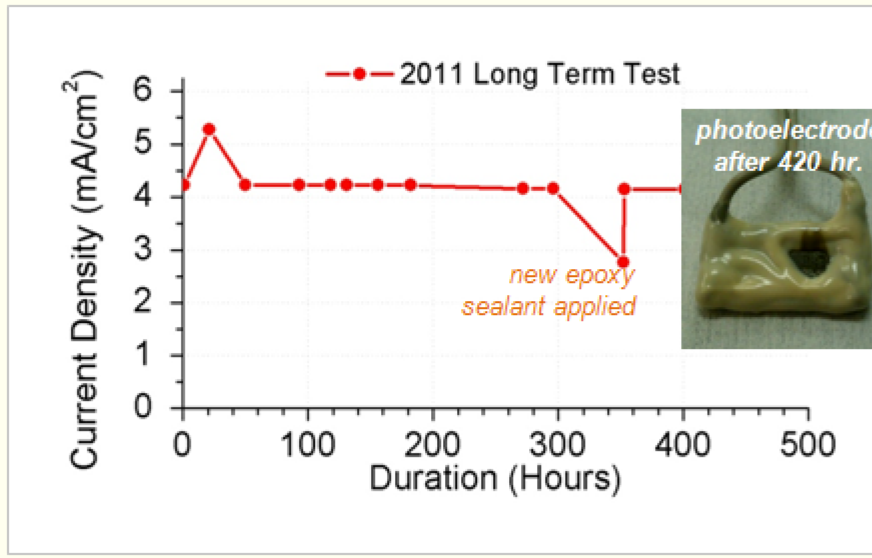
Nitrogen Ion Bombardment
Pristine surface after 115 hours at current density equivalent to 12% STH

Next step: Benchmark device lifetime against the target of 100-hours at 10% STH efficiency.

Extended durability in efficient thin-film CGSe systems to >400 hours

MVSystems / U. Hawaii

Demonstrated long-term durability in thin-film copper chalcopyrite material system with high efficiency potential (for PV and PEC applications).



CGSe photoelectrode: tested for 420 hours under simulated sunlight @1.7V, operating at current density equivalent to 5% STH (exceeding 300hr target)

2012 Biological Progress (longer-term pathway)

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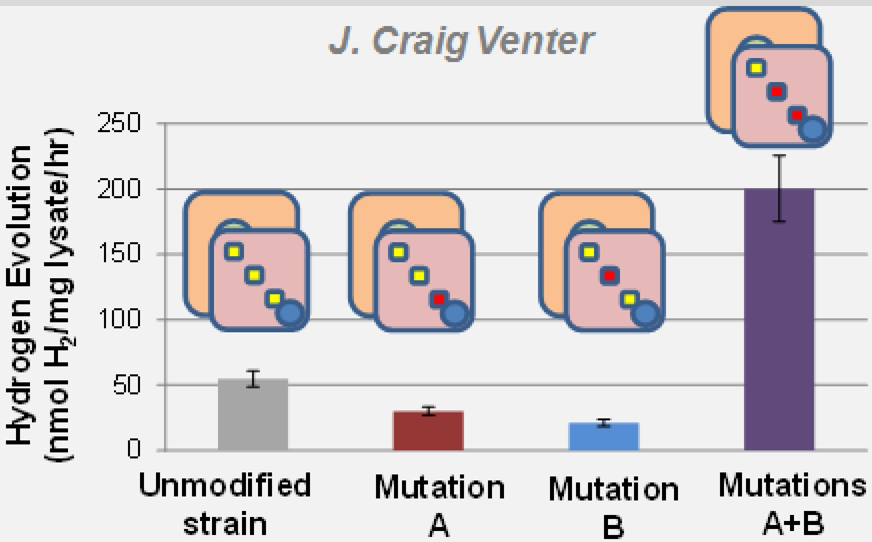
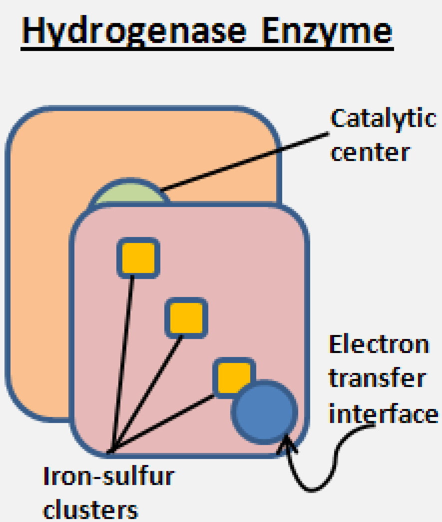
Successful genetic manipulation has improved hydrogen production.

Enhanced production in cyanobacteria

J. Craig Venter



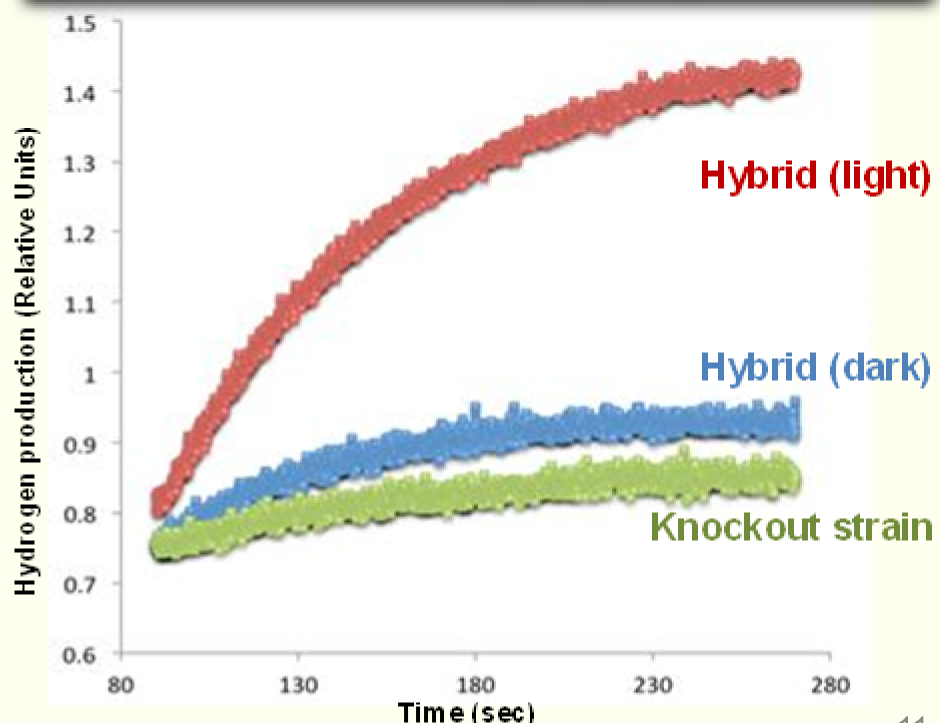
Achieved 300% increase in hydrogen production (from 50 to 200 nmol H_2/mg lysate/hour) through genetic modifications of the hydrogenase enzyme.



Expressed bacterial hydrogenase in algae

NREL

- Introduced gene for O_2-tolerant hydrogenase into a photosynthetic algae (native hydrogenases removed).
- Demonstrated light-induced H_2 production.
- Next steps: determine if activity is more O_2 tolerant than natural algal hydrogenase.



2012 Solar Thermochemical Progress (longer-term pathway)

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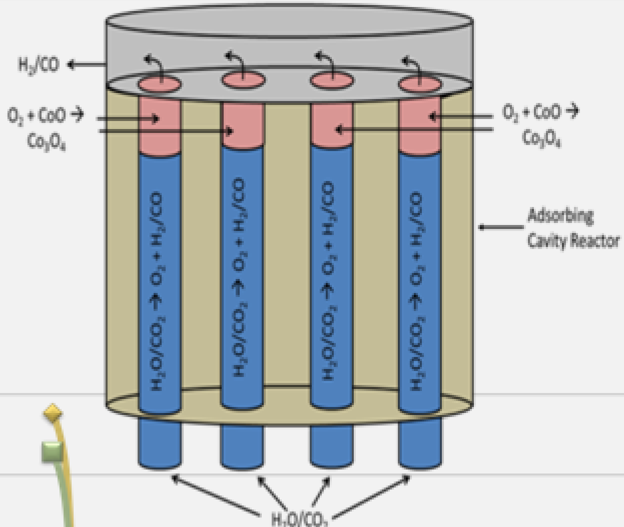
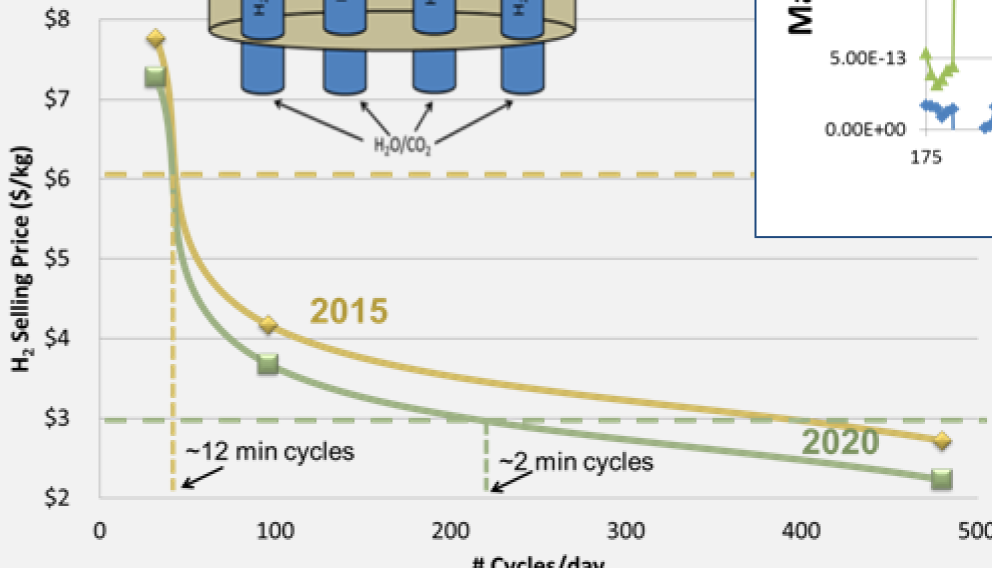
Development of hercynite-based isothermal redox with the potential for efficient and cost-effective solar-thermochemical hydrogen production

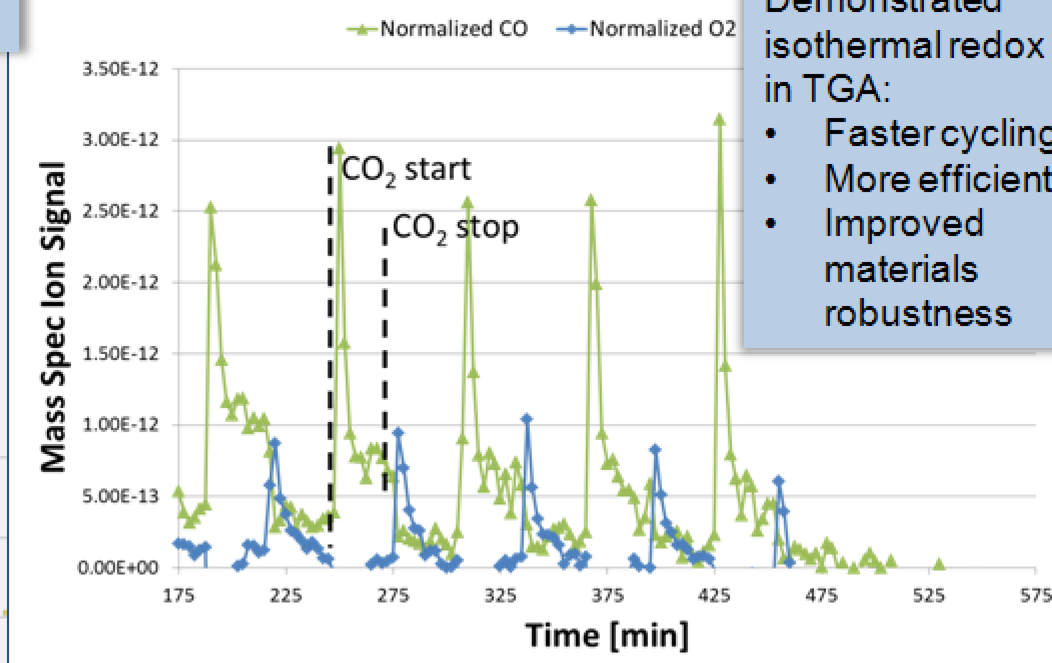
Isothermal reactor concept with feedstock-controlled reactions, and in-situ regeneration





(TIAX, LLC: DE-DT0000951; 2011)

U. Colorado Boulder



Demonstrated isothermal redox in TGA:

- Faster cycling
- More efficient
- Improved materials robustness

Identified isothermal redox system promising to meet DOE 2020 STCH cost target of $3.00/gge

-cost reductions realized through:

- decreased cycle time
- increased heat recuperation

2012 Progress: HTAC H_2 Production Expert Panel

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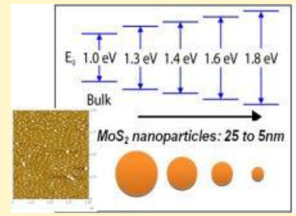
Panel Conducted by HTAC with DOE EERE-FCT Support*

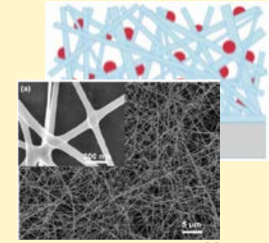
Panel of Experts from Industry, Academia and National Labs Assembled to :

- ***Assess status and prospects for near- and long-term hydrogen production technologies***
- ***Provide guidance to DOE FCT Program on coordination with other agencies and offices***
- ***Identify paths to optimize the DOE Renewable Hydrogen Production Portfolio***

EERE/EFRC Collaboration on PEC

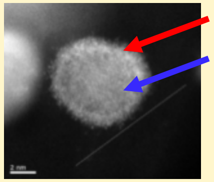


Bandgap tailoring



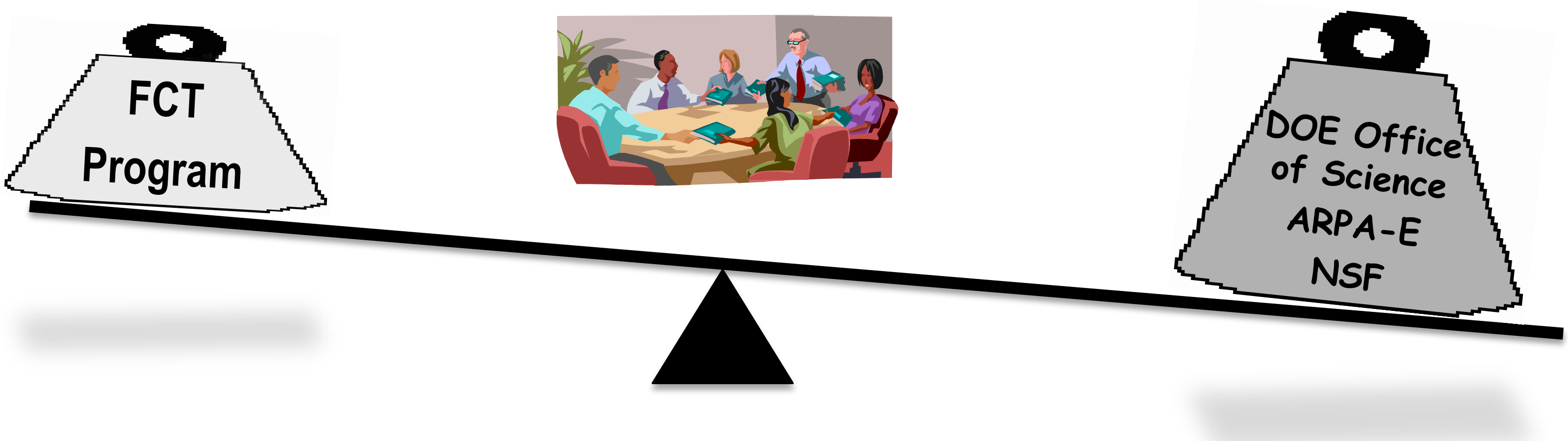
Nano-catalyst support scaffold (Stanford)

Mechanistic understanding of catalysts



Pt monolayer

Pd core



* "Hydrogen and Fuel Cell Technical Advisory Committee", DOE federal advisory committee per the Energy Policy Act of 2005

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

Leveraging Hydrogen Production R&D

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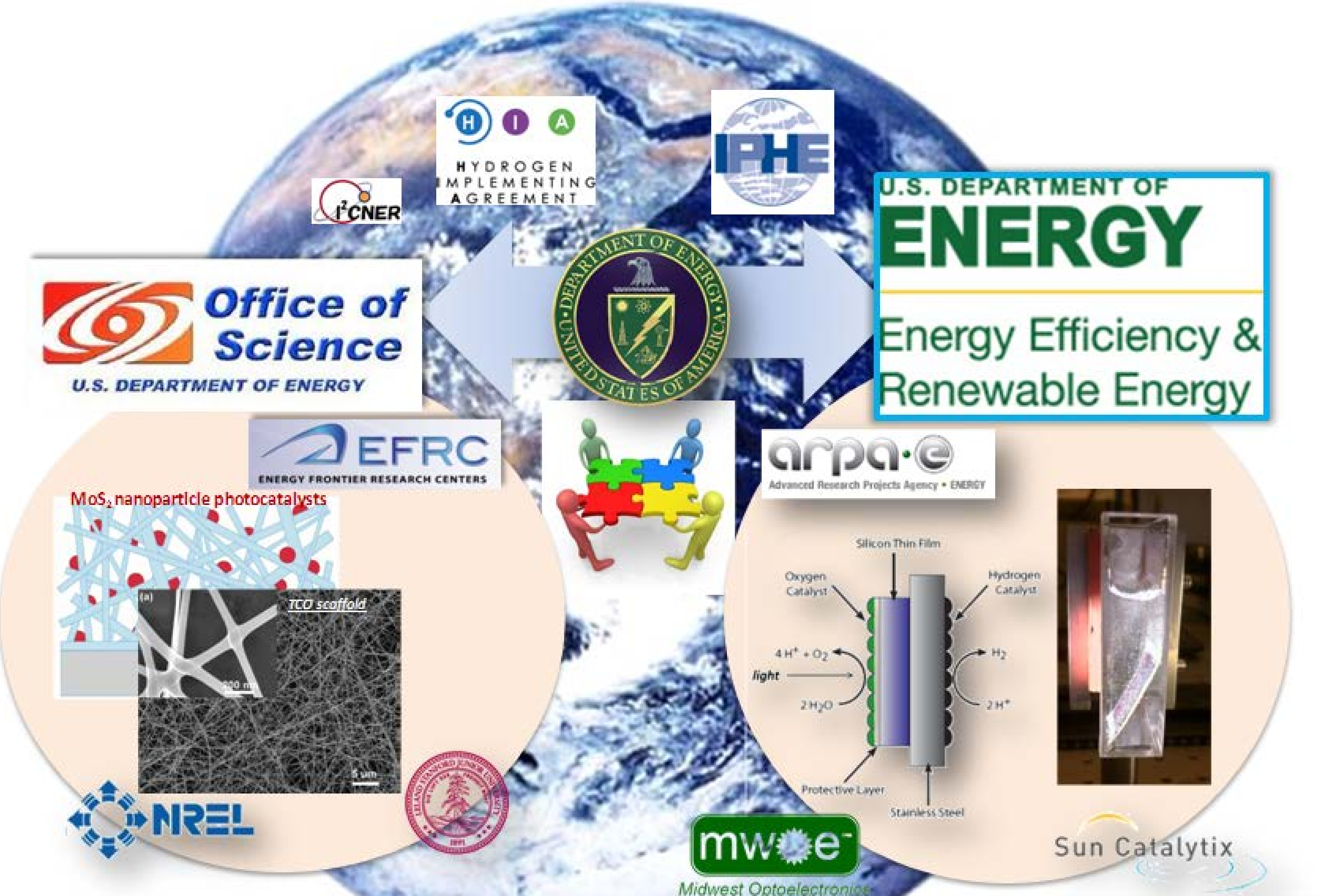

Fundamental and applied research at Stanford to develop quantum-confined photocatalysts and meso-structured supports

Integration of novel Sun Catalytix catalysts with MWOE multi-junction silicon cells to split water using sunlight

Summary

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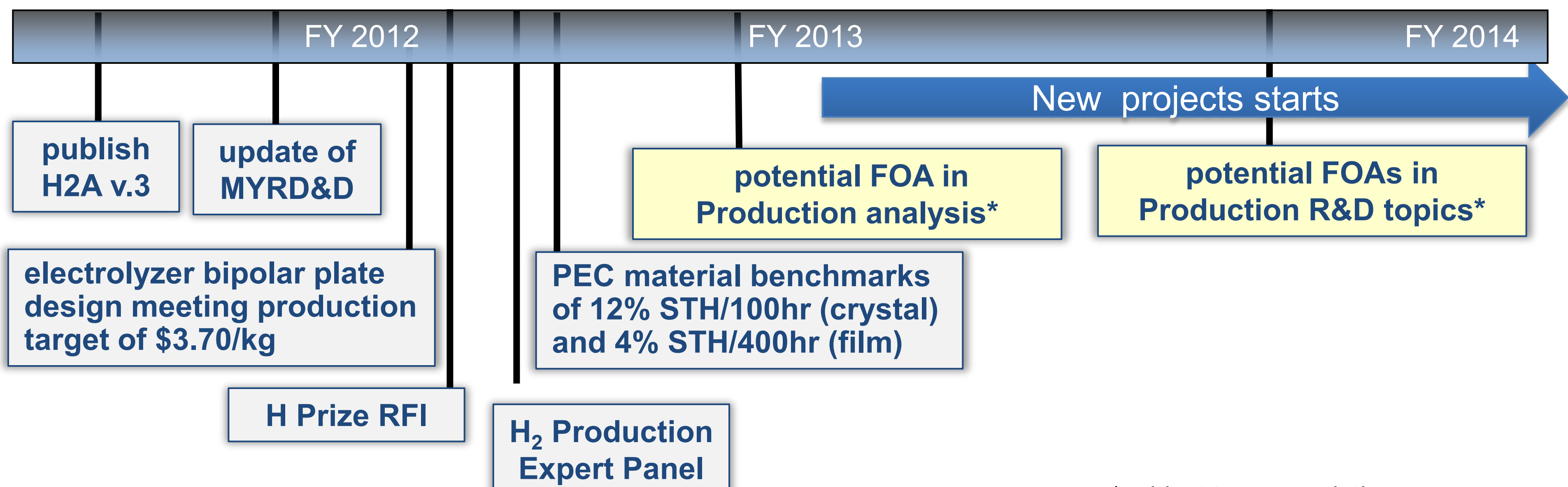
Major milestones & future solicitations

- **Publication of updated H2A version 3 completed**
- **Update of Production cost targets and Multi-Year RD&D completed**
- **Hydrogen Production Expert Panel workshop held and report in progress**
- **Hydrogen Prize RFI released**
- **Bipolar plate design for electrolyzer stacks with sufficient performance and durability to enables cost projections based on early prototypes meeting production target of $3.70/kg**
- **PEC material benchmarks of 12% STH/100hr (crystalline materials) and 4% STH/400hr (thin-films)**
- **Potential FOA in Production analysis, and FOAs in Production R&D: Tentative*- new starts**



*subject to appropriations

Reviewer Reminders

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- Deadline to submit your reviews is **May 25th at 5:00 pm EDT.**

- ORISE personnel are available on-site for assistance.
  - **Reviewer Lab Hours:** Tuesday – Thursday, 7:30 am – 8:30 pm; Friday 7:30 am – 1:00 pm.
  - **Reviewer Lab Locations:**
    - Crystal Gateway Hotel—Rosslyn Room (downstairs, on Lobby level)
    - Crystal City Hotel—the Roosevelt Boardroom (next to Salon A)

- Reviewers are invited to a brief feedback session – at 5:15 pm Thursday, in this room.

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.

For More Information

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**Mansfield Fellow for FY11 and FY12*

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Angelo Cangialosi (Energetics, Inc.)
Kim Cierpik (CNJV)

Key Participants – Hydrogen Production

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- **Analysis & Testing**
  - ORNL
  - PNNL
  - Univ. of Hawaii
  - ANL
- **Bio-Derived Liquids**
  - PNNL
  - NREL
- **Electrolysis**
  - Giner Electrochemical
  - Avalence
  - Proton OnSite
  - ORNL
  - NREL
- **Membranes/Separations**
  - Media and Process Technologies
  - TDA (SBIR Phase III)
- **Biomass Gasification**
  - GTI
- **Solar High Temperature Thermochemical H_2 Production**
  - SNL
  - ANL
  - SAIC
  - Univ. of Colorado, Boulder
  - NREL
- **Photoelectrochemical H_2 Production**
  - LANL
  - LLNL
  - Midwest Optoelectronics
  - MV Systems
  - Stanford University
  - NREL